Remote sensing of animals

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Abstract: The improved accuracy and precision of animal tracking via satellites has made a significant impact on quantifying large-scale biogeographic patterns for a variety of taxa with important implications for conservation and natural resource management. This paper reviews research undertaken from 1995 to 1999 to provide an overview of advances in the remote sensing of animal movements in both terrestrial and marine environments and to identify promising trends for biogeographic research in the twenty-first century. Remote sensing of animals by satellite provides a new method to test a number of biogeographic hypotheses related to migration and can identify a number of environmental correlates associated with the distributions of species. Tracking of smaller species and increases in sample size are sure to occur as transmitter size and cost continue to decrease in the next decade. Geographers can significantly contribute to the understanding of species dispersal and distributional patterns by combining real-time and archived global and regional datasets with existing data from past studies and future research projects. Only four studies used GIS data or remote sensed imagery in this review, while the remaining studies cited used simple digital line graphs of countries, topography, land and sea boundaries.

Key words: biogeography, conservation, marine environments, migration, remote sensing, satellite tracking, terrestrial environments.

1 Introduction

The ecologist and biogeographer James Brown once stated, ‘Imagine that all the individuals of one species could be made to glow so brightly as to be visible from space. If we could take a photograph from a satellite of the entire geographic range of the species, all of the individuals would appear as little points of light. Such a photograph would capture many interesting features of abundance and distribution’ (Brown, 1995: 47). Although it may not be possible to monitor an entire species population in this fashion, sampling of populations, especially endangered species, at a global, regional and local spatial scale may be commonplace in the not-so-distant future. The remote sensed tracking of animal movements via satellite is rapidly becoming a reality through recent advances in technology.
Satellite tracking of animals began in the early 1970s when tags weighing 5–11 kg with an accuracy of 5 km were attached to large mammals (Kenward, 1987). In the late 1980s, platform transmitter terminals were developed that could be attached to smaller mammals and birds. Signals from these transmitters were received by Tiros N series of National Oceanic and Atmospheric Administration (NOAA) satellites and relayed to ground stations in real-time (Seegar et al., 1996). Platform transmitter terminals in the late 1980s and early 1990s weighed between 1.5 and 1.7 kg with an accuracy of approximately 1 km (Messier et al., 1992). Recent technological advances in chip size, battery size and longevity, and an increased number of satellites and ground stations have resulted in transmitters weighing between 20 and 30 g that are capable of locating a species within 150 m (Argos, 2000). The improved accuracy and precision of animal tracking via satellites has made a significant impact on quantifying large-scale biogeographic patterns for a variety of taxa with important implications for conservation and natural resource management. In this paper, I review research undertaken from 1995 to 1999 to provide an overview of advances in the remote sensing of animal movements and migrations in both terrestrial and marine environments and to identify promising trends for biogeographic research in the twenty-first century.

II Terrestrial environments

Traditional methods for monitoring terrestrial animal movements and migrations have used radar, banding and very high frequency (VHF) radiotelemetry. Doppler radar has been used since the 1950s to study bird migration and radar has proved to give an insight into bird speed, direction and altitude, especially for large flocks of seasonal migrants (Eastwood, 1967). However, radar cannot be used to identify individual species and an analysis of avian movements can be complicated by the amount of moisture, smoke and dust particles in the atmosphere (Cohn, 1999). Bird banding has been undertaken for more than a century and presently, there are over 1000 licensed bird banders in the USA alone that band an average of 1.2 million individuals every year (Gauthreaux, 1996; Weidensaul, 1999). Observations and recaptures of banded birds have provided scientists with information on migration flyways, range size and nesting site fidelity. Yet, the temporal and spatial resolution of bird banding data is relatively poor, with recovery rate for small birds less than 2% and waterfowl less than 15% (Weidensaul, 1999). The advent of ground-based VHF-radio tracking in the 1960s allowed scientists to monitor species movements and home ranges over 50 to 300 km² (Kenward, 1987). VHF tracking has a number of advantages over satellite tracking because it can record a species location to within a couple of meters and can be undertaken in areas with dense canopy cover such as tropical rainforests. The advantages of satellite telemetry are that once the transmitter has been attached, the researcher does not need to undertake extensive field triangulation and it is easier to study wide-ranging species that regularly cross international boundaries.

Remote sensing of animals via satellites in terrestrial environments has primarily been undertaken on globally threatened raptors, wetland birds and mammals. Satellite tracking of white-naped cranes (Grus vipio Pallas) and red-crowned cranes (Grus japonensis P.L.S. Muller) in east Asia over three years provided significant and previously unknown insight into migration routes and stopover sites (Higuchi et al.,
In particular, it was discovered that cranes stopped at two sites in Korea’s demilitarized zone for 87% of their total migration time and this has significant conservation implications (Higuchi et al., 1996). Papi et al. (1997) found previously unknown migration routes of the European white stork (Ciconia ciconia (L.)). Some storks did not migrate though the best-known western route at Gibraltar, but over open seas between Europe and Africa. Satellite tracking of the white-faced whistling duck (Dendrocygna viduata (L.)) in South Africa and the houbara bustard (Chlamydotis undulata (Gray)) from the United Arab Emirates to Turkmenistan identified the importance of water availability and temperature for predicting seasonal migration of these species in arid regions (Osborne et al., 1997; Petrie and Rogers, 1997). The monitoring of the migration patterns of the fennoscandian lesser white-fronted goose (Anser erythropus L.) suggested higher hunting pressures along the species eastern route across Russia than the species western route through Europe (Lorensten et al., 1998). Ariza (1998) reported that immature imperial eagles (Aquila heliaca adalberti Brehm) in Spain were killed by electrocution after leaving their nests and, when appropriate changes were made to power lines, mortality dropped from 60% to 10% after the survey. In the western hemisphere, Fuller et al. (1998) tracked 61 peregrine falcons (Falco peregrinus Tunstall) and 34 swainson’s hawk (Buteo swainsoni Bonaparte) that resulted in quantitative data on length, routes and duration of migration that was previously unattainable by other methods. For instance, the swainson’s hawk has a broad northern distribution until it migrates to southern Mexico, where the species begins a very concentrated migration route to South America (Figure 1). High mortality was noted in the swainson’s hawk

![Figure 1](https://example.com/swainson Hawk.png)

**Figure 1** Swainson’s hawk southward and northward migration as recorded by satellite telemetry

*Source: Fuller et al. (1998). Reprint with kind permission from the authors and *Journal of Avian Biology*
wintering grounds in the Pampas of Argentina, and when researchers visited sites from satellite-derived location data, they discovered over 4000 dead hawks (Seegar et al., 1996). The birds had been killed by a toxic pesticide recently introduced to Argentina. After 18 months of international collaboration the situation was remedied.

Satellite tracking of elephants identified larger than expected home ranges that extend well outside national park boundaries in Botswana (Tchamba et al., 1995), different foraging ranges between savanna and forest elephants in Zaire (Holden, 1992) and monitored the success of the elephant translation programme in Malaysia (Stuwe et al., 1998). Verlinden and Gavor (1998) monitored the movements of 47 female elephants via satellite and compared data on patterns of migration with geographic information system (GIS) layers of habitat and water sources in Botswana. They discovered the existence of resident elephant groups that remain close to permanent water sources and migratory herds that travel approximately 200 km to reach water in the dry season. They reported a nonrandom distribution of elephants with regard to habitat type. Resident herds selected woodland dominated by *Baikiaea plurijuga* Harms., *Pterocarpus angolensis* D.C. and *Erythrophleum africanum* Harms., but not *Colophospermum mopane* Kirk ex J. Leonard., while migratory herds selected habitats dominated by *C. mopane*. This suggests that migratory herds selected more nutrient-rich habitats than resident herds throughout the year.

### III Marine environments

Monitoring animal movements in marine environments was always problematic before the advent of satellite telemetry, with information on species movements and migrations collected by direct observations from the shore, boats and aerial surveys. Boat and aerial surveys rely heavily on visual siting of near-shore species with the aid of keys or tags to identify individuals (Garner et al., 1999). Boat and aerial surveys provide important data on abundance and distribution at a local spatial scale; however, these survey methods provided limited spatial and temporal data. The largest aerial surveys collect line transect data that cover less than 1000 km² and surveys are generally undertaken in the summer and cannot be undertaken during inclement weather (Sagar and Weimerskirch; 1996; Wilson et al., 1996; Garner et al., 1999). Before the advent of satellite tracking almost all ecological and distribution data on marine birds were collected from land-based surveys during the breeding season. Direct observation of breeding sites provided data on abundance but it was difficult to monitor or collect data on the movement of species at sea beyond simple data on duration of foraging trip (Weimerskirch et al., 1999).

Satellite tracking of pelagic seabirds has provided a number of insights into biogeographic patterns (Georges et al., 1997). Satellite tracking of the southern buller’s albatross (*Diomedea bulleri* Rothschild) in New Zealand (Sagar and Weimerskirch, 1996) and the wandering albatross (*Diomedea exulans* L.) in the Indian Ocean (Nicholls et al., 1995) identified foraging strategies unique to each species, differences in foraging ranges between males and females and differences in foraging ranges during breeding and nonbreeding periods. Weimerskirch et al. (1999) monitored the white-chinned petrels (*Procellaria aequinoctialis* L.) in the Crozet and South Georgia islands and discovered that this species has the longest mean foraging range ever recorded for a
Breeding birds in the Crozet islands undertake forage trips of over 2300 km during incubation. A number of studies have been performed on penguins: magellanic penguins (*Spheniscus magellanicus* I.R. Forster) off the coast of Argentina (Stokes *et al.*, 1998), humboldt penguins (*Spheniscus humboldti* Meyen) in northern Chile (Culik and Luna-Jorquera, 1997), and adelie penguins (*Pygoscelis adeliae* Hombron & Jacquinot) in Antarctica (Davis *et al.*, 1996). In particular, Stokes *et al.* (1998) discovered that the magellanic penguins initially travel rapidly and make shallow dives and later travel slowly and make deeper dives. The Culik and Luna-Jorquera (1997) study of the humboldt penguin identified a significant correlation between dive duration and sea surface temperature, as well as a negative correlation between dive duration and fishery landings, suggesting that foraging effort increased.

Studies of marine mammals via satellite are possible because these species spend a significant amount of time at the surface, which allows transmitters to report their location. Satellite tracking has been undertaken on five whale species and has revealed important and previously unknown patterns of migration (Mate *et al.*, 1998; Richards *et al.*, 1998). Mate *et al.* (1998) collected the first route and travel speed data for the humpback whale (*Megaptera novaeangliae* (Borowski)) migration from Hawaii to Alaska and showed that humpback whales in Hawaii had faster interisland movements than previously thought. A study of the northern right whales (*Eubalaena glacialis* (Muller)) in Nova Scotia reported that whale distributions coincided with areas intensively used for fishing, shipping and recreation, which has important implications for management (Mate *et al.*, 1997). When the right whale distributions were compared with sea surface temperature images from NOAA satellites, it was discovered that most whales spend extended periods in upwelling zones (Mate *et al.*, 1997). Westgate *et al.* (1998) assessed the success of a rehabilitation programme for harbour porpoises (*Phocoena phocoena* L.) in the Atlantic coast of the USA and showed that reintroduced harbour porpoises had similar patterns of distribution as wild individuals suggesting that they behave in a similar manner. Deutsch *et al.* (1998) tracked 83 west Indian manatees (*Trichechus manatus* L.) along the coast of Florida and Puerto Rico and combined GIS layers of benthic habitats to report that manatees prefer large dense seagrass beds rather than patchy or scattered seagrass beds. The satellite telemetry data also identified manatee travel corridors and high-use areas that provided federal and state managers with data to implement manatee sanctuaries and boat speed regulations. An example of real-time daily movements of manatees in Central America are available at [http://www.wesave.org/mantee](http://www.wesave.org/mantee)

Tracking of leatherback turtles (*Dermochelys coriacea* L.) off South Africa and green turtles (*Chelonia mydas* L.) in the South China Sea revealed the ability of these species to maintain a straight course in open water even when swimming perpendicular to ocean currents (Luschi *et al.*, 1996; Hughes *et al.*, 1998). This provides strong evidence and further supports the hypothesis that sea turtles use geomagnetic features in long-distance navigation in the absence of cues such as coastline and shallow bottom (Lohmann *et al.*, 1999). Block *et al.* (1998) attached pop-off satellite tags to Atlantic bluefin tuna (*Thunnus thynnus* (L.)) to evaluate the movement and survivorship of the species independent of commercial fisheries data (Figure 2). They reported a 95% success rate for data recovery indicating that the technology and concept of pop-off satellite tagging are sound for medium and large fish. Locations of satellite tags were compared with archived data on sea surface temperature acquired from Advanced
Very-High Resolution Radiometer (AVHRR) imagery to identify correlations with species movement and thermal niches. They discovered that Atlantic bluefin tuna has the widest thermal niches of all the Scombridae, experiencing daily average temperatures that range from 6 to 24°C in late winter and early spring.

**IV Prospects**

Remote sensing of animals by satellite provides a new method to test a number of biogeographic hypotheses related to migration and to identify a number of environmental correlates associated with the distributions of species. Tracking of smaller species and increases in sample size will occur as transmitter size and costs continue to decrease in the next decade. Currently, transmitters are being equipped with sensors that collect acoustic data, environmental sensors that measure temperature, altitude, humidity and digital cameras weighing 2 g (Seegar *et al.*, 1996; Cohn, 1999). Geographers can significantly contribute to the understanding of species dispersal and distributional patterns by combining real-time and archived global and regional datasets with existing data from past studies and future research projects. Only four studies in this review used GIS data or remote-sensed imagery, while the remaining papers cited used simple digital line graphs of countries, topography, land and sea boundaries. There are a number of
large temporal and spatial datasets archived for climatic, oceanographic and terrestrial variables that could be used for such research projects (Perry, 1998; Donoghue, 1999; Lillesand and Kiefer, 2000). Data on temperature, precipitation and cloud cover could identify the effects of climatic variables on species movements including the effects of climatic phenomena such as El Niño. Oceanographic variables, such as sea surface temperature, primary productivity and water quality, can be used to predict the distributions of marine animals and correlates of species movements. Global vegetation indices can be used to identify correlates with seasonal dispersal, while at a regional scale, high resolution land use, land cover and habitat types could identify habitat preferences and migration routes and barriers. These physical geography variables, when combined with satellite tracking data, can be used to undertake robust hypotheses tests concerning the movements and migrations of species.

References


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