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Review

Utility of biological sensor tags in animal conservation

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Abstract: *Electronic tags (both biotelemetry and biologging platforms) have informed conservation and resource management policy and practice by providing vital information on the spatial ecology of animals and their environments. However, the extent of the contribution of biological sensors (within electronic tags) that measure an animal's state (e.g., heart rate, body temperature, and details of locomotion and energetics) is less clear. A literature review revealed that, despite a growing number of commercially available state sensor tags and enormous application potential for such devices in animal biology, there are relatively few examples of their application to conservation. Existing applications fell under 4 main themes: quantifying disturbance (e.g., ecotourism, vehicular and aircraft traffic), examining the effects of environmental change (e.g., climate change), understanding the consequences of habitat use and selection, and estimating energy expenditure. We also identified several other ways in which sensor tags could benefit conservation, such as determining the potential efficacy of management interventions. With increasing sensor diversity of commercially available platforms, less invasive attachment techniques, smaller device sizes, and more researchers embracing such technology, we suggest that biological sensor tags be considered a part of the necessary toolbox for conservation. This approach can measure (in real time) the state of free-ranging animals and thus provide managers with objective, timely, relevant, and accurate data to inform policy and decision making.*

Keywords: biologging, biotelemetry, electronic tags

El Uso de Etiquetas de Sensor Biológico en la Conservación de Animales

Resumen: *Las etiquetas electrónicas (plataformas tanto de bio-telemetría como de bio-registro) han informado a la conservación y a la política y práctica del manejo de recursos al proporcionar información vital sobre la ecología espacial de los animales y su ambiente. Sin embargo, la extensión de la contribución de los sensores biológicos (dentro de las etiquetas electrónicas) que miden el estado de un animal (p. ej.: ritmo cardíaco, temperatura corporal y detalles sobre el movimiento y la energética) es menos evidente. Una revisión de la literatura reveló que, a pesar de un número creciente de etiquetas sensoriales de estado disponibles comercialmente y un enorme potencial de aplicación de dichos dispositivos en la biología animal, hay pocos ejemplos de su aplicación en la conservación. Las aplicaciones existentes se rigieron por cuatro temas principales: cuantificar la perturbación (p. ej.: vehicular, de tráfico aéreo o de ecoturismo), examinar los efectos del cambio ambiental (p. ej.: cambio climático), entender las consecuencias de la selección y uso de hábitat, y estimar el gasto energético. También identificamos muchas otras maneras en que las etiquetas sensoriales podrían beneficiar a la conservación, como determinar la efectividad potencial de las intervenciones de manejo. Con el incremento en la diversidad de sensores en plataformas disponibles comercialmente, técnicas menos invasivas de etiquetado, tamaños más pequeños de los dispositivos, y más investigadores adoptando dicha tecnología, sugerimos que las etiquetas de sensor biológico se consideren*

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como una parte de la caja de herramientas necesaria para la conservación. Esta estrategia puede medir (en tiempo real) el estado de animales libres y así proporcionar a los manejadores datos objetivos, oportunos, relevantes y precisos para informar la toma de decisiones y la política.

Palabras Clave: bio-registro, bio-telemetría, etiquetas electrónicas

Introduction

Contemporary conservation science is focused on immediate and proximate solutions (Salafsky et al. 2002) and increasingly embraces allied disciplines and interfaces for answers to conservation problems (Balmford & Cowling 2006). Because animal populations across a range of taxa are in a state of general decline (e.g., Butchart et al. 2010; Hoffmann et al. 2010), there is an urgent need for science to inform conservation actions for effective recovery planning. Over the last decade, the important roles that the fields of animal behavior (Sutherland 1998; Caro 1999) and physiology (Wikelski & Cooke 2006), as well as resulting interactions between the 2 (Cooke et al. 2014), play in conservation has become broadly apparent. Quantification of traits within these respective fields is not trivial, however, given that wild animals are often secretive, cryptic, highly mobile, and may live in environments where it is difficult to collect data (Altmann 1974; Costa & Sinervo 2004). As a possible solution to the problem of gathering data on animals that cannot be observed directly, electronic tagging technologies have evolved. These technologies include telemetry devices that continuously transmit information as well as biologging devices that primarily store data until downloaded. These technologies have existed in one form or another for decades (Adams 1965), but it is only relatively recently that they have garnered serious attention from ecologists (Ropert-Coudert & Wilson 2005; Rutz & Hays 2009; Krause et al. 2013).

Recent innovations have seen this technology applied to an ever-increasing size range of animals, diversity of taxa (insects to whales), spatial scales (habitat patch to continental scale), and environments (coral reefs to rainforests) (Fig. 1) (Cooke et al. 2004*a*), which emphasizes the potential usefulness of employing these tags in conservation. However, such tags are rarely used to solve pressing conservation problems or to inform resource management (Cooke 2008). We believe sensor-equipped electronic tags provide fundamental descriptive information on movement, behavior patterns, and environmental conditions (e.g., temperature, salinity, and pH) (Cooke 2008) and can be part of a much larger effort to bolster evidence-based conservation and environmental management (Sutherland et al. 2004). The idea is that detailed mechanistic data generated throughout an individual's life will help conservation professionals understand the causal relationships and drivers behind changes in animal populations and in doing so will ensure that limited resources are best used to benefit animal populations and the ecosystem services they provide.

If sensor-equipped electronic tags are to contribute to conservation needs in a significant manner, then their strengths and capabilities need to be identified and exploited to their fullest capacity. Physiological sensors that measure animal state via heart rate, body temperature, tissue biochemistry and appendage activity (Table 1) represent particularly underutilized technologies. Failure to recognize the usefulness of these sensors is unfortunate because such technologies can move research beyond questions of when and where animals move by providing in situ and in vivo information on the mechanistic causes that lead to population declines (Wikelski & Cooke 2006). Nevertheless, studies using such biological sensor tags to inform conservation science are still rare due to a variety of factors. However, general interest in the application of these tags by conservation biologists and physiologists is clear, as evidenced by high citation rates for early synthesis articles on this topic (e.g., Cooke et al. [2004*a*] is cited 418 times according to Google Scholar as of 7 December 2014).

We identified examples of how biological sensor tags have informed conservation, demonstrating the potential of this technology across taxa. We also examined fruitful opportunities for sensor tag research and obstacles to the proper use of sensor tags within the framework of conservation. We excluded environmentally oriented sensors that measure light, pressure (i.e., depth or elevation), and conductivity given that those sensors and their application to conservation (especially habitat relations) have been covered elsewhere (e.g., Cooke 2008).

Sensor Tags and Conservation

Physiological sensor tags have demonstrated their importance in a number of thematic areas in conservation. We considered 4 main (but at times overlapping) areas: quantifying the impact of human disturbance on wild animals; understanding and predicting the impact of environmental change; understanding the consequences of habitat selection and animal movement; and implications for animal energetics.

Quantifying Disturbance by Humans

Although it has long been recognized that human actions profoundly impact wildlife, it is only comparatively recently that the technological ability to understand the effects of this impact has existed. Heart-rate sensors have proven particularly useful for quantifying aspects of

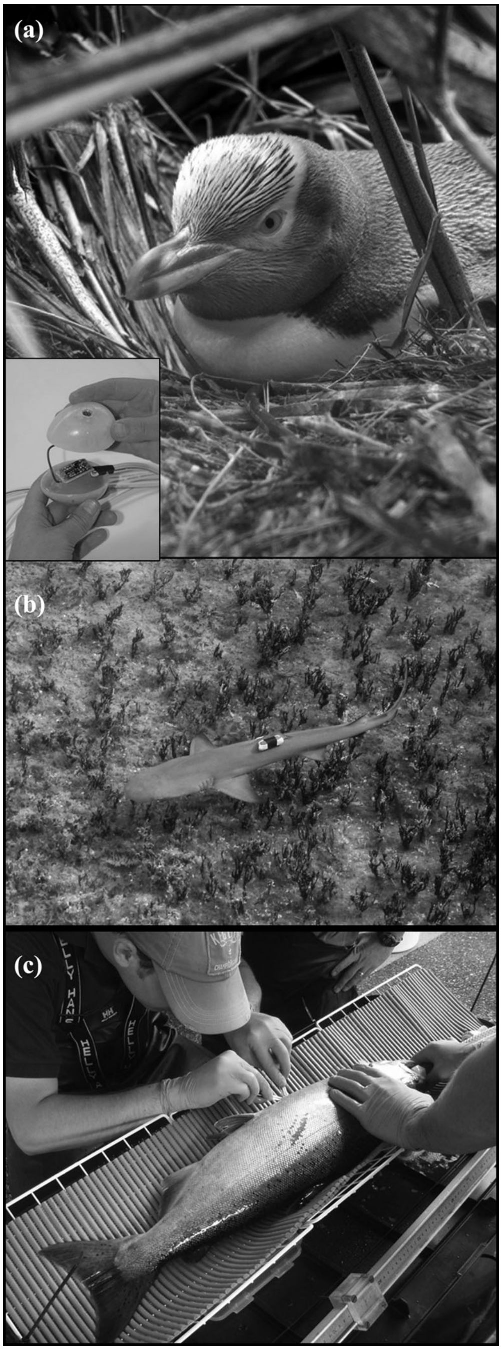

*Figure 1. Examples of electronic tags involving heart rate sensors and accelerometers: (a) unattached oval-shaped devices (to mimic an egg [inset photo]) that measure the effects of human disturbance on Yellow-eyed Penguins (*Megadyptes antipodes*) (photo by U. Ellenberg); (b) attached triaxial accelerometers that measure locomotion and habitat use in juvenile lemon sharks (*Negaprion brevirostris*) (photo by E. Kruthoff); (c) implanted electrodes for a radio transmitter that measures responses of Puntledge River Chinook salmon (*Oncorhynchus tshawytscha*) to pulse flow releases intended to stimulate upstream migration (photo by A. Cooke).*

these effects across a wide range of taxa (Chabot 1991; Buckley 2013). For example, Bisson et al. (2011) used tiny (0.5 g) heart-rate transmitters to examine the energetic response of the endangered songbird (*Vireo atricapilla*) to human-mediated disturbance (e.g., recreational activities near wildlife habitat) and to identify corresponding reaction thresholds. Bisson et al. (2009) used heart-rate transmitters to study *Vireo griseus* and found that this species quickly habituate to nonthreatening human disturbance and in doing so avoids a costly physiological response. Harms et al. (1997) noted a similar response in Black Ducks (*Anas rubripes*) which, when exposed to simulated aircraft noise, quickly habituate to the stimulus despite an initial spike in heart rate on first exposure. Nevertheless, human disturbance is not easy to characterize in a general sense because there is often much interspecific variation in the stress response to perturbation.

Ackerman et al. (2004) noted a 3-fold increase in heart rate (with implanted radio transmitters) of wild geese (*Anser albifrons elgasi*) immediately preceding and following a flight escape response initiated by close human proximity. Similarly, Ellenberg et al. (2012) demonstrated that Snares Penguins (*Eudyptes robustus*) had an elevated stress response to human encounters when nesting if in the previous season, the birds were exposed to intrusive research or filming activities, suggesting a long-lasting human-specific disturbance response. Despite these contextual complexities, sensor tags clearly provide unique insights into human impact on animals because they measure physiological responses directly rather than relying on inference based on observation or post hoc sampling.

Sensor tags can also be used to tease apart the underlying mechanisms and magnitude of an animal's response to different disturbance stressors. For example, Ellenberg et al. (2013) measured the heart-rate response of yellow-eyed penguins (*Megadyptes antipodes*) to ecotourism at breeding sites and determined that it was the duration of a tourist encounter, irrespective of passivity, that critically modulated stress in the nesting birds. These authors used oval-shaped devices with heart-rate sensors and transmitters that mimicked an egg (Fig. 1a). The effects of manipulation of the birds, normally appreciable during tag fixation, were partially mitigated because the eggs were put in place while 1 bird in the pair was absent from the nest. In pioneering studies, Weisenberger et al. (1996) used heart-rate sensors to measure the effect of jet aircraft on desert ungulates. They found that, although such stimuli caused short-term disturbance to the animals, focal individuals recovered quickly (<252 s) and demonstrated a habituation response over time. Conversely, Ward and Cupal (1979) found that wild elk (*Cervus canadensis*) responded most strongly to close human proximity or gun shots rather than motorized vehicles or low-flying aircraft. Heart-rate telemetry was also used to determine that bighorn sheep (*Ovis canadensis*) respond most strongly to the presence of

Table 1. Main categories of physiological metrics that can be monitored with various sensors integrated into telemetry transmitters or biologging devices.[a]

Physiological metric	*Representative sensor options*	*Technical and logistic constraints*	*Potential applications to conservation*[b]
Locomotor activity	multiaxis accelerometer (Shepard et al. 2008; Halsey et al. 2011; Brown et al. 2013); electromyogram (EMG) via electrodes and high input impedance amplifiers (Cooke et al. 2004*b*); magnetically or optically sensed rotors, drag and strain gauges and switches (Sundström & Gruber 1998); pressure transducers (Webber & Odor 1986)	some devices require implantation of electrodes; calibration required to estimate energetic costs and speed for swimming, flying, and running; numerous sensor options for both telemetry (usually requires sending some form of aggregated data due to data packaging and transmission limitations; Wilson et al. 2013) and biologging; cost effective and commercially available from numerous suppliers; applicable to all appropriately sized animals	estimate energetics consequences of habitat selection or interaction with humans (e.g., fish passage; bycatch) assess welfare status for captive breeding programs understand specific behavioral responses of individual animals toward disturbance possible use in wildlife disease studies by measuring “sickness behavior”
Cardiac activity (including blood pressure)	ECG via electrodes and high input impedance amplifiers (Priede 1983; Butler et al. 2004); flow transducer (e.g., Doppler; Grans et al. 2009); pressure transducers	some devices require implantation of electrodes near pericardial cavity or placement of flow probes near or around blood vessels so requires specialized training/knowledge although increasing number of noninvasive approaches (e.g., birds sitting on fake sensor- equipped egg that records ECG; Ellenberg et al. 2013); calibration required to estimate metabolic costs; few commercially available options until recently; mostly biologger style although some telemetry options for heart rate; applicable to most vertebrate taxa	energetic consequences of disturbance unbiased estimate of the stressfulness of a situation, even if the individual freezes in behavior or shows no behavioral change validation of the background stressfulness of living in a certain habitat or under certain environmental conditions assessing the scope of reactivity the individual has toward unexpected situations
Ventilation rate	EMG (Rogers & Weatherley 1983) and derivation from ECG; (Moody et al. 1985); strain gauges and switches; pressure transducers (Halsey et al. 2011)	some devices require implantation of electrodes; calibration required to estimate energetic costs; sensor options for both telemetry and biologging; relatively few commercially available options; applicable to all appropriately sized animals where respiration/ventilation are reasonably pronounced	similar to cardiac activity above

Continued

Table 1. Continued

Physiological metric	*Representative sensor options*	*Technical and logistic constraints*	*Potential applications to conservation*[b]
Neural activity	EEG micro electrodes inserted into innervated tissue and high input impedance amplifiers (Nieder & Wagner 2001)	very few options available; some limited proof of concept studies but no commercially available options; may require somewhat invasive surgery for placement of electrodes; limited to larger animals (probably vertebrates); still in its infancy	allowing the understanding of decision rules for individuals in their environment sleep studies: Can an individual find enough rest in its current environment?
Body/tissue temperature	thermistors, thermocouples, heat flux sensors (Dawson & Fanning 1981; Brain & Mitchell 1999; Bulte & Blouin-Demers 2010)	numerous sensor options for both telemetry and biologging platforms; least expensive sensor option (as low as $15 for a thermal biologger); many commercial options for purchase; one of the smallest tag options; easy to use although implantation required to obtain body temperature; tissue-specific temperatures (e.g., brain; Fuller et al. 1999) require specialized training and knowledge; applicable to all appropriately sized animals	assessment of the health status of an individual via a fever response assessment of the scope of behavioral flexibility (e.g., Can an individual still escape a stressful situation?) How close is an individual to its thermal maximum or minimum provided it is pushed to the habitat limits through disturbance of climate change?
Chemistry of body fluids	fluors or colorimetric compounds measured by LEDs and phototransistors (Poitout et al. 1993); ion-specific electrodes; conductivity cells	very few options available (e.g., blood glucose and oxygen; Heller 1999); mostly conceptual with research and development efforts underway and many patents filed; would likely be for short duration (hours to days); likely with be focused on larger vertebrates; rapid developments forthcoming attributed to human medicine	salinity of milieu, ionic strength of body fluids; enables the monitoring of simple blood biochemical properties such as glucose or stomach pH multisensing nano platforms can assess physiological and health state including stress-hormone breakdown products, thus assessing the scope of reactivity toward additional stress

[a] *Key technical references specific to the measurement of a given physiological metric with sensor-borne electronic tags are also provided.*

[b] *New sensors are continually being developed and the potential applications listed are not intended to be exhaustive. See Cooke et al. (2004a) and Payne et al. (2014) for additional detail on sensor capabilities.*

wild canids, followed by humans in prolonged close proximity (1–10 min, <50 m) and nearby vehicular traffic or aircraft (<200 m) (Macarthur et al. 1979).

Sensor tags have also been used to determine the impact of recreational and commercial harvesting of animals. For example, Donaldson et al. (2010) used heart-rate loggers to measure the physiological response of coho salmon (*Oncorhynchus kisutch*) to simulated fisheries encounters, thereby informing fisheries managers about recovery times for discarded fish. Laske et al. (2011) used heart sensors to look at the impact of human and environmental stressors on wild bears, observing dramatically elevated heart rates in response to interactions with hunters.

In addition to heart-rate telemetry, accelerometers (Fig. 1b) have also been used to quantify human disturbance on wildlife (Shepard et al. 2008; Brown et al. 2013). For example, Stoot (2013) used fine-scale accelerometry to assess the sublethal effects of entrapment on the locomotory behavior of freshwater turtles as a result of commercial fyke-net fisheries and found significant effects for more than 6 hours postrelease. Similarly, Brownscombe et al. (2013) used triaxial accelerometer loggers to study locomotor behavior of bonefish (*Albula* spp.) in response to recreational angling. They determined that traditional angling practices (immediate release) resulted in higher risk of predation postrelease and advocated other mitigation methods (e.g., recovery bags) be used to avoid such consequences in angled fish.

Understanding and Predicting Environmental Change

Researchers have used physiological sensor tags to examine how animals respond to natural and human-induced environmental changes, including the introduction of invasive species, thermal variability, ocean acidification, hypoxia, and extreme weather. For example, Hetem et al. (2012) used activity and body temperature loggers to reveal that free-ranging oryx (*Oryx leucoryx*) have substantial flexibility in their behavioral response to heat, which the authors surmised might help the animals buffer the adverse effects of the progressively hotter and drier conditions predicted to occur with climate change. Vitousek et al. (2010) used internal heart rate data-loggers to measure the stress response of marine iguanas (*Amblyrhynchus cristatus*) to novel and familiar predator cues and found the first mechanistic evidence regarding the underpinnings of the muted escape behavior of species that have been evolutionarily isolated from predators (i.e., exhibit island tameness). Sensors were also used by Bowlin et al. (2005) to measure heart rate and wing beat frequency to gain insights into the in-flight physiology and energetic trade-offs of natural migration in songbirds, an important prerequisite to understanding how changing conditions could influence migration biology.

Despite diverse taxonomic usage, physiological sensor tags have been most commonly used to examine the effects of environmental changes on fishes. For example, Clark et al. (2013) used sensors to shed light on how the cardiorespiratory system of bluefin tuna (*Thunnus orientalis*) maintains thermal equilibrium in dynamic thermal environments. Similarly, Donaldson et al. (2009) used body temperature loggers to assess the extent to which sockeye salmon (*Oncorhynchus nerka*) could behaviorally thermoregulate in rivers by seeking thermal refugia. Fish body temperatures in this study mirrored mean water temperatures; thus, the salmon were largely unable to regulate internal temperatures. This finding highlights a potential conservation concern given future expected increasing summer temperatures. However, concerns with thermal dynamics are not limited to fish. Jackson et al. (2009) studied endangered golden moles (Chrysochloridae) using temperature-sensing implant tags in an effort to better understand how behavioral patterns and subterranean microclimatic conditions impact ecological responses, providing urgently needed information for conservation planning. Similarly, implanted tags helped clarify how the energy expenditure of bats is affected by changes in ambient temperature during torpor (Currie et al. 2014). Such tools and approaches can now be used to understand how species cope with environmental challenges (i.e., climate change) and other anthropogenic impacts over a variety of time scales.

Consequences of Habitat Selection and Movement

Microclimatic variables such as temperature have been postulated to influence animal physiological capacities, with carryover effects for ecological and demographic performance (Huey 1991). Physiological sensor tags could therefore provide the link between habitat use and physiology as well as inform species and environmental management needs (Jackson et al. 2009). This ties in directly with other tag attributes, such as position determination (Cooke 2008), that provide detail on movement, foraging, reproduction, and dispersal. For example, Fossette et al. (2012) used accelerometer tags to demonstrate that breeding female loggerhead turtles (*Caretta caretta*) seek out warm water areas to speed up egg development. Such distinct behavioral patterns might assist in understanding how sea turtles are likely to expose themselves to, for example, gillnet bycatch or directed hunting (Senko et al. 2010). Webb and Shine (1998) used radio tags to investigate the role of thermal factors in retreat-site selection in an endangered snake (*Hoplocephalus bungaroides*). Using sensor data, the authors determined seasonal patterns of habitat use and provided a basis from which to plan the protection and restoration of critical habitat components.

The ability to determine the value and status of particular habitats relative to population dynamics is central to many conservation strategies. Correspondingly, there is clear value in studies such as Akamatsu et al.'s (2007). These authors used acoustic data loggers to study click trains and calling intervals in coastal and riverine porpoises, thereby identifying periods when and general locations where these species were susceptible to entanglement in commercial fishing nets. Similarly, Koenig et al. (2001) used radio tags with body temperature sensors to assess how successfully a large lizard (*Tiliqua scincoides*) was able to adapt to living in suburban residential neighborhoods by avoiding humans and their domestic pets.

Sensor tags have also been used to determine how fish respond to dynamic regulated river environments (e.g., Quintella et al. 2004; Hasler et al. 2012) and to examine the efficacy of management interventions. For example, Enders et al. (2007) used electromyogram radio telemetry (EMG) to examine how salmonids respond to an artificial fluvial habitat created to simulate natural spawning and rearing habitat that was lost or degraded due to anthropogenic changes.

Energetics

Given that energy is a key currency for wildlife and that energy abundance factors into population well being (Ricklefs & Wikelski 2002), any sensors within electronic tags that can help determine metabolic rate (Wilson et al. 2008) have clear value in conservation science. For instance, the energetic costs of operating within the landscape, the so-called energy landscape (Shepard et al. 2013), can help explain space use in wild animals. Wilson et al. (2012) used accelerometer tags to construct an energy landscape around a Cormorant (*Phalacrocorax atriceps*) breeding colony and determined that the birds selected foraging areas that, although varying significantly in terms of distance from the colony and depth, were all characterized by minimal power requirements relative to other areas in the available landscape. The ability to characterize the environment in terms of energetic costs to animals promises to be an important consideration for captive breeding and rehabilitation programs that intend to release animals into the wild. Similarly, the ability to measure heart rate and wing beat frequency in migrating songbirds (Bowlin et al. 2005) should help quantify the energetic value of flight corridors (Shepard et al. 2013) that they may preferentially use. Such an approach will also help identify the costs of animal avoidance of human-made structures (e.g., birds and windfarms [Desholm & Kahlert 2005]). This approach has already been used in fishes. For example, using acoustic accelerometer transmitters, Burnett et al. (2014) quantified how an anadromous fish (*O. nerka*) navigates through artificial fishways and dam-spill discharge during migration. Similarly, Cocherell et al. (2011) used EMG transmitters to assess the swimming behavior of and associated energetic costs to rainbow trout (*Oncorhynchus mykiss*) as a result of pulsed (fluctuating) water flows generated by hydroelectric power generation. Fish had increased energetic costs and decreased foraging opportunities during high flows. In contrast, Taylor et al. (2012) found that pulsed flows were no more energetically costly than stable flows in mountain whitefish (*Prosopium williamsoni*).

Direct observation and physiological assays can be used to complement bio-logging data and provide a more holistic view of an animal's ecology and therein its conservation needs. For example, Ismail et al. (2012) used direct observation and digital data loggers (accelerometry and temperature) on captive milky storks (*Mycteria cinerea*) to help put logger data derived from wild storks into perspective. In fishes, Pon et al. (2009) used EMG radio telemetry in conjunction with physiological biopsy (nonlethal blood samples assayed for lactate, cortisol, glucose, and ions) to relate prior physiological condition and subsequent swimming energetics to passage (fishway) success in sockeye salmon. Ely et al. (1999) simultaneously measured heart rate and behavior in wild geese (*Anser albifrons*) and suggest that such instantaneous measurement of physiological parameters (i.e., heart rate) can be a better indicator of response to external stimuli than traditional visual observation.

Finally, data from sensor tags can be used to develop bioenergetics models, which are often used in fish and wildlife management (Hansen et al. 1993), as well as to understand how energetic needs vary relative to ontogenetic and ecological processes. Sauve et al. (2014) used gastric temperature telemetry to examine the transitional nature of nutritional independence, pre-weaning growth, and survival in harbor seals (*Phoca vitulina*) and found that stomach temperature may inform understanding of ontogenetic processes in endotherms. Robinson et al. (2010) used a combination of satellite tracking and depth-logging electronic tags to better understand spatiotemporal patterns of prey acquisition and habitat use in the foraging ecology of northern elephant seals (*Mirounga angustirostris*).

Testing the Effectiveness of Proposed Solutions

Although most research using physiological sensor tags has been about seeking causes for effects, an emerging theme is directed toward testing how effective management interventions have been. For example, Alexandre et al. (2013) used electromyogram (EMG) radio transmitters to demonstrate that fishways intended to facilitate upstream passage of Iberian barbel (*Barbus bocagei*) did so without exceeding the aerobic swimming capacity of the fish, hence informing the design of future fishways. Electromyogram radio tags were also used to determine that pulse flows intended to stimulate upstream movement of endangered chinook salmon over areas of known difficulty did not result in an increased level of locomotory or therefore energetic expenditure (Hasler et al. 2014).

Innovative use of animal-tracking technology and the advent of real-time telemetry of positional data through sensors attached to animals also offer the opportunity to provide substantial conservation benefits. Wall et al. (2014) recently presented a novel approach combining telemetry with continuous algorithm-based analytics to identify animals in distress (ill or deceased) via deviations in their locomotory profiles (i.e., movement rate, immobility) in real time, providing an innovative way to combat poaching and monitor management and implemented conservation initiatives directly. To date, however, the bulk of the research devoted to evaluating success of management interventions (such as habitat restoration) has focused on tags that do not have physiological sensors (Lapointe et al. 2013).

Realizing the Potential of Sensor Tags

Physiological sensor tags, particularly when combined with other traditional tracking technologies, have the potential to revolutionize the way ecologists view animal physiology and behavior and offer important new directions for conservation and resource management. Hesitation to adopt sensor tag findings within the management community might largely be due to several factors, including small sample sizes within studies (because sensor-equipped electronic tags are relatively expensive), short time spans of data collection (typically hours to days [Fuller et al. 2005; Wilson et al. 2008]), concerns about tagging effects (lengthy surgical procedures and placement of electrodes near vital organs [McMahon et al. 2011]), and a lack of expert knowledge and understanding about the potential applications of the technology (Cooke et al. 2004*a*; Young et al. 2013). Many physiological sensor tags are not yet commercially available and therefore often require customized solutions and costly trial and error approaches to their application. Given these challenges, it is often hard to see how tag-derived data can be scaled up to populations or ecosystems—levels of interest to managers (Wikelski & Cooke 2006; Cooke & O'Connor 2010).

Yet the conservation opportunities provided by sensor tags are numerous. A park planner, for example, could use these technologies to understand how species' respond to various anthropogenic activities, therein providing important information regarding park zoning. Sensing technology might also be used to evaluate and refine existing management interventions, including reintroduction programs and habitat restoration initiatives to determine if they yield the desired outcomes. Sensor tags can also allow for the use of fewer individuals in studies because of the inherent sensitivity and low error rates in data collected relative to more traditional methods such as random physiological sampling (e.g., blood sampling). Sensitivity and accuracy is important when working with vulnerable or endangered species. Last, sensory tag technology might be used to improve understanding of the biology of threatened species and thus to determine their conservation needs (e.g., protected areas of high vulnerability).

Sensor tags do not integrate responses over long periods, which is typical of most hormonal stress studies, but they do allow for the identification of a specific environmental stressor in space and time. This makes sensor tags particularly promising for the identification of disturbance thresholds (e.g., ecotourism, urbanization, and resource extraction) given their potential to help in the study of the mechanistic responses of animals to various stimuli in the wild. One of the greatest strengths of sensor tags is that they allow researchers to work in the field and yet generate types and quality of physiological data that were previously attainable only in the laboratory (Costa & Sinervo 2004). Sensor tags also have great potential for studying the effects of environmental change and providing data to populate models for predicting the impacts of phenomena such as ocean acidification and climate change.

Technological innovation in sensor tag development is another area of significant research and conservation potential. Every year tags shrink in size and are used for more diverse purposes (e.g., Gräns et al. 2009; Meyer & Holland 2012; Williams et al. 2014) as well as species (e.g., Australian giant cuttlefish [*Sepia alpama*] [Payne et al. 2011]). Sensor tags can also be used to build and improve on existing research and data collection protocols, particularly in species that are difficult to observe directly in the wild (Chinnadurai et al. 2010; McFarland et al. 2013). As such, sensor tags present a valuable opportunity to link behavior, physiology, and ecology in wild animals (Whitney et al. 2012) as well as provide new insights on trophic ecology and ecological processes (Kays et al. 2011).

Given the links between behavior and physiology (Cooke et al. 2014), sensor tags provide unique opportunities to integrate paradigms and perspectives from these 2 disciplines to yield a more holistic and integrated conservation science. Data on spatial ecology, often derived from electronic tags, can be combined with physiological sensor data (e.g., heart rate) to provide spatially explicit information on the effects of, for example, human disturbance and environmental variation on animals. Such comprehensive and mechanistic information is of direct relevance to organismal fitness and population-level processes (Ricklefs & Wikelski 2002) and enables researchers to study animals at temporal and spatial scales that are of direct relevance to conservation.

We encourage researchers to incorporate current and future biological sensor tags wherever possible to generate the understanding needed to achieve evidence-based conservation and environmental management in the 21st century. Doing so will require creativity (Aslan et al. 2014) and overcoming the conceptual and practical barriers that impede the adoption of sensor-based findings by conservation practitioners and resource managers as well as cognizance of animal ethics (McMahon et al. 2007; Jewell 2013). Continued efforts to publish success stories supported by rigorous tagging validation studies, robust sample sizes and efforts to link mechanistic findings with population-level processes represent the most likely means of establishing greater recognition for physiological sensor tags as part of the conservation tool box.

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