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Biotelemetry and biologging in endangered species research and animal conservation: relevance to regional, national, and IUCN Red List threat assessments

Steven J. Cooke*

Fish Ecology and Conservation Physiology Laboratory, Department of Biology and Institute of Environmental Science, Carleton University, 1125 Colonel By Drive, Ottawa, Ontario K1S 5B6, Canada

ABSTRACT: The current biodiversity crisis is characterized by the decline and extinction of numerous animal populations and species world-wide. To aid in understanding the threats and causes of population decline and the assessment of endangerment status of a species, conservation scientists and practitioners are increasingly relying on remote assessments using biotelemetry (radio telemetry, acoustic telemetry, satellite tracking) and biologging (archival loggers) or hybrid technologies (e.g. pop-up satellite tags). These tools offer increasingly sophisticated means (e.g. large-scale telemetry arrays, fine-scale positioning, and use of physiological and environmental sensors) of evaluating the behaviour, spatial ecology, energetics, and physiology of free-living animals in their natural environment. Regional, national, and international threat assessments (e.g. the International Union for the Conservation of Nature [IUCN] Red List) require basic knowledge of animal distribution, emigration, behaviour, reproductive potential, mortality rates, and habitat use, which in many cases can all be obtained through biotelemetry and biologging studies. Such studies are particularly useful for understanding the basic biology of animals living in harsh environments (e.g. polar regions, aquatic environments), for rapidly moving or cryptic animals, and for those that undertake large-scale movements/migrations (e.g. birds, insects, marine mammals and fish). The premise of this paper is that biotelemetry and biologging have much to offer and should be embraced by the conservation science community to aid in assessment of threats and endangerment status. It is crucial that studies on endangered species must not further contribute to species decline or retard recovery. As such, there are complicated ethical and legal considerations that must be considered prior to implementing tracking studies on endangered wildlife. Furthermore, as many endangered animal species occur in developing countries, there is a need to develop capacity (financial support for the research and technical telemetry skills) for designing and conducting tracking studies. To stem the loss of biodiversity and aid in the recovery of endangered animal populations, there is a need for innovative and interdisciplinary research, monitoring programs and research initiatives to inform decision makers. It is clear that biotelemetry and biologging are not a panacea; however, they are valuable tools available to conservation practitioners. Used appropriately, biotelemetry and biologging have the potential to provide data that is often unattainable using other techniques, and can reduce uncertainty in the assignment of conservation status.

KEY WORDS: Biotelemetry · Biologging · Tracking · Conservation · Methods · Endangered species

*Email: steven_cooke@carleton.ca

INTRODUCTION

The first step to initiating conservation actions for endangered[1] organisms is to identify the populations or species that are in decline (deterministic processes) or are faced with risk of extinction because they are small (stochastic processes; Caughley 1994, Brook et al. 2006). Key to this process is the use of objective, quantifiable, and consistent criteria to assess the status of a species. Included in this analysis is the identification of threats which are used to inform conservation actions if required. Globally, the Species Survival Commission (SSC) of the IUCN World Conservation Union (IUCN; www.iucn.org) produces the IUCN Red List of threatened species (i.e. the Red List). The Red List classifies globally endangered plant and animal taxa and is regarded as the most comprehensive and authoritative list of its kind (Lamoreux et al. 2003, Rodrigues et al. 2006). IUCN has developed a clear and standardized framework for the assessment of species status which increasingly relies on rigorous scientific input (rather than subjective expert opinion) and has become more recognized by the scientific community as a valuable and necessary tool in biodiversity conservation and research (Rodrigues et al. 2006). Nonetheless, decisions are often made in the face of uncertainty because for many species we do not have a complete understanding of their natural history, let alone their demography (Akçakaya et al. 2000).

A candidate species (or group of species) is evaluated relative to a number of criteria which are then used by the IUCN and their expert panels to assess the need for designation within formal categories, including threatened, endangered, critically endangered, and extinct (Mace 1994). Formal thresholds based on population size, population dynamics, geographic range, connectivity, etc. are used for categorization. Once an animal has been classified as 'endangered', recovery plans can be developed and conservation actions implemented (Mace 1995, Collar 1996). For instances in which there is insufficient information to assess the status, the phrase 'data deficient' is used. Similar assessments also occur at a local, regional, and national scale, although many rely at least in part on the IUCN criteria (Gardenfors et al. 2001, Miller et al. 2007). In recent years, the Red List is increasingly being used not only as a system for assigning endangerment status, but also as a means of aiding conservation science, although the utility of this for some groups is limited (Hayward et al. 2007a). Indeed, Butchart et al. (2005) suggested that Red List indices could be used to evaluate progress towards meeting biodiversity targets. For the Red List and other related assessments to be useful in conservation, data used to evaluate and assign endangerment status must be rooted in sound, robust science.

Scientific data that form the basis of threat identification and endangerment assessments typically come from field studies of natural history and population biology. The study of animal ecology and demographics is challenging, as many species tend to avoid human observers and travel great distances, often in environments that present numerous challenges to humans. As a result, population estimates generated for wildlife populations are notoriously fraught with bias and error, which brings uncertainty to threat assessments and the management (see Williams et al. 2002). However, improvements in statistical techniques and, more critically, innovations in technology, have enabled scientists to generate robust population estimates and to understand the extent to which different populations interact (which is linked to the declining population paradigm). In particular, methods such as biotelemetry and biologging (defined below; herein biotelemetry is simply called 'telemetry' and biologging 'logging') are increasingly being applied to the study of animal ecology in the wild because they can provide detailed information on the fundamental biology of animals, including assessments of behaviour, survivorship, spatial ecology (i.e. the distribution of animals in space and time), energetics, and physiology that is often unattainable using other techniques (Cooke et al. 2004, Block 2005, Ropert-Coudert & Wilson 2005, Hooker et al. 2007). Telemetry and logging are also being used to address more applied questions associated with wildlife medicine (Karesh 1999) and wildlife management (Millspaugh & Marzluff 2001). However, only in the last decade or so have these tools been regarded as having utility in studies specifically related to animal conservation.

[1]For this review I have elected to use the word 'endangered' when referring to the status of animal populations/species that are regarded as 'threatened', 'endangered', 'special concern', 'vulnerable', etc. This term is more generic than IUCN terminology (i.e. my definition includes all categories and terms including those used by regional and national bodies that do not follow the terminology used by the IUCN), but this follows the same approach as the journal 'Endangered Species Research' in that the word 'endangered' is used in the broadest possible sense and includes organisms of conservation concern. I also adopt the terminology of different authors. For example, if a species is described as 'critically endangered', I adopt their terminology when summarizing their findings. On occasion, I also use the words 'endangerment status' or 'endangerment assessments' when referring to evaluations of whether or not an animal is endangered (or some other specific status) according to some regional, national or international body

Although there have been several recent syntheses on telemetry (Cooke et al. 2004) and logging (Block 2005, Ropert-Coudert & Wilson 2005), none of these reviews have explicitly considered or focused on how these tools could be used to aid in understanding the endangerment status of species and the threats that have lead to population declines. Hence, the purpose of this paper is to describe and evaluate the extent to which telemetry and logging could be embraced by the conservation science community. The focus is intentionally broad, encompassing all animal taxa and habitats including vertebrates and invertebrates (note that there are reasonably few studies of invertebrates that use telemetry, so their coverage is minimal). However, an assessment of the use of telemetry and logging to identify or assess conservation actions is beyond the scope of this paper. Because of the nearly universal acceptance of the Red List species assessment criteria (Miller et al. 2007), the analysis uses their assessment criteria and threat categories as a foundation for the analysis, based on the assumption that this information could easily be adapted to local, regional, or national assessments. Considering the current biodiversity crisis (Mace 1995) and the extent to which various animal taxa are in decline or considered endangered, there is a clear need for novel approaches to aid conservation practitioners in making decisions that will promote the development of effective conservation strategies (Salafsky et al. 2002) focused on the species that are most at risk of extinction (Miller et al. 2006).

TOOLS

Overview

Prior to addressing opportunities and applications of telemetry and logging technology, it is first necessary to understand the range of tools available and their capabilities. The characteristics of telemetry and logging are similar; both involve the remote monitoring of some behavioural, physiological, or environmental information. However, there are fundamentally different means of collecting the information. For telemetry, a signal emanating from a device carried by the animal (transmitter) sends the information to a receiver. At times, the power for transmission can be derived from an external energy source (e.g. Passive Integrated Transponders, PIT tags; see Gibbons & Andrews 2004; however, this is not within the scope of this paper). The most common means of signal transmission is radio frequencies. Some devices emit radio signals that can be detected by satellites (designated satellite telemetry herein), whereby the devices periodically uplink (i.e. send a signal) to orbiting satellites; the location of the transmitter is then estimated using mathematical equations (Fancy et al. 1988, Harris et al. 1990). However, in some environments, radio signals are not well propagated (e.g. marine environments or deep freshwaters). Acoustic (or ultrasonic) telemetry is thus favoured for some aquatic systems but does not work in a terrestrial setting. For logging, the information is recorded and stored in an animal-borne device (archival logger) and information is downloaded when, and if, the logger is retrieved (Boyd et al. 2004). To date, logger technologies have primarily been used in aquatic/marine environments (e.g. Block 2005, Hooker et al. 2007) but are becoming increasingly common in terrestrial (including avian) applications. There are an increasing number of techniques that couple these 2 technologies, first logging information on board and, when possible, then transmitting the information, usually to a satellite (e.g. pop-up satellite tags which are used with aquatic animals and only transmit to satellites when they fall off the animal and float to the surface; see Block 2005) or to a receiving station by means of communicating histogram acoustic transponder (CHAT) tags; see Voegeli et al. 2001). Increasingly, global positioning system (GPS) techniques are being used where an animal-borne device determines and logs (or transmits) its geographic position (often within 5 m; Rodgers et al. 1996). In this case, the satellites function as a transmitter and the telemetry device serves as the receiver. The telemetry device then calculates the location of the animal based on the time required for the signal to be received, and the data are stored for remote downloading (e.g. via satellite) or subsequent retrieval.

When using telemetry devices, it is possible to use manual tracking, deploy fixed telemetry arrays, or combine the 2 approaches. Increasingly, telemetry arrays have been deployed, enabling far more continuous monitoring of animals (Heupel et al. 2006), sometimes in 3 dimensions. Some arrays are localized and provide precise information on animal positions, sometimes encompassing multiple species (i.e. community level tracking of predators and prey). For example, the Warner Lake ecological observatory in eastern Ontario uses a whole lake 3D telemetry system to position fish and turtles continuously in 3 dimensions throughout the year (including under ice; Cooke et al. 2005). There is a comparable terrestrial array in the Smithsonian Research Project in Panama where massive antennas are used to automatically position animals such as ocelots and song birds (Wikelski et al. 2007; see www.princeton.edu/%7Ewikelski/research/index.htm). Large-scale arrays have been deployed in oceans, and this network continues to grow (as the Ocean Tracking Network; see www.oceantrackingnetwork.org/index.html). Although these systems have not been implemented to specifically study endangered species, this technology can be applied to systems that contain animals of conservation concern, to gain better insight into the species' fundamental biology, ecology and environmental interactions, all of which are relevant to the assessment of endangerment status. Currently, the Pacific Ocean Shelf Tracking (POST) project has acoustic telemetry arrays deployed from the Bering Sea to northern California, as well as into several inland rivers (e.g. the Fraser River and Columbia River; Welch et al. 2002; see www.postcoml.org/). The POST project has already documented unexpected movements of endangered white sturgeon *Acipenser transmountanus* tagged in California into the coastal waters of British Columbia, thus expanding its known range (Welch et al. 2006). In addition to the deployment of fixed arrays, there is also an increased emphasis on multi-species and multi-trophic level coordinated tagging studies (e.g. the Tagging of Pacific Pelagics [TOPP] project covers sea birds, marine mammals, pelagic fish, and turtles; Block et al. 2002). Such studies provide the opportunity to identify hotspots i.e. not the classical definition of areas with high levels of endemism (Myers et al. 2000), but those where multiple animals congregate (see Hooker et al. 2007). Continuous tracking studies in marine environments for monitoring highly mobile species or migratory birds have been replaced with satellite and/or logging technologies that enable the scientists to assess movements at the scale of entire oceans or continents (e.g. Shaffer et al. 2006), and for studies that focus on smaller, often discrete geographic areas, fixed-station telemetry receiver arrays can be implemented.

Beyond simply providing information on the position of an animal, logging and tracking devices are becoming increasingly sophisticated and can now be used for the monitoring of biological and environmental variables which can help to define critical habitats (i.e. those specific areas within the geographical area occupied by the species on which are found those physical or biological features essential to the conservation of the species). Indeed, logging techniques all rely on the sensing and logging/recording of information derived from one or more sensor (Boyd et al. 2004). Sensors provide detailed information on habitat use and environmental relations, such as temperature, depth, light levels, salinity, and dissolved oxygen. In recent years, loggers and telemetry devices have also been equipped with imagery sensors so that scientists can obtain photographs or video footage from the animals' vantage point (Marshall 1998). Furthermore, some devices focus on the behaviour (e.g. monitoring sounds to assess chewing/feeding activity), energetics (e.g. measuring fin or wing beats), and physiology (e.g. heart rate or the chemistry of body fluids) of the organism being studied. Cooke et al. (2004) provide a detailed overview of sensor technology and its application to the field of ecology. To date, there have been reasonably few applications of sensor technology to understand animal endangerment and conservation status. However, there are many options including the determination of the effects of environmental change of phenology (e.g. Cooke et al. 2006) and the thermal ecology of sensitive species (Parmesan 2006).

As noted above, not all telemetry techniques are suitable for all environments or species. However, there is a telemetry or logging tool that should work in almost any environment or on any species (except for size limitations with smaller animals). Minituarization of these devices is an ongoing process such that the number of species suitable for such research is steadily increasing. For each primary habitat type, the opportunities and challenges of telemetry were summarized using the IUCN authority file on habitat types (IUCN Habitats Authority File Version 2.1; available at: www.iucn.org/themes/ssc/sis/authority.htm) (Table 1). As evident from Table 1, one must have a thorough understanding of the technological choices available as well as their strengths and weaknesses prior to selecting a technology for a given environment. Similarly, having a basic understanding of the natural history of a given species will also help to ensure that the appropriate technology is considered. Although Table 1 provides an overview, it is important for new telemetry users to consult telemetry engineers and other telemetry practitioners when designing a study that relies on this technology.

Desirable characteristics

One of the most desirable characteristics of telemetry and logging for the study of endangered species is that one can study free-living animals in their natural environment. This is particularly relevant to endangered species where removal of the animals to captivity would typically only be done as a conservation measure (e.g. to establish a captive breeding species). In nature, animals face a suite of site-specific biotic (e.g. predation) and abiotic (e.g. weather, habitat heterogeneity) conditions that cannot be adequately replicated in captivity and that need to be characterized and understood in an effort to understand the population ecology of an endangered animal. The monitoring of unrestrained free-ranging animals in their own environment eliminates laboratory artifacts but also eliminates the need to remove animals with reproductive potential from an endangered population. Depending on the technology used, these tools also provide the

Table 1. Relevance of biotelemetry and biologging techniques to different habitat types. Habitat types based on the IUCN authority file, available at: www.iucn.org/themes/ssc/sis/authority.htm

Habitat type	Technology	Benefits and opportunities	Challenges
(1) Forest	Radio telemetry (arrays and manual tracking; e.g. Vilella & Hengstenberg 2006), satellite	Trees can be used for establishing large-scale radio telemetry arrays that reach from the ground to the canopy; antennas can be deployed at strategic points (e.g. wildlife trails, nest boxes)	Dense foliage can impede aerial radio tracking from planes and can interfere with satellite tracking; manual tracking typically restricted to foot or helicopter
(2) Savanna	Radio telemetry (arrays and manual tracking; e.g. Loveridge et al. 2007), satellite	Open environments are conducive to satellite tracking; radio telemetry effective in open environments (manual plane, truck, foot, or arrays)	Manual tracking likely has limited utility
(3) Shrubland	As (2), e.g. Haupt et al. (2006)	As (2)	Dense shrub growth can make manual tracking difficult
(4) Grassland	As (2), e.g. Haupt et al. (2006)	As (2)	As (2)
(5) Wetlands (inland lakes and rivers, terrestrial and aquatic animals)	Radio (arrays and manual tracking; Zurstadt & Stephan 2004) and acoustic (arrays and manual tracking; Cooke et al. 2005); satellite for terrestrial organisms (McCulloch et al. 2003)	Manual tracking can be done on foot, by boat, canoe, or plane	When tracking aquatic organisms, acoustic telemetry may not work well in shallow or noisy (river) environments; conversely, radio telemetry does not work well in deep water
(6) Rocky areas	Radio telemetry (arrays and manual tracking; Dickson & Beier 2007), satellite (McCarthy et al. 2005)	Manual tracking can be done on foot, by helicopter, and plane	May be difficult to determine precise locations; radio signal reflections from rock faces can make pin-pointing animals difficult
(7) Caves and subterranean habitats	Radio telemetry (arrays and manual; Clark et al. 1993)	Radio telemetry arrays could be deployed at entrances and choke points	Radio signal reflections; lack of room for radio telemetry antennas
(8) Desert	As (2)	As (2); watering holes may serve as an appropriate site for arrays	As (2)
(9) Sea	Acoustic telemetry (arrays and manual; Zeller 1997), satellite tags (conventional; Call et al. 2007; pop-up and other loggers; Block et al. 2001), radio (manual combined with other techniques; Ries et al. 1998, Deutsch et al. 1998)	Acoustic telemetry extremely effective in marine environments; arrays frequently used to track movements; radio tracking can be used to locate animals (e.g. marine mammals) during periods where they are on the surface or shore	Difficult to deploy acoustic arrays in deep environments; satellite transmissions limited to periods when animals (or transmitters; i.e. pop-up) are at the surface; loggers must be retrieved for downloading
(10) Coastline	As (9), Starr et al. (2005)	As (9), acoustic telemetry arrays useful for monitoring coastal movements	Nearshore regions can be noisy, making acoustic telemetry challenging
(11) Artificial terrestrial	As (2), Gehrt (2005)	As (2)	Electrical interference from human infrastructure can make radio tracking difficult; use of some manual tracking methods difficult; potential for vandalism to arrays
(12) Artificial aquatic	As (5), Szedlmayer & Schroepfer (2005)	As (5)	As (5)
(13) Introduced vegetation	As (1) or (2) depending on density of foliage	As (1) or (2)	As (1) or (2)

opportunity to focus on animal behaviour across a variety of scales. For example, to identify the seasonal critical habitats and geographic range of a species, telemetry or logging could be used at a spatial (e.g. site, regional, continental) and temporal (e.g. hours, days, years) scale that coincides with the biology of the animal.

Another benefit of telemetry and logging technology is that they can produce continuous data streams (through use of arrays, loggers, or satellites) that eliminate data gaps during periods when animals are not monitored manually by research team members. Long-term and continuous records of behaviour facilitate the detection of trends through time in terms of spatial ecology and phenology. Indeed, data can be collected day and night and in harsh environmental conditions for extended periods without requiring continuous human support. Such an approach is particularly important for organisms that inhabit large ranges, exhibit rapid movement, or occupy habitats that are difficult to study. These tools also enable a researcher to characterize the variation among individuals and to recognize the plasticity of the responses. Individual variation in behaviour is increasingly being recognized as important for the conservation of biodiversity, as the variation can provide a better idea of the extent to which animals will differ from a 'mean' response (e.g. how far will they range from their 'mean' home range). Telemetry is also an ideal tool for linking individual behaviour with physiology and energy status (Wikelski & Cooke 2006), information that is fundamental for conservation. This integration can be achieved through the use of sensors (discussed in 'Overview' above) or by obtaining non-lethal biopsies (e.g. blood samples). Energetic analyses are particularly useful in conservation, as energy is the common currency in ecology and is essential for inferring the bioenergetic costs of different behaviours or exposure to different stressors.

Limitations and challenges

A detailed evaluation of the limitations and challenges of telemetry and logging is presented in Cooke et al. (2004). Here, a similar framework is used to understand the specific limitations and challenges in the context of endangered species research. One of the primary limitations and challenges to the study of animals, but in particular endangered species, is the need to minimize the burden of the device and associated attachment/implantation on the animal (Wilson & McMahon 2006). The trade-off between battery size and longevity continues to limit research on small organisms or long-term monitoring and also limits the complexity (mass) of the required circuitry. The types of transmitter and sensor, and the biology of the organism of interest will determine the type of attachment and implantation procedure that is possible and appropriate. Godfrey & Bryant (2003) reviewed the literature on telemetry studies and determined that only 10.4 % of 836 studies in the 1990s directly addressed the effect of (radio) tags on their bearers. Alarmingly, they reported that conservation-oriented studies were less likely to assess effects compared with studies on non-endangered animals. The authors attributed this pattern to the use of tags for conservation studies that were better designed to avoid adverse effects, and to a publication bias whereby deleterious effects were simply not reported. Clearly, there is a need for consideration of tagging effects as well as more transparent reporting of tagging effects on all studies involving endangered species. To this end, when dealing with vertebrates or any endangered animals, consultation with veterinarians early in the study design is essential (see Hutchins et al. 1993). Furthermore, any surgical implantation will require specialized training that only veterinarians might have (Mulcahy 2003). However, such assistance may not be required for external attachments (e.g. dart tags on marine pelagics, tape on birds). Surgical and handling practice is needed and this can be obtained by working on similar species (e.g. congenerics or confamilials) that are not endangered. Each species, environment, and technology has specific challenges that must be considered when determining which techniques are appropriate for a given objective. For some taxa, there are published guidelines on the maximum size (mass) of device that can be deployed on an organism of a specific size (e.g. Phillips et al. 2003) or recommendations for the physical placement of the device (e.g. Bannasch et al. 1994).

Another challenge is that many researchers (as well as conservation practitioners) are unfamiliar with the telemetric techniques that are now available to monitor the behavioural, physiological and microenvironmental variables that would most effectively address their research question. A further problem may be a lack of commercial suppliers for much of the telemetry apparatus; the inability to purchase an existing device and obtain adequate technical support would impede researchers from adopting these techniques. In developing countries the capacity to implement a telemetry study may not exist. To this end, there is a need to build capacity within the local research communities and ensure effective transfer of technology (Marmulla & Bénech 1999). There have been some attempts to develop training materials and hold telemetry workshops in developing countries (e.g. Baras et al. 2002) although this is still not widespread. Information and training can also be obtained through attendance at relevant conferences or symposia and some conferences include specific workshops on technology and tagging techniques that are often part of continuing education and professional certification initiatives through scientific societies (e.g. American Fisheries Society).

Finally, there is a perception that the cost of telemetry is rather high. Indeed, there can be some initial capital expenses, and devices themselves can be expensive (in some cases leading to low sample sizes). However, this must be contrasted with the benefit derived from data that cannot be collected using other techniques and should not be the sole reason for not conducting a sorely needed telemetry study on an endangered species. It is important to include system maintenance as well as data processing and archiving services (large volumes of data can be generated) in any budgets for a telemetry study. Franco et al. (2007) conducted one of the first assessments of the cost effectiveness of different techniques for assessing habitat selection of lesser kestrels *Falco naumanni* with a focus on radio telemetry and transect surveys. The authors reported that, in general, both techniques produced similar findings, with the telemetry technique being more sensitive to detecting differences in habitat selection. When the authors expressed the costs, radio telemetry data (€ 312 per statistically significant difference) was more costly to obtain than transect data (€ 82.5). The authors concede that their results are quite specific to their study species and the focus of the study. As such, it is not possible to directly extrapolate their findings to other studies. The authors also emphasized that comparisons between techniques are rarely simple because the selection of the best method will depend on the time, budget and equipment, and human resources available.

Ethical and legal perspectives

The paradox is that field research activities that use telemetry have generated valuable information which informs conservation efforts, yet there are also potential negative impacts on individuals (i.e. welfare) and populations (Cooper & Carling 1995). Government agencies around the world as well as peer reviewed publication outlets (e.g. *Animal Behaviour*, *Conservation Biology*) are increasingly asking for researchers to account for their potential impacts. Although welfare issues were once restricted to 'higher vertebrates' (i.e. birds, mammals), there is now recognition that welfare of all vertebrates such as fish, reptiles, and amphibians, must be considered. In some jurisdictions, permits are required for the scientific collection of wildlife and study of endangered wildlife even if the animals are to be released with a telemetry transmitter (e.g. Peck & Simmonds 1995). Failure to obtain permits is not only wrong on ethical grounds, but could lead to prosecution and a halt even to well intended research. At the least, all relevant levels of government (from local to national) as well as the Convention on the Trade of Endangered Species (CITES) should be consulted if any tissue samples associated with tagging (e.g. blood sample, feather, scale) are kept and transported across international borders.

The ethical considerations of tagging endangered animals is a complex issue, as one of the assumptions of telemetry is that the tagging and presence of the device do not deleteriously affect the individual (Wilson & McMahon 2006). However, sample sizes are relatively low (relative to other methods) and animals can be studied in their natural environment. Several explanations have been proposed to account for a perceived lack of public ethical discourse among field scientists (reviewed in Farnsworth & Rosovsky 1993). Of particular relevance to telemetry studies is the assumption that the relative benefits of the research technique outweigh potential short-term costs to the study organism or population (i.e. increased knowledge may inform and promote its long-term conservation; Farnsworth & Rosovsky 1993). Institutional animal care committees usually require researchers to consider the impacts of their tagging activities on populations, and this is coupled with the development and testing of tagging techniques. There has been an explosion of studies that compare and contrast different tagging techniques with the purpose of trying to identify techniques that minimize the impact on the animal. Indeed, data derived from telemetry and logging studies would not be useful if the observations generated were not genuine. A number of authors have proposed that ethical considerations must be considered when conducting research on all animal species (particularly those that are endangered) and when developing conservation measures (Farnsworth & Rosovsky 1993, Putman 1995, Wilson & McMahon 2006). In many cases, the burden still lies on the telemetry practitioner (Minteer & Collins 2005), as not all countries (or institutions) regulate or require ethical approval to conduct research on wild animals (Peck & Simmonds 1995). In such cases, it would be worthwhile to obtain external peer review from experts in the field (including a veterinarian) prior to embarking on research on endangered species. Typically, if animal care approvals are needed by a researcher's home country/jurisdiction, the permit must be obtained there, even if the research is to be conducted elsewhere. In some cases, this means obtaining approvals from 2 jurisdictions (home institution and study site).

Understanding IUCN threat categories

Papers located from the ISI Web of Science (see http://scientific.thomson.com/products/wos/), with search terms including 'conserv* or endanger* or imperil* or threatened or IUCN' and 'tracking or biotelemetry or telemetry or archival or loggers or satellite or biologging', were qualitatively examined to identify how telemetry and logging can be used to assess conservation status. The IUCN uses a hierarchical classification system on the causes of species decline and requires assessors to indicate the threats that triggered a listing of the taxon concerned at the finest level possible. The IUCN and the Conservation Measures Partnership are currently updating and standardizing the direct threats classification system. For the purpose of this paper, the forthcoming classification system (see www.iucn.org/themes/ssc/redlists/classification.htm) was used as a framework for listing all of the possible threats to species decline and making a critical assessment of the potential for telemetry and logging to contribute to understanding the respective threats and their consequences on endangered vertebrates.

This exercise revealed that every single threat listed could be identified or better understood through the use of telemetry or logging (Table 2). The most common application would be to document the spatial ecology of animals relative to different threats. For example, in the case of residential and commercial development pressures, telemetry could be used to understand the displacement of animals, their interactions with humans and human infrastructure, and associated altered habitats. Telemetry and logging can also be used to evaluate mortality-specific threats (e.g. bird strikes, bycatch of sea turtles, birds, marine mammals and fish). Knowledge of the specific threats and their impact on animal populations is essential for the development and implementation of conservation actions, although this goes beyond the scope of the present review.

IUCN RED LIST STATUS: OPPORTUNITIES FOR BIOTELEMETRY AND BIOLOGGING

The IUCN uses a series of consistent and defensible criteria (with thresholds) to objectively assess endangerment status. I contend that telemetry has the potential to yield important information needed to assess the endangerment category into which a given species would be placed. For example, for a taxon to be classified as critically endangered, endangered, or vulnerable, they must meet a number of well-defined criteria as outlined by the IUCN (www.iucn.org/themes/ssc/redlists/RLcategories2000.html). Core to the classification of species by the IUCN is information on the population trends and mortality rates of a given species (Lamoreux et al. 2003). It is also obvious that in the case of a 'data deficient' categorization (not a threat category per se, as listing of taxa in this category indicates that more information is required), telemetry could provide information such as described above that would be needed to make a more informed classification. A taxon in this category may be well studied, and its natural history well understood, but appropriate data on abundance and/or distribution are lacking. Many assessments are conducted at a regional or national level and the following discussion is equally relevant on a regional, national and international level).

Mortality rates and causes

For some species, telemetry and logging provide the only tools for reliably assessing mortality rates in wild populations. This is particularly true for wide-ranging (e.g. whale sharks *Rhincodon typus*; Gifford et al. 2007) or cryptic species (e.g. flying-foxes *Acerodon jubatus*; Mildenstein et al. 2005) as well as those that occupy environments that are poorly accessible by humans (e.g. loggerhead turtles *Caretta caretta* in marine pelagic systems; Chaloupka et al. 2004, and snow leopards *Uncia uncia* in steep and rugged terrain of Mongolia; McCarthy et al. 2005). There are a number of studies that have been conducted to document mortality rates and identify the causes of mortality for endangered species (or to be used to determine if a species is endangered). In fact, there are many species for which demographic models are routinely used, yet there is no information on life-stage specific mortality rates except from studies recently conducted with telemetry.

McIntyre et al. (2006) used satellite telemetry to estimate the probability of first-year survival for migratory golden eagles *Aquila chrysaetos* raised in Denali National Park and Preserve, Alaska, USA. The authors revealed that first year survival was low, with 0.34 survival probability for an 11 mo period for the 1997 cohort and 0.19 for an 11 mo period for the 1999 cohort. The majority of mortalities focused on the autumn migration and early winter period and were attributed to starvation, electrocution, and poaching. It was found that low first-year survival may limit recruitment, and the causal factors of mortality that could be addressed through conservation actions were identified. In Australia, Hayward et al. (2005) used radio telemetry to determine the survival rates and causes of mortality for a threatened macropodid marsupial, the quokka *Setonix brachyurus*. Predation was determined as the

Table 2. Threats to animal species decline and opportunities for telemetry to enhance the understanding of the threat and its impact on the threatened species. Threats were identified from the IUCN-Conservation Measures Program (CMP) unified classification of direct threats document (Version 1.0; 2006) and listed in the same order in the table. Beyond identifying opportunities, the perceived current status of the use of telemetry as well as the potential opportunity for telemetry for each threat are ranked as 'low', 'moderate', or 'high' based on author assessment. Note that the IUCN-CMP document will soon replace the Threats Authority File (Version 2.1) that is currently used by the IUCN (see www.iucnredlist.org/info/major_threats and www.iucn.org/themes/ssc/sis/authority.htm). Perceived current status is based on the author's research associated with the present study and the frequency with which biotelemetry or biologging techniques were used to assess a specific threat. Potential opportunity is based on the author's assessment of the potential for biotelemetry and biologging to be used for the assessment of a given threat

General threat	Specific threat	Opportunities and applications	Perceived current status	Potential opportunity
(1) Residential and commercial development	(1.1) Housing and urban areas	Understanding the displacement of animals or their spatial ecology in urban environments; evaluation of human–wildlife interactions including potential for disease transmission; evaluation of bird behaviour in relation to windows and buildings; documentation of survival rates and emigration (including dispersal) relative to development intensity; evaluation of patch dynamics and gap crossing in urban systems	Moderate	High
	(1.2) Commercial and industrial areas	As (1.1) with greater emphasis on industrial ecology rather than urban ecology	Moderate	High
	(1.3) Tourism and recreation areas	Understanding the displacement of animals or their spatial ecology in or adjacent to recreational environments such as golf courses or ski hills; documentation of survival rates and emigration relative to changes in landscape; evaluation of patch dynamics and gap crossing	Low	High
(2) Agriculture and aquaculture	(2.1) Annual and perennial non-timber crops	Determination of spatial ecology relative to agricultural crops (including monoculture) and associated farm infrastructure; understanding of human–wildlife interactions to reduce potential of culling (e.g. deer, elephants). Documentation of survival rates relative to different agricultural landscapes	Moderate	High
	(2.2) Wood and pulp plantations	Evaluation of shifts in species distribution associated with harvest; understanding spatial ecology of animals and predator-prey dynamics in monocultures; experimental evaluation of animal survival relative to polyculture scenarios	Low	Moderate
	(2.3) Livestock farming and ranching	Understanding direct interactions with wildlife; evaluation of changes in spatial ecology relative to fences and landscape clearing	Low	Moderate
	(2.4) Marine and freshwater aquaculture	Evaluation of spatial ecology relative to alteration in habitats associated with production (e.g. flooding of mangroves for shrimp production; sea cages); determination of the fate of released organisms	Moderate	Moderate
(3) Energy production and mining	(3.1) Oil and gas drilling	Documentation of the responses of animals to drilling activity; evaluation of footprint impacts and potential spills at source on animal distribution	Low	High
	(3.2) Mining and quarrying	Understanding habitat shifts and spatial ecology relative to extraction of surface-based or aquatic/marine aggregate resources	Low	Moderate
	(3.3) Renewable energy	Understanding animal interactions with power production infrastructure (e.g. birds and windpower; marine mammals and tidal power; note: excludes hydropower); documentation of the spatial ecology of animals relative to energy production and infrastructure	Low	High
(4) Transportation and service corridors	(4.1) Roads and railroads	Evaluation of patch dynamics and gap crossing; determination of animal collision frequency and associated mortality; determination of animal behaviour relative to roads and railroads with specific reference to crossing	High	High
	(4.2) Utility and service lines	Understanding the consequences of utility and service lines on spatial ecology of animals	Low	Moderate
	(4.3) Shipping lanes	Understanding the impacts of dredging of benthic and pelagic organisms; understanding spatial ecology and behaviour of animals relative to vessel traffic (e.g. marine mammals); documentation of marine animal and vessel collision rates; understanding wave-induced disturbance on animal distribution, energetics, and stress	Moderate	High

Table 2 (continued)

General threat	Specific threat	Opportunities and applications	Perceived current status	Potential opportunity
	(4.4) Flight paths	Understanding spatial ecology and behaviour of animals (i.e. birds) relative to air traffic; determination of animal collision frequency and associated mortality	Moderate	High
(5) Biological resource use	(5.1) Hunting and collecting terrestrial animals	Understanding animal distribution relative to hunting and collecting practices and specific habitats (includes documenting human behaviour such as during bushmeat harvest); understanding size-selective or sex-specific harvest patterns; documentation of overall harvest and natural mortality rates	Low	High
	(5.2) Gathering terrestrial plants	Determination of the consequences of terrestrial plant harvest on the spatial ecology of animals (e.g. removal of critical habitats or food resources)	Low	Low
	(5.3) Logging and wood harvesting	Determination of the consequences of different harvest strategies on animal distribution, behaviour, and survival; documentation of animal use of cleared habitats during regeneration/replanting	Moderate	High
	(5.4) Fishing and harvesting aquatic resources	Understanding the behaviour and fate of animals that are captured (intentionally or unintentionally) and released (commercial or recreational); documentation of the spatial ecology of animals relative to harvesting activities and management jurisdictions	Moderate	High
(6) Human intrusions and disturbance	(6.1) Recreational activities	Documentation of animals' behaviour relative to human disturbance; evaluation of the energetic and physiological consequences of recreational activities on animals	Moderate	High
	(6.2) War, civil unrest and military exercises	Evaluation of animal responses to altered habitats; determination of the energetic and physiological consequences of military activity on animals	Low	Moderate
	(6.3) Work and other activities	As (6.1); determination of animals' response to research collection, handling, and release	Low	Moderate
(7) Natural system modifications	(7.1) Fire and fire suppression	Evaluation of animal movement relative to human-induced fires; documentation of habitat use post fires; comparison of animal responses to fire in regions with different fire regimes	Low	Low
	(7.2) Dams and water management/use	Documentation of mortality associated with passage of animals through hydroelectric infrastructure; identification of barriers to river connectivity and their impact on animal behaviour, energetics, and survival; understanding the response of animals to different water management activities (e.g. water withdrawals, peaking flows); comparison of animal behaviour in systems before and after dam construction or removal	High	High
	(7.3) Other ecosystem modifications	Evaluation of animal movements and habitat use relative to human alterations of habitat	Low	Moderate
(8) Invasive and other problematic species and genes	(8.1) Invasive non-native/alien species	Determination of direct interactions between threatened animals and invasive non-native or alien species (including domestic animals); identification of spatial ecology, population dynamics, and energetics in animal populations induced by invasive species (e.g. zebra mussels changing water clarity, mountain pine beetle altering forest cover); determination of the behaviour and survival of animals relative to disease or parasites	Low	Moderate
	(8.2) Problematic native species	Determination of the behavioural and energetic response of animals to altered habitats, disease, competition, or predation from problematic species	Low	Moderate
	(8.3) Introduced genetic material	Documentation of interactions between animals and the introduced organism	Low	Moderate
(9) Pollution	(9.1) Household sewage and urban waste water	Determination of the spatial ecology and exposure potential of animals relative to sewage and waste water; evaluation of animals' survival following exposure to sewage and waste water	Low	Moderate

Table 2 (continued)

General threat	Specific threat	Opportunities and applications	Perceived current status	Potential opportunity
	(9.2) Industrial and military effluents	As (9.1); determination of the movement of pollutants between habitats as transported by animals; spatial ecology of animals relative to polluted sites and habitats; determination of potential food chain biomagnification through studies on animal spatial ecology	Low	High
	(9.3) Agriculture and forestry effluents	Determination of animal responses (including changes in behaviour and habitat use) to effluents and altered nutrient dynamics	Low	Moderate
	(9.4) Garbage and solid waste	Evaluation of animal behaviour and survival relative to entanglement in debris/trash; documentation of animal movement and habitat use relative to garbage; determination of changes in foraging activity relative to garbage sites	Low	Moderate
	(9.5) Air-borne pollutants	Determination of changes in habitat use or behaviour relative to changes in habitat (e.g. acid rain, smog); determination of the spatial ecology and exposure potential of animals	Low	Low
	(9.6) Excess energy	Determination of the spatial ecology and exposure potential of animals relative to pollution; determination of the energetic consequences of exposure to pollutants (especially thermal pollution and associated thermoregulatory behaviour); determination of behavioural disturbance relative to pollution (e.g. noise from highways or planes, sonar noise and impacts on marine mammals, light pollution from urban environments)	Moderate	High
(10) Geological events	(10.1) Volcanoes	Determination of animal responses (behaviour, movement, survival, and habitat use) relative to geologic events and associated impacts on habitat and directly on the animal	Low	Low
	(10.2) Earthquakes/ tsunamis	As (10.1)	Low	Moderate
	(10.3) Avalanches/ landslides	As (10.1)	Low	Low
(11) Climate change and severe weather	(11.1) Habitat shifting and alteration	Evaluation of animal habitat use during and after habitat alterations (e.g. from coral bleaching, tundra thawing); determination of animal emigration or mortality relative to habitat alterations	Low	High
	(11.2) Droughts	As (11.1); determination of estivation periods and habitats	Low	High
	(11.3) Temperature extremes	As (11.1); documentation of changes in animal migration patterns relative to thermal environments (e.g. loss of glaciers, heat waves); evaluation of thermal ecology of animals	Low	High
	(11.4) Storms and flooding	As (11.1); determination of animal displacement	Low	High

major cause of death, followed by road kills, with individuals having an 81% chance of surviving for 1 yr. The authors found no evidence of differences in survivorship between adults (of both sexes) and juveniles. Bright & Hervert (2005) used radio collars and weekly tracking by fixed-wing airplane to document adult mortality and fawn recruitment of a population of endangered Sonoran pronghorn A*ntilocapra americana sonoriensis* in Arizona. Once mortalities were detected during flights, sites were visited in an effort to determine the cause of mortality. Over the several years of study, annual adult mortality rates varied from 11 to 83%, with mortality associated with predation and drought, whereas for fawns, drought was the primary source of mortality. Collectively, all of these studies provided information that could be used in demographic models, and also data on the timing (season- and life-stage specific) and causes of mortality, enabling the development of appropriate conservation actions. Although the analysis of survival/mortality data from telemetry and logging studies is not straightforward (White & Garrott 1990), the data sets arising from these technologies typically have many advantages relative to conventional techniques.

Population size

Biologists are continually in search of tools or approaches that enable cost-effective, simple, and accurate estimates of population size with minimal assumptions (Boyce 1992, Brook et al. 2000). Population viability analysis (PVA; Boyce 1992) and other metrics for evaluating the population biology of animals all depend on some estimate of population size and are routinely used for the assessment of conservation status (Brook et al. 2000). Many studies attempting to estimate population size have included telemetry and logging data, but rarely are data from those sources used in isolation to estimate population size. Instead, telemetry and logging are coupled with other techniques such as photocounts, line-transects, scat counts, mark-resight, and mark-recapture. In fact, many studies involve comparing multiple techniques in the quest for the best method. For example, Fisher et al. (2000) studied the critically endangered bridled nailtail wallaby *Onychogalea fraenata* in central Queensland, Australia. Because of its small size and its nocturnal, solitary, and cryptic behaviour, evaluation of population size was difficult. Using mark-recapture, mark-resight, radiotagging, and line-transect methods, the researchers assessed biases and the value of each method for management. Interestingly, the projected value of lambda (finite rate of increase) based on radio-tagging data was most sensitive to adult survival (see 'Mortality rates and causes'), and line-transect estimation was found to be the most appropriate long-term monitoring method. In many studies, data from telemetry is considered to be the 'gold standard' to which other metrics are compared (e.g. in a study of endangered white-crowned pigeon *Columba leucocephala* in Florida, USA; Strong et al. 1994, and in a study of Lower Keys marsh rabbit *Sylvilagus palustris hefneri* on Boca Chica Key, Florida; Forys & Humphrey 1997).

Reproductive biology and potential

Knowledge of the reproductive biology of animals is critical to understanding population dynamics, particularly in the case of endangered species. For many endangered species, there is a rudimentary understanding of basic natural history information related to reproduction, including the reproductive timing and output, which is critical to the understanding of endangerment risk and status. One of the unique characteristics of telemetry and technology is that it enables the same individuals to be monitored throughout multiple periods of their life cycle.

When an animal engages in reproduction, additional information can be obtained with respect to differential reproductive success, age at maturation, and reproductive output. For example, Litzgus & Mousseau (2006) used radio telemetry to study the reproductive biology of spotted turtle *Clemmys guttata* in South Carolina, USA. They documented the timing of courtship, the proportion of females that were gravid in each year, the timing duration of the nesting period, nesting times (nocturnal) and habitats, and clutch size. Palomares et al. (2005) used radio tracking over a 9 yr period to study the reproductive biology of the Iberian lynx *Lynx pardinus*, the most endangered felid in the world, in a population in southwestern Spain. The authors found that the potential breeding subpopulation was usually composed of 3 adult females (which were tracked for almost their complete reproductive life) with a lifetime reproductive output of between 11 and 19 cubs. However, mortality rates for young (predispersal) cubs were sufficiently high that the authors proposed the extraction of cubs from a mother with a low survival probability.

In some cases, telemetry can be used to locate reproductive sites, enabling researchers to collect data on reproductive potential. For example, Fox et al. (2000) used both acoustic and radio telemetry to monitor the movements of endangered adult Gulf sturgeon *Acipenser oxyrinchus desotoi* as they moved between Choctawhatchee Bay and the Choctawhatchee River system. Telemetry results coupled with egg sampling were used to identify Gulf sturgeon spawning sites, the timing of reproduction, and sex-specific behaviour. Results from histology and their telemetry data supported the hypothesis that male Gulf sturgeon may spawn annually, whereas females require more than 1 yr between spawning events. By combining telemetry with other approaches (e.g. histology, in the above example) conservation scientists can elucidate the subtle mechanisms of reproductive biology to improve conservation efforts.

Geographic range

Another metric used to assess endangerment status is a decline in the area of occupancy, extent of occurrence and/or quality of habitat. Telemetry and logging are typically the most reliable means of determining the spatial ecology of animals, particularly those that are migratory. The occupancy of a small geographical range is one of the potential justifications for categorizing species (or populations). The criteria include specific spatial distribution thresholds (e.g. from 10 000 km^2 to 10 km^2). Telemetry can be used to identify the exact boundaries of an animal's range and is particularly effective in habitats where visual observations may be difficult (e.g. ocean, turbid freshwaters, dense forest canopy). In general, satellite (Fedak et al. 2002) and logger (Block 2005) technologies tend to be best suited to animals with broad geographic distributions.

Many of the studies on the geographic range or distribution of animals are conducted within political boundaries (e.g. states/provinces, countries) or park/

reserve environments. With most conservation actions implemented at the regional and national scale, studies focused on this level are extremely valuable and necessary. For example, Raum-Suryan et al. (2004) studied Stellar sea lions *Eumetopias jubatus* in western Alaska to understand coastal distribution in Alaskan waters, although the entire range of this species extends southward to California. Mills & Gorman (1997) used conventional and satellite radio telemetry to track endangered African wild dogs *Lycaon pictus* in the Kruger National Park, South Africa. Although these animals have a geographic range that extends beyond the park boundary, there was a need to determine the distribution of the dogs within the park. In another application, Wittmer et al. (2005) used radio telemetry to study woodland caribou *Rangifer tarandus caribou* across the entire distribution of an endangered mountain ecotype (i.e. a terrestrial landscape unit) in British Columbia, Canada. In this case, distribution was assessed relative to an endangered habitat type in a specific province.

Relatively few studies evaluate distribution across broader scales, although there are some fascinating exceptions that would not have been possible without telemetry. For example, Tuck et al. (1999) used geolocation (from data loggers) to determine the geographic range of wandering albatrosses *Diomedea exulans*. After tagging in South Georgia and the Crozet Islands, the birds made extensive journeys from southern Africa across the Indian Ocean to southeastern Australia and the east of New Zealand. Such broad movements of seabirds have not previously been documented and will assist assessments of risk, such as those related to seabird by-catch by long-line fisheries (e.g. Weimerskirch et al. 2000). Weng et al. (2005) used satellite tags attached to the dorsal fins of salmon sharks *Lamna ditropis* in the Pacific Ocean and revealed that they have a subarctic to subtropical range, much larger than previously documented. In another example, Cheng (2000) used satellite transmitters to track green turtles *Chelonia mydas* from nesting sites in the Peng Hu Archipelago, Taiwan to the continental shelf east of mainland China, including both trans-oceanic and coastal legs. The authors concluded that the distribution and vagility of the species requires regional and international cooperation. Indeed, as a result of many telemetry and logging studies on marine turtles, international cooperation has now been recognized as fundamental to turtle conservation (Blumenthal et al. 2006). In another study, a single endangered North Pacific right whale *Eubalaena japonica* was tagged with a satellite radio transmitter (Wade et al. 2006). The animal was tracked for a 40 d monitoring period during which it moved throughout a large part of the southeast Bering Sea shelf and traversed regions of the outer-shelf where right whales have not been seen in decades, thus expanding the known range of the species. Although relatively few studies have used telemetry to explicitly determine the global geographic range of a species, information from telemetry and logging studies often is used to supplement other information to determine the full geographic distribution.

There has been much research on endangered species at the edges of their geographic distribution (e.g. Hoving et al. 1994 studied the threatened [according to the United States Endangered Species Act, US ESA] Canada lynx *Lynx canadensis* in the United States with radio telemetry; Galois et al. (2002) used radio telemetry to study threatened spiny softshell turtle *Apalone spinifera* in northern Lake Champlain [Quebec, Canada and Vermont, USA] at the northern limit of its range) and it is likely that this research will grow, given the recent finding that those populations/individuals may be particularly important (Hampe & Petit 2005). Furthermore, research at the edges of geographic ranges is also relevant to the prediction and monitoring of climate change impacts on animal distributions (e.g. Hampe & Petit 2005).

Habitat associations

Identification of habitat association is essential to determine the habitats which an animal can occupy as well as to understand their spatial ecology. When critical habitats (e.g. hibernation sites, reproductive sites, feeding areas) are identified, it is possible to determine the extent to which those habitats are threatened. Identification of critical habitats is also a prerequisite for conservation actions, such as habitat restoration or protection. For example, Prior & Weatherhead (1996) used radio telemetry to identify the hibernacula of black rat snakes *Elaphe obsoleta obsoleta* in Ontario at the northern edge of their range, where winter protection is essential. The authors revealed that rat snake hibernacula could not be predictably located by searching for surface habitat features and suggested that radio telemetry be used to identify and protect additional hibernacula as well as to preserve basking trees at known hibernacula. In another example, Sedgley & O'Donnell (1999) identified the factors that influenced the selection of roost cavities by the threatened New Zealand long-tailed bat *Chalinolobus tuberculatus* in a rainforest in Fiordland, New Zealand. Using radio telemetry, they identified that all day roost sites were in tree cavities and compared those that were actually used to those available. Factors such as distance to the nearest vegetation, cavity condition (wet or dry inside), and height from the ground explained 97% of the variance between used and available roosts.

A number of studies have used telemetry to identify key reproductive sites or sites traversed or used as stopovers during migration. For example, Paragamian et al. (2002) studied the endangered (US ESA) Kootenai River white sturgeon using radio and acoustic telemetry and identified critical spawning habitats. They identified at least 5 primary spawning locations, most in the vicinity of outside bends, which tend to have sandy substrate. Due to low recruitment, it is suspected that the animals are spawning in unsuitable habitat, which may indicate that this is the site of historic spawning sites that have been degraded. Hayward et al. (2007b) determined that adequate prey resources were critical for lions *Panthera leo* by using telemetry to test predictions of their diet at reintroduction sites. Kanai et al. (2002) used satellite transmitters to track critically endangered Siberian cranes *Grits leucogeranus* from breeding grounds in northeastern Siberia to wintering sites in China. Throughout the migration, several key wetland stopover sites were identified in China. Collectively, the identification of critical habitats is fundamental to identifying the threats facing an organism and in identifying potential conservation actions. Such studies also have the potential to generate political conflicts when long-distance migrants cross political borders and are exposed to different levels of protection.

Connectivity of subpopulations

Several assessment criteria deal with the extent to which the species range (or habitat) is fragmented. Indeed, a fundamental challenge in conservation biology is delineating discrete population units, especially in highly mobile animals with large geographic ranges. Telemetry and logging provide insight into the movement of animals between fragmented habitats (i.e. vagility, dispersal, and emigration) and can define the extent to which these animals are isolated or form subpopulations. Telemetry and logging tools, particularly when combined with other techniques such as stable isotope and genetic analyses, provide the opportunity to determine the connectivity of populations of animals even when they are highly mobile and migrate vast distances (Webster et al. 2002). For example, Selonen et al. (2005) used genetic tools (microsatellites) and complementary radio telemetry data to study gene flow of declining Siberian flying squirrel *Pteromys volans* in Finland. Radio telemetry studies indicated that the flying squirrels had good dispersal abilities, but the high level of genetic differentiation between sampling sites indicated that the actual gene flow over large distances was low.

Some studies have used telemetry tools without genetic tools to assess connectivity. For example, Iverson & Esler (2006) studied the demographic connectivity among population segments of Harlequin ducks *Histrionicus histrionicus* during the non-breeding season in Prince William Sound, Alaska. They radio-tagged 434 ind. over a 6 yr period and tracked them by aircraft. Home range analyses indicated restricted movement of individuals (mean 95% kernel home range estimates, 11.5 ± 2.2 km^2). The authors then developed a demographic model, which incorporated estimates for population size, survival, and movement rates (all obtained from telemetry data), to infer the degree of independence among population segments. In another study, Tyus (1990) radio-tracked endangered Colorado squawfish *Ptychochelius lucius* in the Green River basin of Colorado and Utah, USA from 1980 to 1988. A high proportion (63%) of individuals was highly mobile. However, a number of telemetered individuals spawned at the same site for more than 1 yr after migrating from both upstream and downstream areas, indicating potential for subpopulations.

Telemetry can also be used to assess movement of animals between fragmented habitats. For example, Riley et al. (2006) studied 2 highly mobile carnivores (i.e. coyotes *Canis latrans* and bobcats *Felis rufus*) across the Ventura Freeway near Los Angeles, California. Combining radio telemetry data and genetically based assignments to identify individuals, revealed that although there were moderate levels of migration, populations on either side of the freeway were genetically differentiated. Hence, the authors inferred that the individuals that cross the freeway rarely reproduce. Smyth & Pavey (2001) used radio telemetry to study the movement of endangered black-breasted button-quail *Turnix melanogaster* in 13 rainforest patches of an agricultural landscape in eastern Australia. No movement was observed between patches, with animals only resident in the 3 largest patches. Telemetry has also been used to detect the presence of metapopulations of endangered species. Quokkas *Setonix brachyurus* are restricted to isolated habitat patches, which led researchers to conclude the species originally occurred as a natural metapopulation (Hayward et al. 2003). However, restriction to those patches today suggests the metapopulation has collapsed and regional extinction is imminent (Hayward et al. 2004). Collectively, telemetry and logging have much promise for providing information on the connectivity of populations, which should enhance the evaluation and assignment of endangerment status.

REDUCTION OF UNCERTAINTY

One of the challenges that face the assessors of endangerment status is how to make consistent classifications when faced with uncertainty. Even though there are clear decision rules based on established thresholds, the data for these parameters are often estimated. Hence, uncertainty can arise from measurement error and natural biological variation (Akçakaya et al. 2000). Considering that the interpretation of uncertain data by different assessors may lead to inconsistent classifications which could ultimately affect conservation actions and the fate of a species, there is a clear need to reduce uncertainty (Burgman et al. 1999, Akçakaya et al. 2000). However, an alternative and longer-term approach is to reduce uncertainty by selecting an appropriate means of collecting the necessary data and reducing measurement error. The other primary source of uncertainty, natural biological variability (both spatially and temporally) in demography and distribution is fundamentally more difficult to incorporate into decision making because it requires a probabilistic approach (Burgman et al. 1999). However, as mentioned above, understanding individual variation is an important element of conservation science. Telemetry and logging, the focus of this paper, both have the potential to illuminate these 2 primary sources of uncertainty and aid in the reliable and consistent determination of endangerment status.

Measurement error

Relative to other study methods such as external marking, telemetry techniques enable the researcher to locate individual organisms through time. External marking and associated mark-recapture methods require that significant time is invested in recapturing or resighting the animals or that no data is provided. Essentially, mark-recapture techniques are biased against the detection of movement and can lead to erroneous conclusions regarding population demographics or the vagility and spatial distribution of a species (Gowan et al. 1994). Conversely, telemetry enables one to locate individuals across broader spatial scales, provided that the technology (e.g. satellite, telemetry array) or tracking protocols are compatible with the scale in question. In a review of techniques for estimating animal populations, Seber (1992) proposed that telemetry could improve population estimates by providing information on emigration, immigration, and spatial distribution relative to the focal area for which the population estimate is required. Nonetheless, there are a number of challenges when dealing with telemetry and logging data (White & Garrott 1990).

A tenet of most mark-recapture studies is that the system is closed, meaning that it is particularly difficult to assess 'edge' individuals (i.e. those individuals that have home ranges that overlap with the region where the population estimate is being conducted; Seber 1992). Techniques now exist for using telemetry data to document the extent to which this closed population assumption is violated and to correct for this bias (Eberhardt 1990). A combined analysis of recapture/resighting data coupled with telemetry data allows separate estimates of true survival and emigration rates to be generated (Nasution et al. 2002). When only using recapture/resighting data, only apparent survival can be estimated. The combined estimates can be more precise. For example, Powell et al. (2000) assessed the survival and movement of wood thrushes *Hylocichla mustelina* in central Georgia, USA, by combining mark-recapture and radio telemetry techniques. The combined model that used both data sources resulted in more precise estimates of movement and recapture rates than separate estimation. However, the authors also identified that there were minimum sample sizes required (for both marked and telemetered individuals) to generate reliable estimates in this system. Other authors have now developed optimal allocation models to determine the number of telemetry devices required relative to standard marking techniques (e.g. Nasution et al. 2002). An additional assumption of population estimates, particularly when using an index, is that the population index is directly proportional to the population density. However, in practice, probability of detection varies through space and time. Pollock et al. (2002) advocate a measure of detection probability that could be built into the monitoring programs through a double sampling approach that could use telemetry.

In some cases, the measurement error is associated with experimental design flaws. For example, Maehr et al. (2004) drew attention to a model of Florida panther *Puma concolor coryi* habitat that erred by arbitrarily creating buffers around radio locations collected during daylight hours, on the assumption that study animals were only at rest during these times. The authors claimed that this error could lead to the impression that unfragmented forest cover is unimportant to panther conservation, and could encourage inaccurate characterizations of panther habitat. Hence, although telemetry data provided important data on habitat use, failure to include activity during night or crepuscular periods lead to the suggestion of conservation actions that were not supported by scientifically derived data. Although this is not truly a measurement error, it serves as an important lesson that telemetry findings are only as good as the experimental design and data quality. In this case, the use of logging (rather than telemetry) could provide a continuous time-budget over a 24 h period and help to describe panther activity at night.

On occasion, IUCN specialist groups develop and publish resolutions intended to advance the study or conservation of a particular species or group of species. The IUCN specialist groups also have a history of developing resolutions that recognize the need for development of techniques that can aid in conservation and management of species in decline. For example, in 1981 the IUCN Polar Bear (*Ursus maritimus*) Specialist Group made a resolution (Res#4-1981) on the development and use of telemetry techniques which stated,

> The IUCN Polar Bear Specialist Group, recognizing that conventional and satellite telemetry are effective techniques to study ecology of polar bears; and, recognizing that existing systems of attaching transmitters to polar bears are not sufficiently reliable; and, recognizing that existing technology for satellite tracking needs significant improvement; therefore urges use of conventional and satellite telemetry to study polar bears and cooperative efforts to improve telemetry techniques.

Such a resolution recognized the potential for studying species such as polar bears that are spatially diffuse and the fact that telemetry had the potential to illuminate the movements of this species. Furthermore, the resolution identified that technological improvements were needed to reduce uncertainty and enhance the reliability of the data.

Since this time, there have been a number of satellite telemetry studies on polar bears focused on understanding their spatial ecology (Messier et al. 1992, Mauritzen et al. 2002) and population structure (Bethke et al. 1996, Mauritzen et al. 2002). In a subsequent resolution published in 1985 (Res#5-1985) the IUCN Polar Bear Specialist Group stated

> that research be directed at improving the cost-effectiveness and statistical reliability of the mark and recapture studies by developing and testing new research designs, and by using movement data gathered from telemetry to understand and develop corrections for capture biases in the mark and recapture data.

In this case, telemetry was suggested as a tool for improving the reliability of mark and recapture data, which is the standard technique for assessing polar bear population dynamics. This example demonstrates the potential of telemetry techniques to reduce uncertainty in the threat assessment process.

It is also worth mentioning that telemetry locations are themselves subject to error. The accuracy of the position estimate can be impacted by signal bounce or multipath (see Cooke et al. 2005). In some systems and for some taxa, it is possible to visually confirm the location of the animal. Trackers should be experienced and trained in a standardized manner that involves frequent assessment using hidden tags to assess the accuracy of the positions. In some habitats (e.g. under ice, dense forest, caves) animals spend significant time in areas where they can not be located, and this can also introduce bias. Substantial bias can also occur when using light-based geolocation tags (Teo et al. 2004) for marine organisms and birds or when using satellite tracking (Hays et al. 2001). Although there are sophisticated algorithms for assigning latitude and longitude positions, the error can at times be on the order of tens to hundreds of kilometers (indeed, the definition of geolocation is 2 points per day with errors around the equinoxes). Understanding the capabilities of the technology is critical to determining the extent to which telemetry can address the study objectives and provide reliable data that reduces uncertainty regarding the biology or status of a species (Hays et al. 2001).

Natural biological variability

Immense variation is inherent in biological systems. Although biologically important and of fundamental interest, attempts to assess threats to populations, determine the conservation status of a species, and develop and implement management plans in cases where variation among individuals and populations occurs, pose some unique challenges to the conservation practitioner. The idea of intra-specific variation is not, however, new in biology (e.g. Bennett 1987). Individuals and populations can vary in such basic attributes as physiology, behaviour, morphology, and life history. Telemetry and logging have recently provided unique insight into the magnitude and biological consequences of natural variability. For example, recent work on sooty shearwater *Puffinus griseus* using loggers has revealed that different individuals use different migratory routes, thus exposing them to different threats (Shaffer et al. 2006). Cooke et al. (2006) revealed that a segment of the sockeye salmon *Oncorhynchus nerka* populations that initiated migration early relative to the historical norm, tended to have much reduced survivorship as well as a unique physiological signature. As noted above (see 'Mortality rates and causes of mortality'), different sexes and different life stages can exhibit substantially different patterns in mortality and emigration, all data that should be embraced, not 'averaged' and considered statistical noise (Bennett 1987). Natural biological variability (both spatial and temporal) in demography and distribution is difficult to both quantify and predict (Burgman et al. 1999), leading to uncertainty. However, a greater focus on individual and intra-specific variation in organismal biology that is inherent in telemetry and logging studies will help to provide greater context to the divergent patterns observed in nature and help to reduce uncertainty in decision making in applied conservation questions. Integration of telemetry and logging studies with physiological and condition-related measures will be useful in understanding the consequences of individual variability on population level phenomena (O'Connor et al. 2006).

CONCLUSIONS AND OUTLOOK FOR THE FUTURE

Telemetry and logging have much to offer endangered species research and conservation. Indeed, there have already been many advances in ecology owing to these technologies (e.g. Cooke et al. 2004, Block 2005). This paper has revealed that there are clear opportunities to obtain the novel data needed to assess IUCN or regional population status and to identify the causes of population declines. There are still challenges with respect to the application of telemetry and logging data to conservation and management actions, as the data generated by these techniques are always retrospective and rarely probabilistic (Amstrup et al. 2004). Nonetheless, the focus of the present paper is on using telemetry and logging to inform threat assessments and conservation status evaluations, a task that tends to be retrospective. Telemetry and logging are particularly powerful techniques when combined with other assessment methods such as point-counts or mark-recapture enabling the cross calibration and validation of different population estimate tools (e.g. Amstrup et al. 2004). Telemetry and logging can also be linked with other tools and disciplines to quantify animal responses to stress (e.g. conservation physiology, Wikelski & Cooke 2006; field physiology, Goldstein & Pinshow 2006), identifying discrete populations (e.g. through genetic analyses; Fernando & Lande 2000), or assessing animal nutritional/energetic condition (e.g. stable isotope analysis, Cunjak et al. 2005; non-lethal energetic assessment, Cooke et al. 2006).

Despite the fact that telemetry and logging have much promise for endangered species research, some challenges remain. Fundamental to all tagging studies is the need to attach or implant a device on or in an animal. Therefore, the premise of all studies should be that the population does not suffer any harm and that the welfare status of individuals is taken into consideration. Essentially, this means considering the ethics of tagging and telemetry studies when dealing with endangered species. This does not mean that telemetry should be avoided. Instead, when a telemetry or logging study is determined to be the best method for achieving a desired objective, all efforts must be taken to minimize the burden of the transmitter and the attachment/implantation on the individuals. There are now a number of syntheses that provide telemetry practitioners with guidance for minimizing the impact of telemetry techniques on animals. However, even with ethical guidelines and governmental regulations, the burden is often left on the practitioners to ensure that their research techniques do not contribute to species declines. Interestingly, an important study that outlined the research needs for enhancing the assessment and management of species at risk (e.g. Mace et al. 2001), failed to list telemetry as a tool to fill research gaps, perhaps emphasizing the need for a study such as the present one to highlight opportunities.

Given the limited funds available for conservation research (Myers et al. 2000, Halpern et al. 2006), it is essential that the most cost-effective research method is used. Considering the perceived high cost of telemetry, it would be useful for authors to include data on the cost of their studies as well as the resources required (staff, equipment, time) in published works; this would make it possible to conduct formal evidence-based assessments to determine the effectiveness of different research techniques (e.g. comparing telemetry to more traditional marking and monitoring techniques) relative to their cost (cost-effectiveness; Sutherland et al. 2004). At present, there are few data available for a global assessment (but see Franco et al. 2007). As many endangered species occur in developing countries, it is important to build the capacity (financial and technical training) to do such studies if needed. It may be possible for research teams from comparatively wealthy institutions or countries to share their devices and expertise (via a retribution such as co-authorship) with researchers from other institutions and countries. Telemetry and logging are not a panacea and as with any tool, should only be used after considering alternatives and determining what is the best approach to achieve the desired objective — and which techniques will have the least impact on the animal. Indeed, there are several comparative studies that have determined that telemetry techniques were not the most appropriate for their given conservation application (e.g. McCann et al. 2001). In summary, telemetry and logging can provide conservation practitioners with data that is unattainable using other techniques. However, it is important to only use these technologies when they are determined to be the best means of achieving a specific conservation objective. Telemetry and logging, as well as other innovative research, assessment, and monitoring tools are needed in order to inform decision makers and thus achieve biodiversity targets (e.g. the Convention of Biological Diversity 2010 targets; see Balmford et al. 2005) and reverse the apparent global decline of many animal species.

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