

2016

Success Stories and Emerging Themes in Conservation Physiology

Christine L. Madliger
University of Windsor

Steven J. Cooke
Carleton University


Erica J. Crespi
Washington State University

Jennifer L. Funk
Chapman University, jlfunk@chapman.edu

Kevin R. Hultine
Desert Botanical Garden, Phoenix, AZ

Follow this and additional works at: http://digitalcommons.chapman.edu/sees_articles

See next page for additional authors

 Part of the [Comparative and Evolutionary Physiology Commons](#), [Environmental Education Commons](#), [Environmental Health and Protection Commons](#), [Environmental Indicators and Impact Assessment Commons](#), [Environmental Monitoring Commons](#), [Food Science Commons](#), [Nutrition Commons](#), [Other Ecology and Evolutionary Biology Commons](#), [Other Environmental Sciences Commons](#), [Other Life Sciences Commons](#), [Other Physiology Commons](#), [Sustainability Commons](#), and the [Systems and Integrative Physiology Commons](#)

Recommended Citation

Madliger CL, Cooke SJ, Crespi EJ, Funk JL, Hultine KR, Hunt KE, Rohr JR, Sinclair BJ, Suski CD, Willis CKR, Love OP (2016) Success stories and emerging themes in conservation physiology. *Conserv Physiol* 4(1): cov057; doi:10.1093/conphys/cov057.

This Article is brought to you for free and open access by the Biology, Chemistry, and Environmental Sciences at Chapman University Digital Commons. It has been accepted for inclusion in Biology, Chemistry, and Environmental Sciences Faculty Articles and Research by an authorized administrator of Chapman University Digital Commons. For more information, please contact laughtin@chapman.edu.

Success Stories and Emerging Themes in Conservation Physiology

Comments

This article was originally published in *Conservation Physiology*, volume 4, issue 1, in 2016. DOI: [10.1093/conphys/cov057](https://doi.org/10.1093/conphys/cov057)

Creative Commons License



This work is licensed under a [Creative Commons Attribution 4.0 License](https://creativecommons.org/licenses/by/4.0/).

Copyright

The authors

Authors

Christine L. Madliger, Steven J. Cooke, Erica J. Crespi, Jennifer L. Funk, Kevin R. Hultine, Kathleen E. Hunt, Jason R. Rohr, Brent J. Sinclair, Cory D. Suski, Craig K. R. Willis, and Oliver P. Love

Success stories and emerging themes in conservation physiology

Christine L. Madliger^{1,*}, Steven J. Cooke², Erica J. Crespi³, Jennifer L. Funk⁴, Kevin R. Hultine⁵, Kathleen E. Hunt⁶, Jason R. Rohr⁷, Brent J. Sinclair⁸, Cory D. Suski⁹, Craig K. R. Willis¹⁰ and Oliver P. Love^{1,11}

¹Department of Biological Sciences, University of Windsor, Windsor, ON, Canada N9B 3P4

²Fish Ecology and Conservation Physiology Laboratory, Department of Biology and Institute of Environmental Science, Carleton University, Ottawa, ON, Canada K1S 5B6

³School of Biological Sciences, Washington State University, Pullman, WA 99164, USA

⁴Schmid College of Science and Technology, Chapman University, Orange, CA 92866, USA

⁵Department of Research, Conservation and Collections, Desert Botanical Garden, Phoenix, AZ 85008, USA

⁶John H. Prescott Marine Laboratory, Research Department, New England Aquarium, Boston, MA 02110, USA

⁷Integrative Biology, University of South Florida, Tampa, FL 33620, USA

⁸Department of Biology, Western University, London, ON, Canada N6A 5B7

⁹Department of Natural Resources and Environmental Sciences, University of Illinois at Urbana-Champaign, Urbana, IL 61801, USA

¹⁰Department of Biology and Centre for Forest Interdisciplinary Research, University of Winnipeg, Winnipeg, MB, Canada R3B 2E9

¹¹Great Lakes Institute for Environmental Research, University of Windsor, Windsor, ON, Canada N9B 3P4

***Corresponding author:** Department of Biological Sciences, University of Windsor, 401 Sunset Avenue, Windsor, ON, Canada N9B 3P4.

Tel: +1 519 253 3000. Email: madlige@uwindsor.ca

The potential benefits of physiology for conservation are well established and include greater specificity of management techniques, determination of cause–effect relationships, increased sensitivity of health and disturbance monitoring and greater capacity for predicting future change. While descriptions of the specific avenues in which conservation and physiology can be integrated are readily available and important to the continuing expansion of the discipline of ‘conservation physiology’, to date there has been no assessment of how the field has specifically contributed to conservation success. However, the goal of conservation physiology is to foster conservation solutions and it is therefore important to assess whether physiological approaches contribute to downstream conservation outcomes and management decisions. Here, we present eight areas of conservation concern, ranging from chemical contamination to invasive species to ecotourism, where physiological approaches have led to beneficial changes in human behaviour, management or policy. We also discuss the shared characteristics of these successes, identifying emerging themes in the discipline. Specifically, we conclude that conservation physiology: (i) goes beyond documenting change to provide solutions; (ii) offers a diversity of physiological metrics beyond glucocorticoids (stress hormones); (iii) includes approaches that are transferable among species, locations and times; (iv) simultaneously allows for human use and benefits to wildlife; and (v) is characterized by successes that can be difficult to find in the primary literature. Overall, we submit that the field of conservation physiology has a strong foundation of achievements characterized by a diversity of conservation issues, taxa, physiological traits, ecosystem types and spatial scales. We hope that these concrete successes will encourage the continued evolution and use of physiological tools within conservation-based research and management plans.

Key words: Conservation physiology, ecotourism, invasive species, nutrition, sensory ecology, toxicology

Editor: Craig Franklin

Received 19 September 2015; Revised 5 November 2015; accepted 9 November 2015

Cite as: Madliger CL, Cooke SJ, Crespi EJ, Funk JL, Hultine KR, Hunt KE, Rohr JR, Sinclair BJ, Suski CD, Willis CKR, Love OP (2016) Success stories and emerging themes in conservation physiology. *Conserv Physiol* 4(1): cov057; doi:10.1093/conphys/cov057.

Introduction

Although the discipline of conservation physiology was formally defined only recently (Wikelski and Cooke, 2006), physiology has permeated conservation biology for decades (reviewed by Cooke *et al.*, 2013). The mechanistic approach espoused by conservation physiologists is considered powerful because it allows for the determination of cause–effect relationships (Carey, 2005; Wikelski and Cooke, 2006), contributing a valuable, evidence-based approach to conservation (Sutherland *et al.*, 2004). More specifically, the discipline integrates functional and mechanistic responses at all scales (Cooke *et al.*, 2013), leveraging diverse techniques from genomics and immunology to energetics and sensory physiology with the goal of fostering conservation solutions (Carey, 2005; Tracy *et al.*, 2006; Wikelski and Cooke, 2006; Cooke and O'Connor, 2010; Seebacher and Franklin, 2012; Cooke *et al.*, 2013). As a synergistic union of two disciplines, conservation physiology has the potential to lead to diverse tools and new theoretical paradigms (Coristine *et al.*, 2014); however, it must also contend with the differing perceptions, knowledge bases and logistical constraints from each independent discipline (Cooke and O'Connor, 2010) that may inhibit full integration (Lennox and Cooke, 2014). Importantly, successful integration of the disciplines is a multistep process that links ecological context and variation in physiology to the fitness parameters that drive population persistence (Coristine *et al.*, 2014). To have a tangible conservation impact, this information must then be translated into management recommendations, recovery plans or policy initiatives (Cooke and O'Connor, 2010; Coristine *et al.*, 2014).

To date, perspectives on the field of conservation physiology have focused primarily on the future potential of the discipline (Carey, 2005; Stevenson *et al.*, 2005; Wikelski and Cooke, 2006; Cooke *et al.*, 2013; Madliger and Love, 2015) and have lacked syntheses of past successes and their commonalities (but see Cooke *et al.*, 2014 for a discussion of successes in the integration of behaviour, physiology and conservation). Thus, it appears that the field of conservation physiology may still be largely theoretical. We argue, however, that success stories in conservation physiology are accumulating. Moreover, these successes share commonalities that allow us to delineate themes that characterize the successful application of conservation physiology and highlight where further growth is possible and required.

Here, we posit that conservation physiology has progressed from a nascent, theoretical discipline to an applied one with tangible successes. Specifically, we outline eight diverse topics spanning chemical contamination, integrative wildlife monitoring, nutritional management, disease control, entanglement and collision mediation, control of invasive species, fisheries management and ecotourism, where conservation physiology has resulted in measureable conservation successes. We conservatively define a success as a change in human behaviour, management or policy to the benefit of conservation that has

been driven by physiological information. Although we do not provide an exhaustive review, this cross-section highlights the major areas in which conservation physiology has been successful and demonstrates the important role that physiology can play across a broad range of conservation issues (Fig. 1). Finally, we draw on the common features of these successes to identify five emerging themes in the discipline that help to define its current status and breadth. Researchers or managers working within or considering the field of conservation physiology as a framework (see Coristine *et al.*, 2014) for their research activities or management strategies can use this foundation to identify productive pathways forward and foster additional conservation successes.

Successes in conservation physiology

Toxicology informs regulatory approaches to environmental chemicals

Environmental toxicology probably represents the longest-standing discipline linking physiological investigations to conservation (Stevenson *et al.*, 2005), with a classic example being that of dichlorodiphenyltrichloroethane (DDT) exposure and biomagnification causing reproductive failure in birds of prey. Specifically, physiologists identified how the breakdown product of DDT inhibits Ca^{2+} -ATPase in the shell gland, reducing the deposition of calcium carbonate to the eggshell and resulting in thinner eggshells and reproductive failure (Faroon *et al.*, 2002). These discoveries led to a ban of DDT in many industrialized countries and the consequent recovery of the bald eagle (*Haliaeetus leucocephalus*), brown pelican (*Pelicanus occidentalis*), peregrine falcon (*Falco peregrinus*) and osprey (*Pandion haliaetus*) in North America (Faroon *et al.*, 2002). The DDT success story also spurred the development of other physiological end points used in the ecological risk assessment of chemicals, a process that is ultimately used to assess safety for wildlife (Dickerson *et al.*, 1994). Physiological end points or biomarkers (indicators of a particular disease state or other physiological state of an organism) are now commonly used and range from acetylcholinesterase inhibition to oxidative stress status to immunological indices (Cajaraville *et al.*, 2000; Martin *et al.*, 2010; Beaulieu and Costantini, 2014). In amphibians, the most threatened vertebrate taxon (Stuart *et al.*, 2004; Rohr *et al.*, 2008a), physiological end points such as circulating corticosterone and liver damage have been used as early warning signs of negative effects of fungicide (e.g. chlorothalonil) exposure (McMahon *et al.*, 2011, 2012), and herbicide-induced immunomodulation has been linked with elevated amphibian mortality associated with trematode and chytrid fungal infections (Rohr *et al.*, 2008b,c, 2013). As a result of such research on non-target freshwater vertebrates, regulations on fungicides have been altered to protect susceptible ecosystems better. For example, the Canadian Pest Management Regulatory Agency now requires products containing chlorothalonil to include advisory statements on risk-reduction measures that reduce surface water contamination, such as maintenance of buffer



Figure 1: Conservation physiology successes cover a diversity of taxa, ecosystems, landscape scales and physiological systems. For example: (A) Birds of prey, such as osprey, have rebounded following regulations on DDT. (B) Plague is being combated in the endangered black-footed ferret via a targeted vaccination programme. (C) Caribou and wolf populations are being effectively managed via physiological monitoring of scat. In the right photo, a scat detection dog locates samples for subsequent physiological processing. (D) Nutrition programmes support successful breeding in the critically endangered kakapo. (E) Ecotourism feeding practices are regulated for stingrays in the Cayman Islands. In the right photo, a blood sample is obtained from the underside of the tail to monitor multiple physiological traits. (F) Sensory physiology has informed shoreline lighting regulations for nesting sea turtles. (G) Physiological monitoring of incidentally-captured fishes can be accomplished through blood sampling (left photo), and recovery chambers have been designed that decrease the stress associated with by-catch in salmonids (right photo). (H) Physiological studies have identified native species that tolerate fire caused by exotic species (top panel) and recruit under low light conditions in heavily invaded forests (bottom panel) in Hawaii Volcanoes National Park. Photograph credits: Randy Holland (A); United States Geological Survey National Wildlife Health Center (B); Wayne Sawchuk and Samuel Wasser (C); Kakapo Recovery (D); Christina Semeniuk (E); Sea Turtle Conservancy (F); Cory Suski and Jude Isabella (G); and Jennifer Funk (H).

zones between application sites and aquatic areas, and controlled maximal application rates (Health Canada, 2011).

Toxicologists have also demonstrated the mechanisms by which endocrine disruptors cause vertebrate population declines (Vos *et al.*, 2000). Much of this work began when researchers observed male fish producing vitellogenin (a protein normally synthesized by females during oocyte maturation) and eggs in their testes. This feminization was associated with exposure to estrogenic substances, such as synthetic estrogen used in contraceptive pills (Jobling *et al.*, 1996, 1998), and was supported by experimental evidence that synthetic estrogen within the range observed in municipal waste waters can lead to the feminization of males, intersex males, altered oogenesis in females and population declines in fish (Kidd *et al.*, 2007). Likewise, pesticide exposure has been linked to disruption of reproductive and thyroid hormone production, reproductive impairment and disease in amphibians and other vertebrates (Hayes *et al.*, 2006; Rohr *et al.*, 2006; Rohr and McCoy, 2010; Hayes *et al.*, 2011). The clear impacts of estrogens and endocrine disruptors on the sustainability of wild vertebrate populations have encouraged the USA, Japan, European Union and Organization for Economic Co-operation and Development to establish testing approaches and regulatory frameworks to assess and manage the risks associated with chemicals that have endocrine-disrupting potential (Hecker and Hollert, 2011).

Panels of physiological markers reveal health and stress in wild animals

'Panels' are suites of physiological measures (i.e. more than one measure) that provide comprehensive insight into the health and stress status of an individual, and are routinely used in human and veterinary clinical practice (Hindmarsh and Lyon, 1996; Thrall *et al.*, 2012). For example, a wildlife faecal endocrine panel could include glucocorticoids, progestins, androgens and estrogens and sometimes thyroid hormones as well. There is a growing suite of analytical tests, including point-of-care devices that can be used in the field to generate real-time data (Stoot *et al.*, 2014), sophisticated gene expression profiles generated from genomic analyses (e.g. gene arrays, chips) that provide insight on immune function, pathogen presence and metabolic state (Cruz *et al.*, 2012), and novel measures related to oxidative stress (Beaulieu *et al.*, 2013) or telomere length (Lewin *et al.*, 2015; Young *et al.*, 2015). As a result, there is no shortage of tissue-based assays available for assessing the health and physiological status of wildlife.

There have also been major innovations in our ability to collect non-invasive samples from a wide range of species. Given that faeces, urine, hair, feathers, sloughed skin and even respiratory vapour all contain molecules of physiological interest, these samples can be used non-invasively to assess health and stress in wild animals (Hunt *et al.*, 2013; Dantzer *et al.*, 2014). Faecal samples, for example, contain an array of steroid and thyroid hormones, as well as DNA from both prey and host species (Wasser *et al.*, 2010; Vynne *et al.*, 2014).

Thus, analysis of faecal hormone titres produces a 'faecal endocrine panel' that can provide information on stress physiology (e.g. glucocorticoids and mineralocorticoids), reproductive status (progestins, androgens and estrogens) and nutritional state and metabolic rate (thyroid hormones; Wasser *et al.*, 2011; Ayres *et al.*, 2012; Vynne *et al.*, 2014; Joly *et al.*, 2015). When combined with faecal DNA analyses to confirm species, determine sex and identify individuals, the result is a powerful analytical tool that can identify different environmental stressors and their relative impacts. Indeed, the utility of multiple-measure panels is often in their ability to separate the effects of different stressors to identify the causes of health decline or stress, leading to concrete recommendations. For example, in woodland caribou (*Rangifer tarandus caribou*), a combination of faecal DNA, corticosterone and thyroid measures has helped to delineate the differential impacts of wolf predation vs. human-use patterns associated with oil sands development, leading to a de-emphasis on wolf removal efforts and increased attention to preserving the caribou's access to lichen (Wasser *et al.*, 2011; Joly *et al.*, 2015; personal communication from Dr Samuel Wasser, University of Washington). A similar approach using a panel of faecal reproductive, adrenal and thyroid hormone measures allowed Ayres *et al.* (2012) to compare the impacts of boat traffic and nutritional stress on Puget Sound killer whales (*Orcinus orca*), identifying preservation of the prey base (salmon) as the more important conservation priority.

Beyond faecal hormones, -omics tools (including transcriptomics, proteomics and genomics) are increasingly being applied to conservation problems, enabling the rapid screening of thousands of genes related to physiological and biochemical end points, such as immune function and metabolic state. For example, Miller *et al.* (2011) took minimally invasive gill biopsies from migrating sockeye salmon (*Oncorhynchus nerka*) that were released with telemetry transmitters, enabling researchers to identify physiological signatures associated with failed migrants. Transcriptomics has also been used for environmental screening of condition, immunity and stress in steelhead (*Oncorhynchus mykiss*) on the Columbia River (Connon *et al.*, 2012). These tools have helped to identify suites of factors that are associated with environmental stressors and disease in wild salmonids, thus improving management actions by allowing practitioners to refine and justify harvest restrictions in Canada, leading to a greater balance among different stakeholder groups (Cooke *et al.*, 2012). It is anticipated that as more multipanel assessments become part of long-term routine monitoring, it will be possible to develop mechanistic models to determine better how human activities influence a multitude of animal populations.

Nutritional physiology improves management of captive and wild populations

The physiology underlying the nutritional needs of animals has been well explored in the context of agriculture (McDonald *et al.*, 2002) and zoos (Dierenfeld, 1997), and—particularly

for mammals—there are well-established markers available to allow assessment of nutritional health (e.g. Underwood, 1977; McDowell, 1989). In the context of conservation, nutritional physiology is particularly important in captive rearing programmes, in captive rearing for release programmes and in heavily managed populations, where food supplements may be provided to avoid disease and improve performance (Tracy *et al.*, 2006). Specifically, captive populations are a critical component of final-stage species conservation and have been somewhat successful for recovering critically endangered species and for supplementing populations (Philippart, 1995; Snyder *et al.*, 1996). Captive animal nutrition (including captivity for conservation purposes) is often developed through trial and error, combining field observations with *ad hoc* choice experiments, with reference to existing captive diets or nutritional information for related laboratory model species (Dierenfeld, 1997). Although health and performance provide the most appropriate measure of success, sometimes simply identifying suitable food can be a challenge (e.g. Honan, 2008). In other cases, physiological studies can be used to simplify captive diets. For example, tuatara (*Sphenodon* spp.), reptiles endemic to New Zealand, have been observed to eat seabird chicks in the wild, resulting in free-living individuals having high plasma levels of polyunsaturated fatty acids (Cartland *et al.*, 1994; Cartland-Shaw *et al.*, 1998). Although dietary supplementation with fish oil modified the plasma composition, this did not affect growth rate, metabolic rate or survivorship, requiring no change to the diet in captivity (Blair *et al.*, 2000), and no specific changes to captive diets were made (personal communication from Dr Alison Cree, University of Otago).

Nutrition-based diseases may be avoided by the provision of micronutrients, and often the underlying cause of such diseases can be detected only via a combination of physiology and pathology. For example, threatened black stilts (kāki, *Himantopus novaeseelandiae*) are captive reared for release in New Zealand's South Island, but there was initially considerable variation in hatching mortality between eggs collected from the wild (<15%) and those derived from captive birds (>50% perihatching mortality). Although the diet contained sufficient iodine for domestic poultry, increased incidence of goitres and low thyroxine titres in captive vs. wild birds led to a hypothesis of iodine deficiency. Supplementation of dietary iodine in the entire captive population increased serum thyroxine levels and led to consistently low perihatching mortality (Sancha *et al.*, 2004), and remains part of the captive diet (personal communication from Dr Richard Maloney, New Zealand Department of Conservation).

Nutritional physiology can also inform management decisions in wild and semi-wild populations at both the individual and landscape scales. For example, Bryant (2006) used doubly (isotopically) labelled water to estimate the energy expenditure in both free-ranging and captive kakapo (*Strigops habroptilus*). Mass-corrected estimates of energy expenditure are used specifically to determine the supplementary feeding protocol for this critically endangered parrot. As the diet of both

males and females is supplemented to achieve a threshold minimal mass for breeding, these data on energy expenditure allow managers to regulate the mass of birds in the approach to the breeding season to prevent females from crossing an upper threshold at which offspring become male-biased (personal communication from Daryl Eason, New Zealand Department of Conservation). At the landscape scale, understanding the physiology underlying threatened desert tortoise (*Gopherus agassizii*) nutritional requirements (Tracy *et al.*, 2006) has determined management decisions regarding habitat quality (US Fish and Wildlife Service, 2011).

Finally, nutritional physiology can identify sublethal impacts that can be traced back to large-scale ecosystem processes that, in some instances, have informed intervention. For example, the Laurentian Great Lakes have experienced widespread changes in food web structure owing to overexploitation, changes in habitat quality and introduction of non-native species (Mills *et al.*, 1994). Native lake trout (*Salvelinus namaycush*) populations have experienced dramatic population declines, which are partly attributed to thiamine (vitamin B₁) deficiency arising from a switch to consumption of non-native alewife (*Alosa pseudoharengus*), which contain high levels of thiaminase that breaks down thiamine (Brown *et al.*, 2005). After this problem was identified (Krueger *et al.*, 1995), fisheries managers were able to reduce populations of alewife in efforts to restore native lake trout populations, which has been somewhat successful as part of a multifaceted native restoration plan (Dettmers *et al.*, 2012).

Principles of ecological immunology aid in disease control

An understanding of the physiological function of immune systems, and acquired immune mechanisms specifically, has been instrumental to the development of successful vaccination campaigns with dramatic conservation implications. The key precursor of a successful vaccination programme for a host species of conservation concern is demonstrating that the host has the physiological capability to acquire immunity upon exposure to either dead or attenuated pathogen, and that this enhanced immunity is greater than any immunosuppressive effects of the pathogen. As an example, amphibians are experiencing widespread population declines and extinctions associated with chytrid fungal infections (Rohr and Raffel, 2010; Raffel *et al.*, 2013; Venesky *et al.*, 2014). Recent work revealed that repeated exposures of amphibians to chytrid increased lymphocyte abundance in hosts and lymphocyte proliferation when cultured with the dead pathogen. Moreover, immune memory stimulated by exposure to dead chytrid exceeded the immunosuppression caused by the fungus, resulting in reduced chytrid loads and enhanced frog survival (McMahon *et al.*, 2014).

The concept of induced adaptive immunity has been applied successfully to rescue several host species that experienced declines from introduced pathogens. For example, the morbillivirus that causes rinderpest was introduced into

northwestern Africa in the 1880s and resulted in 90% mortality of domestic and wild ungulates (Mariner *et al.*, 2012) and subsequent declines of their canid and felid predators (Dobson *et al.*, 2011). A thermostable vaccine was administered to domestic livestock throughout Africa and resulted in an elimination of the disease from wild ungulates and a subsequent surge in lion and hyena populations (Dobson *et al.*, 2011). When rabies outbreaks threatened the world's rarest canid, the Ethiopian wolf (Randall *et al.*, 2006), managers implemented a baited oral vaccination campaign focused at the corridor between an outbreak and susceptible wolf subpopulations and successfully prevented incursion of the epidemic into the vaccination zone (Haydon *et al.*, 2006). Likewise, plague caused by the introduced bacterium *Yersinia pestis* is considered a factor in the declines of prairie dogs and the black-footed ferret, possibly the most endangered mammal in North America. Laboratory studies revealed that a vaccine conferred protection against *Y. pestis*, and agencies have now widely distributed vaccine-laden bait and are tracking the recovery of prairie dog and ferret populations (USGS, 2011). Finally, the discovery of persistence of maternal antibodies in chicks of a long-lived colonial seabird species, the Cory's shearwater (*Calonectris borealis*), has influenced the design of vaccination programmes to protect nestlings of Procelariiforms (shearwaters, albatrosses and petrels) against recurrent epizootics in breeding colonies (Garnier *et al.*, 2012). Specifically, female albatross species threatened by avian cholera (*Pasteurella multocida*) on Amsterdam Island, southern Indian Ocean are being vaccinated to allow transmission of persisting maternal antibodies to their chicks over several breeding attempts (Weimerskirch, 2004; Garnier *et al.*, 2012; Ramos *et al.*, 2014; personal communication from Dr Thierry Boulinier, Université Montpellier). In summary, these examples emphasize the value of understanding immunology in a physiological context and, subsequently, implementing vaccines to manage threatened host species over vast geographical regions.

Sensory-based conservation strategies mitigate human–wildlife conflicts

Sensory physiology has guided conservation management in diverse scenarios, dictating strategies that exploit sensory modalities either to attract animals to desirable locations or to deter them from undesirable ones (Cooke *et al.*, 2013). Environmental alterations resulting from anthropogenic activities can create novel sensory cues (visual, auditory, olfactory, etc.) that mimic naturally occurring signals (Robertson *et al.*, 2013) or create features that are not easily detectable and can lead to collisions or entanglement (Martin and Crawford, 2015). Sensory-based interferences have been documented in relationship to a variety of structures and objects, such as light sources (Gaston *et al.*, 2012), fishing nets and lines (Southwood *et al.*, 2008), marine debris (Horváth *et al.*, 2009), wind turbines (Kuvlesky *et al.*, 2007), windows (Klem, 2009), power lines (Alonso *et al.*, 1994) and reflective solar panels (Horváth *et al.*, 2009). Overall, the associated negative

consequences for wildlife of such sensory traps often manifest as suboptimal choices of habitat, mates, migration routes or food and, in some cases, death (Schlaepfer *et al.*, 2002).

A consideration of sensory physiology has allowed managers and industries to alter structures and equipment to minimize influences on wildlife by tailoring aversion measures to the sensory capacities of targeted wildlife (Madliger, 2012; Martin and Crawford, 2015). Specifically, the measurement of visual and auditory sensitivities has pinpointed the most effective strategies for deterring wildlife. This approach has been particularly successful in the fishery sector, where acoustic alarms have been designed to take advantage of the auditory sensitivities of aquatic mammals, subsequently reducing incidental captures (i.e. by-catch; Cox *et al.*, 2007). This is critical to conservation because estimates of total global by-catch are as high as 38.5 million tonnes per year (Davies *et al.*, 2009) and thus, mitigation measures based on targeted sensory approaches can have far-reaching implications for wildlife incidentally influenced by fishing practices. For example, 'pingers', which create continuous bursts of sound, have been implemented in the US Northeast gillnet fishery and have reduced harbour porpoise (*Phocoena phocoena*) by-catch rates by 50–70% (Palka *et al.*, 2008). Likewise, in the California drift gill net fishery, pingers reduced beaked whale (*Ziphiidae* spp.) by-catch to zero (Carretta *et al.*, 2008) and have significantly decreased incidental captures of short-beaked common dolphins (*Delphinus delphis*) and California sea lions (*Zalophus californianus*; Barlow and Cameron, 2003). In the context of hydropower facilities, a host of stimuli, such as strobe lights, high-intensity sound and bubble curtains (tactile deterrents) have been used to prevent impingement or entrainment of fishes (Noatch and Suski, 2012). Other acoustic alarms that use low frequencies and harmonics have also reduced whale collisions with cod (*Gadus morhua*) and capelin (*Mallotus villosus*) fishing gear in Newfoundland, Canada (Lien *et al.*, 1989). Beyond noise-based mitigation measures, there is extensive research into gear modifications that can exploit other sensory systems through olfactory, visual and chemosensory cues to decrease incidental captures in cetacean, avian, sea turtle and elasmobranch species (Brothers *et al.*, 1999; Pierre and Norden, 2006; Wang *et al.*, 2010; Chosid *et al.*, 2012; Jordan *et al.*, 2013).

A sensory-based approach has also been applied to the problem of avian collisions with buildings. Birds are particularly vulnerable to collisions with human structures because their high-resolution vision is limited to the lateral view, lighted buildings can act as an attractant (Martin, 2011), and they are unable to distinguish the reflection of vegetation in mirrored surfaces from natural features (Klem *et al.*, 2009). In the USA alone, annual mortality caused by building collisions is estimated to be between 365 and 988 million birds (Loss *et al.*, 2014), and collisions are thought to represent the second largest cause of anthropogenically linked mortality in birds worldwide (Klem, 2009). However, a number of approaches based on knowledge of the visual perception of

birds can reduce window collisions by nearly 60% (Klem and Saenger, 2013). Fritted (patterned) glass, uniformly spaced decals and ultraviolet-absorbing and -reflecting films targeted to wavelengths visible to birds effectively reduce avian collisions with buildings (Klem, 2009; Klem and Saenger, 2013). Importantly, many major cities, including Toronto, Vancouver, Chicago, New York City and San Francisco, are incorporating bird-friendly, sensory-based guidelines into legislation, development plans and 'lights out' awareness programmes to minimize mortality of avian species caused by building collisions, particularly during migratory periods (City of Chicago, 2007; City of Toronto, 2007; New York City Audubon Society, 2007; San Francisco Planning Commission, 2011; City of Vancouver, 2015). In addition, larger federal programmes in the USA, such as Leadership in Energy and Environmental Design (LEED), which provides certification for green buildings, have also begun to provide credits for building designs that include high-visibility facades for bird-collision reduction (US Green Building Council, 2015). In another vision-based conservation strategy, federally listed sea turtle hatchlings that are disoriented by shoreline lighting have benefited from regulations in Florida and South Carolina aimed at altering the intensity and wavelengths of light sources based on the visual sensitivities of affected species (Lohmann *et al.*, 1997; Salmon, 2006).

Physiological knowledge aids in control of invasive species and subsequent restoration

Invasive species are considered to be a leading cause of animal extinctions worldwide (Clavero and Garcia-Berthou, 2005) and can have many complex and often negative ecological and evolutionary impacts across taxa (Vitousek *et al.*, 1997; Wilcove *et al.*, 1998; Pimentel *et al.*, 2000; Vilá *et al.*, 2011). Although the concept of conservation physiology has been applied most directly to the study of native species threatened by environmental change, it has also aided in the identification of physiological traits of invasive species that can be harnessed to direct control and mitigation efforts and to predict further spread (Funk *et al.*, 2008; Funk, 2013; Lennox *et al.*, 2015). Specifically, the application of physiology to combat invasive species typically identifies traits that impact whole-organism function, such as metabolism, nutritional status or thermal tolerance (Chown, 2012). In this way, physiology can be used to determine management approaches that may best exploit a given trait, which weakens or eliminates the capacity of a species to invade a non-native habitat. For example, the thermal tolerances of wood-boring insects [e.g. Asian longhorned beetle (*Anoplophora glabripennis*)] have been used to determine the minimal heat treatments required by the International Plant Protection Convention for phytosanitary treatment of wood packaging material (e.g. pallets and crates). The associated international phytosanitary standards (IPPC, 2009), which allow for heat or fumigation as control measures, are estimated to have decreased infestation rates of wood and bark pests by 36–52% worldwide (Haack *et al.*, 2014). This reduction in infestation will decrease propagule

pressure (i.e. the number of viable insects entering a new location) and therefore the likelihood of subsequent invasion (Brockerhoff *et al.*, 2014).

In other cases, a consideration of physiology has contributed to the control of invasive species in already-established locations by decreasing their ability to function or survive. For example, sea lamprey (*Petromyzon marinus*), which parasitize adult top-predator fish during the juvenile stage, colonized the Laurentian Great Lakes during the late 1900s and caused severe losses to sport and economically important fishes (Chapman and Bolen, 2015). Research conducted in the 1960s–1970s indicated that application of the chemical 3-trifluoromethyl-4-nitrophenol (TFM) inhibited ATP production and mitochondrial oxidative phosphorylation, thus shutting down aerobic respiration and causing mortality, while posing minimal health risks for other wildlife or humans (Menzie and Hunn, 1976; Hubert, 2003). According to the Great Lakes Fishery Commission (2015), the application of TFM, along with building barriers and trapping, has been a 'remarkable success', because it has reduced sea lamprey populations by 90% in most areas of the Great Lakes.

A consideration of physiology has also refined management decisions involving use biological control agents. For example, the *Tamarix* leaf beetle, *Diorhabda* spp. (Chrysomelidae), was released in the USA to control *Tamarix* (DeLoach *et al.*, 2003), an invasive tree/shrub that has negatively impacted biodiversity, water resources and ecosystems functions in arid and semi-arid riparian ecosystems of the western USA and Northern Mexico (Shafroth *et al.*, 2005). Ongoing research has identified geographical gradients in plant tolerance to herbivory, such that *Tamarix* populations from warmer climates are more susceptible to defoliation by *Diorhabda* than populations from cooler climates (Williams *et al.*, 2014). Gradients in herbivory tolerance appear to be related to specific physiological traits, such as the allocation of recent photosynthates to growth and labile carbon storage, which may make *Tamarix* genotypes in some regions more susceptible to biocontrol than others (Hultine *et al.*, 2015). Specifically, riparian restoration priorities are currently being targeted in Arizona based on the identification of *Tamarix* carbon allocation strategies across broad, macrophysiological scales (Orr *et al.*, 2014).

A consideration of the physiological differences among native and invasive plant species can also directly improve management practices (e.g. Funk *et al.*, 2008; Funk, 2013). Physiological studies of light and fire tolerance have impacted management protocols in Hawaii Volcanoes National Park (HAVO), where managers are tasked with conserving large tracts of native forests that are threatened by invasive species. For example, shade-intolerant invasive grasses suppress the recruitment of native ferns and woody canopy species in mesic forests. Funk and McDaniel (2010) manipulated light levels in a disturbed forest and assessed species differences in photosynthetic rate, growth and survival. They concluded that lowering light levels by establishing canopy species may suppress

the growth of invasive grasses with no adverse effects on native woody species. The study identified several fast-growing native species ideal for restoration, and the resultant planting palette has been applied to restoration of 12–16 hectares. Understanding the effect of light on seedling emergence and growth has also shaped how HAVO managers restore forests in the presence of a woody canopy invader. Girdling invasive fire tree (*Morella faya*) was found to be more effective in promoting native species than logging trees (Loh and Daehler, 2007, 2008). Logging increased light levels, which promoted invasion by fast-growing shade-intolerant exotic species, whereas the slow death of fire tree by girdling allowed establishment of native plants accustomed to partial shade. During the 1960s, the invasion of fire-adapted invasive grasses increased fire frequency 3-fold in seasonally dry woodland in HAVO. Given that these grasses are impossible to eradicate, fire will continue to hinder restoration efforts. When planting native species, managers now eschew previously dominant but fire-sensitive species (e.g. *Metrosideros polymorpha*) for fire-adapted native species. Studies of fire tolerance and colonization potential after fire led to plant palettes for several large-scale restoration efforts in the park (Loh *et al.*, 2007, 2009; McDaniel *et al.*, 2008).

Fisheries management is improved through physiological monitoring

Inland and marine fisheries resources are globally important as a food supply and are culturally and economically important in many places for recreation. When coupled with anthropogenic stressors, such as habitat destruction or alteration (e.g. construction of dams, land use change), pollution and climate change, a diversity of fishes have been experiencing population declines at both a local and global scale. Despite decades of regulation and oversight, many marine fishery stocks are currently being fully exploited or overexploited (FAO, 2012), while globally, freshwater fishes are among the most threatened taxa on the planet (Ricciardi and Rasmussen, 1999; Dudgeon *et al.*, 2006). This decline in abundance and richness speaks to the need for the development of novel tools and technologies to monitor the health of animals and provide effective mitigation strategies to maintain populations.

Studies related to the conservation of Pacific salmon (*Oncorhynchus* spp.) represent one of the most celebrated and relevant models of using animal physiology to achieve conservation success. Historically, Pacific salmon were abundant on the west coast of North America and provided a host of critical ecosystem services ranging from a food source for humans to delivering nutrients to terrestrial ecosystems to cultural value (Janetski *et al.*, 2009; Hocking and Reynolds, 2011). Owing to logging, dams, irrigation, commercial and sport fisheries, as well as increased human populations, Pacific salmon numbers have declined precipitously in the past century, with a number of species and stocks throughout their range currently listed as threatened or endangered (Gresh *et al.*, 2000; Ford, 2011; Quinones *et al.*, 2014). Farrell *et al.*

(2001a) used physiological response variables to demonstrate that towing non-target Coho salmon (*Oncorhynchus kisutch*) captured as by-catch in commercial nets promotes physiological recovery and increased post-release survival, even for fish that appeared moribund at the time of capture in gill nets (Farrell *et al.*, 2001a,b), leading to regulations requiring gill net boats to have recovery boxes attached to vessels to facilitate recovery of coho by-catch. Likewise, Donaldson *et al.* (2013) demonstrated that comparative physiology and radio-telemetry could be combined with human dimensions surveys to address revival strategies for angled and released sockeye salmon (*Oncorhynchus nerka*), leading to public outreach activities intended to improve handling of fish that are to be released. In addition, Young *et al.* (2006) identified biomarkers correlating with physiological performance that could be used to predict whether individual fish were likely to reach spawning grounds compared with those that did not continue migrations, providing managers with a tool to identify instances where escapement targets may not be met because of en route mortality. Together, these studies, as well as others (e.g. Cooke *et al.*, 2012), demonstrate how integrating physiological tools into biological problems can achieve conservation success for an economically and ecologically important group of fish species.

The recent development of metrics to assess the whole-animal response to capture stressors has also provided fisheries managers with a simple yet effective method for defining capture stress and improving conservation activities. A number of fish species are captured by either recreational or commercial harvesters and are subsequently released, owing to regulations mandating release (i.e. time of year, size) or a voluntary conservation-based ‘catch-and-release’ ethic (Davis, 2002; Arlinghaus *et al.*, 2007). However, during a capture event, fish can experience a range of different stressors, such as depth change, exercise, crowding and handling, all of which can lead to elevated levels of physiological stress (Farrell *et al.*, 2001b; Suski *et al.*, 2003). In extreme cases, the stress and disturbance related to capture can cause mortality, which can negate efforts to release captured individuals successfully and can translate to negative population-level changes (Davis, 2002). Davis (2010) showed that fish have a number of ecologically relevant, involuntary reflex responses that are correlated positively with the magnitude of a physiological stressor. As such, these reflex indices can be collected easily and rapidly in the field from a range of fish species, and subsequently, used to predict disturbance level and subsequent mortality using a process called Reflex Action Mortality Predictor (RAMP; Davis, 2007). For example, Raby *et al.* (2012) showed that RAMP scores, collected as part of a fishery mandating the release of non-target coho salmon (*Oncorhynchus kisutch*), were able to predict both mortality and behaviour of wild fish after release. As a result, the RAMP procedure provides a simple, inexpensive and effective protocol to collect data on fisheries mortality rates quickly and easily in the field that has been ground-truthed in relationship to physiological parameters and provides

information on how changes to fishery practices can translate to improved survival for released individuals.

Monitoring of energetics and stress refines ecotourism practices

Ecotourism refers to a sector of the tourism industry that is nature based, rooted in environmental education and sustainably managed (Blamey, 2001) and, ideally, represents an opportunity to promote the conservation of ecosystems or species of interest while achieving economic benefits (Ellenberg *et al.*, 2006). However, many of the activities associated with ecotourism can lead to disturbances in the behaviour, reproduction and persistence of terrestrial and aquatic wildlife (Newsome *et al.*, 2005). Measures of physiological traits have allowed for the relatively rapid assessment of these effects in a diversity of wildlife and, most importantly, in many instances have enabled researchers to make management recommendations that can reduce the associated impacts on sensitive populations.

A particularly strong example of the power of physiological measures for the assessment of effects and subsequent refinement of the ecotourism industry focused on southern stingrays (*Dasyatis americana*). This species is the basis of a feeding attraction at 'Stingray City Sandbar' (SCS) in the Cayman Islands that brings in more than 1 million tourists annually. Stingrays at SCS are part of a wild population, but can be subjected to up to 2500 tourists simultaneously (from up to 40 boats) participating in diving, snorkelling, touching and feedings (Semeniuk *et al.*, 2007). By comparing stingrays inhabiting tourist sites and non-visited sites, Semeniuk *et al.* (2009) showed that animals exposed to ecotourism had lower haematocrit, lower total serum protein concentrations and reduced antioxidant capacity, indicating negative physiological consequences of tourism operations. In addition, fatty acid profiles of stingrays fed the non-natural diet associated with tourism activities did not obtain a nutritional lipid composition comparable to prey eaten in the wild, with potential consequences for growth, immune function, parasite and disease prevalence, and ultimately, survival (Semeniuk *et al.*, 2009). Based on tourist surveys and the predicted health effects from the physiological studies, Semeniuk *et al.* (2010) then developed an integrated system dynamics model for the management of tourist–stingray interactions at SCS, which predicted the state of the tourism attraction over time in relationship to stingray population size, life expectancy and tourist visitation under various management scenarios. These findings allowed for management recommendations directly to Caymanian stakeholders that included decreasing the amount of artificial food to promote natural foraging, changing the composition of supplemented food, continued monitoring of fatty acid levels as a bioindicator, limiting total numbers of boats and people to eliminate crowding, and expanding tourism sites (Semeniuk *et al.*, 2007, 2009, 2010; Semeniuk and Rothley, 2008). Overall, this approach enabled regulators to choose management plans that would ensure tourist satisfaction and continued visitation despite stricter regulations that benefit

wildlife (personal communication from Dr Christina Semeniuk, University of Windsor). Taken together, these studies have inspired a call for change in policies for recreational marine ecotourism to minimize the impacts on population health for rays in other areas, such as the Mediterranean, Southeast Asia and Africa (Lloret, 2010; Corcoran *et al.*, 2013; Ward-Paige *et al.*, 2013), as well as for other marine fishes (e.g. Hammerschlag *et al.*, 2012).

Many other species targeted specifically by or indirectly exposed to the tourism industry have also been assessed using diverse physiological tools. For example, endangered yellow-eyed penguins (*Megadyptes antipodes*; Ellenberg *et al.*, 2007), juvenile hoatzins (*Opisthocomus hoazin*; Müllner *et al.*, 2004) and Western capercaillie (*Tetrao urogallus*; Thiel *et al.*, 2008) in areas with tourism exposure show higher levels of glucocorticoids (i.e. stress hormones) than individuals in undisturbed sites. In many cases, glucocorticoid levels and heart rate telemetry metrics have correlated with reproductive and/or survival parameters that justify regulation of tourism activities based on life-history stage, location and intensity (i.e. distance) for avian species (Müllner *et al.*, 2004; Ellenberg *et al.*, 2006, 2007). In particular, this type of work in yellow-eyed penguins (Ellenberg *et al.*, 2006, 2007), one of the world's rarest penguin species, has improved visitor information panels and viewing hides for tourists, and breeding areas are routinely closed to access during the breeding season (personal communication from Dr Ursula Ellenberg, La Trobe University). In addition, at a viewing site where visitors must walk along the beach to access viewing hides (Sandfly Bay, New Zealand), a volunteer warden programme has been coordinated by the New Zealand Department of Conservation to keep visitors out of breeding areas and to reduce disruption of penguin landing (personal communication from Dr Ursula Ellenberg, La Trobe University). Overall, the measurement of physiology has provided robust biomarkers of condition and disturbance level that can refine ecotourism activities to minimize impacts on wildlife.

Emerging themes and conclusions

Conservation physiology goes beyond documenting change

The success stories we have outlined indicate that conservation physiology is, in many cases, fulfilling the goal outlined in its most recent definition, which places specific emphasis on 'solving conservation problems across the broad range of taxa' (Cooke *et al.*, 2013). In addition to identifying impacts of disturbance or environmental change, physiology has allowed managers to delineate and prioritize mitigation strategies, often because physiology provides mechanistic insight into the causes of change (Carey, 2005; Wikelski and Cooke, 2006). As a result, conservation physiology has allowed for targeted strategies that can: (i) limit anthropogenic activities in space, time or intensity (e.g. yellow-eyed penguin ecotourism); (ii) focus strategies to target certain life-history stages or

aspects of ecology/habitat (e.g. control of invasive sea lamprey); (iii) control the spread of disease (e.g. rinderpest eradication in Africa); and (iv) alter human structures and activities to limit influences on wildlife (e.g. window redesign to limit bird strikes). Moving forward, we propose that conservation physiology be viewed more strongly as a set of tools for addressing, rather than merely documenting, conservation issues.

The tools available and contributing to the field are more diverse than glucocorticoids

Although measurements of stress hormones (i.e. glucocorticoids) dominate the conservation physiology literature for vertebrates (Lennox and Cooke, 2014), the successes we have identified are varied and rely on diverse physiological traits related to immunity, nutrition, toxicology, sensory physiology, oxidative status, haematology, metabolism and reproduction. Thus, rather than defaulting to the measurement of stress hormones, which are often highly context dependent and difficult to interpret (Breuner *et al.*, 2008; Bonier *et al.*, 2009; Madliger and Love, 2014), conservation physiologists should incorporate additional measures into their panels. Using physiological measures that provide meaningful information, rather than assuming that any disturbance will be reflected unambiguously in stress levels, will push conservation physiology further towards the diverse discipline it has been proposed to be (Wikelski and Cooke, 2006; Cooke *et al.*, 2013), in terms of both on-the-ground conservation and the accumulation of a literature base that can benefit evidence-based conservation.

Conservation physiology approaches can be transferable among species, locations and times

In our experience, physiological approaches to conservation are sometimes criticized for being species, site or time specific, thereby limiting the general utility of the solutions. Although in some cases management strategies may be very specialized, the outlined successes indicate that conservation physiology has not suffered from a lack of transferability in many areas. For example, toxicological research on pesticides and other endocrine-disrupting chemicals has had far-reaching conservation implications for birds of prey and aquatic wildlife worldwide. Likewise, sensory physiology work that has helped to identify window designs that prevent bird strikes has benefited hundreds of species of migratory songbirds in cities throughout North America, and vaccination campaigns, such as the targeted programme for rinderpest, have eradicated disease from multiple ungulate species across entire continents. Importantly, conservation physiology approaches are contributing to both reactive conservation, such as the problem solving associated with sensory interferences, disease epidemics, ecotourism and fisheries by-catch, and proactive conservation, such as the modelling of invasive species spread, biological control of invasive species, health and reproductive monitoring, and forecasting of how organisms will respond to

climate change or other environmental alterations. Finally, the knowledge gained through general studies in physiological ecology and evolutionary physiology continues to inform the rapid development of tools for conservation physiology, and many more opportunities are available to advance this development further (Madliger and Love, 2015).

Highly targeted solutions can allow for human use while simultaneously benefiting imperiled populations

Given that physiology can impart the ability to pinpoint the mechanism behind a conservation issue (Carey, 2005), techniques can often be highly targeted to accomplish conservation goals in the most parsimonious way possible. As a result, many solutions based on physiological knowledge have allowed human use or activity to continue to occur, while benefiting or ameliorating conflicts for wildlife. For example, recovery techniques, harvesting regulations and deterrents used in the fishery sector have initiated strategies that simultaneously allow harvest and maintenance of wild populations of commercially important fish species while minimizing impacts to non-target species. The sensory-based modifications to windows and shoreline lighting that have benefited migratory birds and endangered sea turtles, respectively, continue to allow for building facades and lighting of structures to maintain aesthetic and human use. Finally, the physiological knowledge gained from studies in the ecotourism industry has refined practices so that tourist visitation can continue while minimizing negative influences on wildlife such as yellow-eyed penguins and stingrays. Overall, the incorporation of physiology has provided concrete evidence for how and why conservation strategies are necessary, allowing for justification of strategies, maintenance of stakeholder relationships and beneficial changes for humans and wildlife.

Evidence of success can be difficult to find in primary literature, but it is gradually and continuously occurring

A repeated lesson across the above studies has been that, although policy changes can often be slow and incremental, change occurs if very clear recommendations are persistently brought to managers, mass media and/or policy-makers. As with any conservation endeavour, changes in human behaviour, management or policy can take time because of logistical, monetary and dissemination constraints. As a result, the identification of success stories where physiological work led to downstream management effects often required the piecing together of multiple, sometimes disparate, studies. In many cases, conservation results were not easily accessible through searches of the primary literature and required direct communication with researchers or practitioners, or searches of government websites and other documents. However, conservation physiology has been accumulating success stories prior to its formal description as a discipline, and we argue that it is keeping pace with other more recent subfields of conservation

biology, such as conservation behaviour. Overall, we support a recent suggestion by Cooke (2014) that the single biggest challenge for conservation physiology is to ensure that findings are relevant to practitioners (Cooke and O'Connor, 2010), but we advocate that the highlighted successes provide optimism regarding our ability to overcome this impediment.

Conclusion: conservation physiology is progressing past theoretical and proposed applications

The potential applications of a physiological approach to conservation are well established (Carey, 2005; Wikelski and Cooke, 2006; Cooke *et al.*, 2013), and a theoretical framework has recently been proposed to guide progression of the field further by defining information flows within and between science and policy-makers (Coristine *et al.*, 2014). Although many of the concrete successes in the field have occurred in animal systems, the potential for success in plants is clear and also gaining momentum. Although a recent bibliographic analysis concluded that, from a publication perspective, the overall pace of integration between conservation and physiology has been slower than the opportunities would potentially warrant (Lennox and Cooke, 2014), the concerted summary of successes provided here indicates that conservation and physiology have been well integrated in diverse, far-reaching and beneficial ways that may not be readily apparent from a standardized literature search. Moving forward, further success will be fostered by linking individual-level physiological traits with population- and species-level phenomena (Cooke and O'Connor, 2010; Cooke *et al.*, 2013). In addition, many successful strategies have come and will continue to be developed from merging multiple approaches with conservation and physiology, such as behaviour, genetics, social science and medicine. In this way, conservation physiology is becoming a body of work that is not defined by one type of approach, physiological measure, taxa or conservation issue, but by the diversity it encompasses. Most importantly, the success stories discussed here illustrate that physiological knowledge continues to have the potential to make considerable contributions to conservation, that it has been doing so for decades and that it will continue to make broad strides during a time when its diversity should be seen as an enormous benefit to global conservation goals (Tallis and Lubchenco, 2014).

Funding

This work was supported by the Society for Integrative and Comparative Biology; the University of Windsor, Ontario, Canada; Dalhousie University, Nova Scotia, Canada; and the Canadian Society of Zoologists. C.L.M. was supported by a Natural Sciences and Engineering Research Council of Canada PGS-D (427552). S.J.C. and O.P.L. are supported by the Canada Research Chairs program. E.J.C. was supported by a grant from the National Science Foundation (BCS-1134687). K.R.H. was supported by grants from the National Science

Foundation's MacroSystems Biology program (award no. 1340856) and the US Department of Agriculture (NRI 2015-67013-23138). J.R.R. was supported by grants from the National Science Foundation (EF-1241889), National Institutes of Health (R01GM109499, R01TW010286), US Department of Agriculture (NRI 2006-01370, 2009-35102-0543) and US Environmental Protection Agency (CAREER 83518801).

References

- Alonso JC, Alonso JA, Muñoz-Pulido R (1994) Mitigation of bird collisions with transmission lines through groundwire marking. *Biol Conserv* 67: 129–134.
- Arlinghaus R, Cooke SJ, Lyman J, Policansky D, Schwab A, Suski C, Sutton SG, Thorstad EB (2007) Understanding the complexity of catch-and-release in recreational fishing: an integrative synthesis of global knowledge from historical, ethical, social, and biological perspectives. *Rev Fish Sci* 15: 75–167.
- Ayres KL, Booth RK, Hempelmann JA, Koski KL, Emmons CK, Baird RW, Balcomb-Bartok K, Hanson MB, Ford MJ, Wasser SK (2012) Distinguishing the impacts of inadequate prey and vessel traffic on an endangered killer whale (*Orcinus orca*) population. *PLoS ONE* 7: e36842.
- Barlow J, Cameron GA (2003) Field experiments show that acoustic pingers reduce marine mammal bycatch in the California drift gill net fishery. *Mar Mammal Sci* 19: 265–283.
- Beaulieu M, Costantini D (2014) Biomarkers of oxidative status: missing tools in conservation physiology. *Conserv Physiol* 2: doi:10.1093/conphys/cou014.
- Beaulieu M, Thierry AM, González-Acuña D, Polito MJ (2013) Integrating oxidative ecology into conservation physiology. *Conserv Physiol* 1: doi:10.1093/conphys/cot004.
- Blair TA, Cree A, Skeaff CM, Grimmond NM (2000) Physiological effects of a fish oil supplement on captive juvenile tuatara (*Sphenodon punctatus*). *Physiol Biochem Zool* 73: 177–191.
- Blamey RK (2001) Principles of ecotourism. In Weaver DB, eds, *The Encyclopedia of Ecotourism*. CABI, Wallingford, pp 5–22.
- Bonier F, Martin PR, Moore IT, Wingfield JC (2009) Do baseline glucocorticoids predict fitness? *Trends Ecol Evol* 24: 634–642.
- Breuner CW, Patterson SH, Hahn TP (2008) In search of relationships between the acute adrenocortical response and fitness. *Gen Comp Endocrinol* 157: 288–295.
- Brockerhoff EG, Kimberley M, Liebhold AM, Haack RA, Cavey JF (2014) Predicting how altering propagule pressure changes establishment rates of biological invaders across species pools. *Ecology* 95: 594–601.
- Brothers NP, Cooper J, Lokkeborg S (1999) The incidental catch of seabirds in longline fisheries: worldwide review and technical guidelines for mitigation. *FAO Fish Circ* 937: 1–100.
- Brown SB, Fitzsimons JD, Honeyfield DC, Tillitt DE (2005) Implications of thiamine deficiency in Great Lakes Salmonines. *J Aquat Anim Health* 17: 113–124.

- Bryant DM (2006) Energetics of free-living kakapo (*Strigops habroptilus*). *Notornis* 53: 126–137.
- Cajaraville MP, Bebianno MJ, Blasco J, Porte C, Sarasquete C, Viarengo A (2000) The use of biomarkers to assess the impact of pollution in coastal environments of the Iberian Peninsula: a practical approach. *Sci Total Environ* 247: 295–311.
- Carey C (2005) How physiological methods and concepts can be useful in conservation biology. *Integr Comp Biol* 45: 4–11.
- Carretta J, Barlow J, Enriquez L (2008) Acoustic pingers eliminate beaked whale bycatch in a gill net fishery. *Mar Mammal Sci* 24: 956–961.
- Cartland LK, Cree A, Sutherland WHF, Grimmond NM, Skeaff CM (1994) Plasma concentrations of total cholesterol and triacylglycerol in wild and captive juvenile tuatara (*Sphenodon punctatus*). *New Zeal J Zool* 21: 399–406.
- Cartland-Shaw LK, Cree A, Skeaff CM, Grimmond NM (1998) Differences in dietary and plasma fatty acids between wild and captive populations of a rare reptile, the tuatara (*Sphenodon punctatus*). *J Comp Physiol B* 168: 569–580.
- Chapman BR, Bolen EG (2015) A selection of special environments. In *Ecology of North America*, Ed 2. John Wiley & Sons Ltd, Chichester, UK.
- Chosid DM, Pol M, Szymanski M, Mirarchi F, Mirarchi A (2012) Development and observations of a spiny dogfish *Squalus acanthias* reduction device in a raised footrope silver hake *Merluccius bilinearis* trawl. *Fish Res* 114: 66–75.
- Chown SL (2012) Trait-based approaches to conservation physiology: forecasting environmental change risks from the bottom up. *Philos Trans R Soc Lond B Biol Sci* 367: 1615–1627.
- City of Chicago (2007) Bird-Safe Building: Design Guide for New Construction and Renovation, 2 pp.
- City of Toronto (2007) Bird-Friendly Development Guidelines, 42 pp.
- City of Vancouver (2015) Vancouver Bird Strategy, 33 pp.
- Clavero M, García-Berthou E (2005) Invasive species are a leading cause of animal extinctions. *Trends Ecol Evol* 20: 110–110.
- Connon RE, D'Abronzio LS, Hostetter NJ, Javidmehr A, Roby DD, Evans AF, Loge FJ, Werner I (2012) Transcription profiling in environmental diagnostics: health assessments in Columbia River basin steelhead (*Oncorhynchus mykiss*). *Environ Sci Technol* 46: 6081–6087.
- Cooke SJ (2014) Conservation physiology today and tomorrow. *Conserv Physiol* 2: doi:10.1093/conphys/cot033.
- Cooke SJ, O'Connor CM (2010) Making conservation physiology relevant to policy makers and conservation practitioners. *Conserv Lett* 3: 159–166.
- Cooke SJ, Hinch SG, Donaldson MR, Clark TD, Eliason EJ, Crossin GT, Raby GD, Jeffries KM, Lapointe M, Miller K *et al.* (2012) Conservation physiology in practice: how physiological knowledge has improved our ability to sustainably manage Pacific salmon during up-river migration. *Philos Trans R Soc Lond B Biol Sci* 367: 1757–1769.
- Cooke SJ, Sack L, Franklin CE, Farrell AP, Beardall J, Wikelski M, Chown SL (2013) What is conservation physiology? Perspectives on an increasingly integrated and essential science. *Conserv Physiol* 1: doi:10.1093/conphys/cot001.
- Cooke SJ, Blumstein DT, Buchholz R, Caro T, Fernández-Juricic E, Franklin CE, Metcalfe J, O'Connor CM, Cassady St Clair C, Sutherland WJ *et al.* (2014) Physiology, behavior, and conservation. *Physiol Biochem Zool* 87: 1–14.
- Corcoran MJ, Wetherbee BM, Shivji MS, Potenski MD, Chapman DD, Harvey GM (2013) Supplemental feeding for ecotourism reverses diel activity and alters movement patterns and spatial distribution of the Southern stingray, *Dasyatis americana*. *PLoS ONE* 8, e59235.
- Coristine LE, Robillard CM, Kerr JT, O'Connor CM, Lapointe D, Cooke SJ (2014) A conceptual framework for the emerging discipline of conservation physiology. *Conserv Physiol* 2: doi:10.1093/conphys/cou033.
- Cox TM, Lewison RL, Žydelis R, Crowder LB, Safina C, Read AJ (2007) Comparing effectiveness of experimental and implemented bycatch reduction measures: the ideal and the real. *Conserv Biol* 21: 1155–1164.
- Cruz F, Brennan AC, Gonzalez-Voyer A, Muñoz-Fuentes V, Eaaswarkhanth M, Roques S, Picó FX (2012) Genetics and genomics in wildlife studies: implications for ecology, evolution, and conservation biology. *Bioessays* 34: 245–246.
- Dantzer B, Fletcher QE, Boonstra R, Sheriff MJ (2014) Measures of physiological stress: a transparent or opaque window into the status, management and conservation of species? *Conserv Physiol* 2: doi:10.1093/conphys/cou023.
- Davies RWD, Cripps SJ, Nickson A, Porter G (2009) Defining and estimating global marine fisheries bycatch. *Mar Policy* 33: 661–672.
- Davis MW (2002) Key principles for understanding fish bycatch discard mortality. *Can J Fish Aquat Sci* 59: 1834–1843.
- Davis MW (2007) Simulated fishing experiments for predicting delayed mortality rates using reflex impairment in restrained fish. *J Conseil* 64: 1535–1542.
- Davis MW (2010) Fish stress and mortality can be predicted using reflex impairment. *Fish Fish* 11: 1–11.
- DeLoach CJ, Lewis PA, Herr JC, Carruthers RI, Tracy JL, Johnson J (2003) Host specificity of the leaf beetle, *Diorhabda elongata desrticola* (Coleoptera: Chrysomelidae) from Asia, a biocontrol agent for saltcedars (*Tamarix*: Tamaricaceae) in the Western United States. *Biol Control* 27: 117–147.
- Dettmers JM, Goddard CI, Smith KD (2012) Management of alewife using Pacific salmon in the Great Lakes: whether to manage for economics or the ecosystem? *Fisheries* 37: 495–501.
- Dickerson RL, Hooper MJ, Gard NW, Cobb GP, Kendall RJ (1994) Toxicological foundations of ecological risk assessment: biomarker development and interpretation based on laboratory and wildlife species. *Environ Health Perspect* 102(Suppl 12): 65–69.
- Dierenfeld ES (1997) Captive wild animal nutrition: a historical perspective. *Proc Nutr Soc* 56: 989–999.

- Dobson A, Holdo RM, Holt RD (2011) Rinderpest. In Simberloff D, Rejmánek M, eds, *Encyclopedia of Biological Invasions*. University of California Press, Berkeley, CA, USA, pp 597–604.
- Donaldson MR, Raby GD, Nguyen VN, Hinch SG, Patterson DA, Farrell AP, Rudd MA, Thompson LA, O'Connor CM, Colotelo AH *et al.* (2013) Evaluation of a simple technique for recovering fish from capture stress: integrating physiology, biotelemetry, and social science to solve a conservation problem. *Can J Fish Aquat Sci* 70: 90–100.
- Dudgeon D, Arthington AH, Gessner MO, Kawabata ZI, Knowler DJ, Lévêque C, Naiman RJ, Prieur-Richard A, Soto D, Stiassny MLJ *et al.* (2006) Freshwater biodiversity: importance, threats, status and conservation challenges. *Biol Rev* 81: 163–182.
- Ellenberg U, Mattern T, Seddon PJ, Jorquera GL (2006) Physiological and reproductive consequences of human disturbance in Humboldt penguins: the need for species-specific visitor management. *Biol Conserv* 133: 95–106.
- Ellenberg U, Setiawan AN, Cree A, Houston DM, Seddon PJ (2007) Elevated hormonal stress response and reduced reproductive output in Yellow-eyed penguins exposed to unregulated tourism. *Gen Comp Endocrinol* 152: 54–63.
- FAO (2012) *World Review of Fisheries and Aquaculture*. FAO, Rome. <http://www.fao.org/docrep/016/i2727e/i2727e01.pdf>.
- Faroon O, Harris MO, Lladós F, Swarts S, Sage G, Citra M, Gefell D (2002) *Toxicological Profile for DDT, DDE, and DDD*. US Department of Health and Human Services, Atlanta, GA, USA.
- Farrell AP, Gallagher PE, Fraser J, Pike D, Bowering P, Hadwin AKM, Parkhouse W, Routledge R (2001a) Successful recovery of the physiological status of coho salmon on board a commercial gillnet vessel by means of a newly designed revival box. *Can J Fish Aquat Sci* 58: 1932–1946.
- Farrell AP, Gallagher PE, Routledge R (2001b) Rapid recovery of exhausted adult coho salmon after commercial capture by troll fishing. *Can J Fish Aquat Sci* 58: 2319–2324.
- Ford MJ (2011) *Status Review Update for Pacific Salmon and Steelhead Listed under the Endangered Species Act: Pacific Northwest*. US Department of Commerce, National Oceanic and Atmospheric Administration, National Marine Fisheries Service, Northwest Fisheries Science Center. pp 281.
- Funk JL (2013) The physiology of invasive plants in low-resource environments. *Conserv Physiol* 1: doi:10.1093/conphys/cot026.
- Funk JL, McDaniel S (2010) Altering light availability to restore invaded forest: the predictive role of plant traits. *Restor Ecol* 18: 865–872.
- Funk JL, Cleland EE, Suding KN, Zavaleta ES (2008) Restoration through re-assembly: plant traits and invasion resistance. *Trends Ecol Evol* 23: 695–703.
- Garnier R, Ramos R, Staszewski V, Militão T, Lobato E, González-Solís J, Boulinier T (2012) Maternal antibody persistence: a neglected life history trait with implications from albatross conservation to comparative immunology. *Proc Biol Sci* 279: 2033–2041.
- Gaston KJ, Davies TW, Bennie J, Hopkins J (2012) Reducing the ecological consequences of night-time light pollution: options and developments. *J Appl Ecol* 49: 1256–1266.
- Great Lakes Fishery Commission (2015) Sea lamprey control in the Great Lakes. <http://www.glfc.org/sealamp/how.php>.
- Gresh T, Lichatowich J, Schoonmaker P (2000) An estimation of historic and current levels of salmon production in the Northeast Pacific ecosystem: evidence of a nutrient deficit in the freshwater systems of the Pacific Northwest. *Fisheries* 25: 15–21.
- Haack RA, Britton KO, Brouckhoff EG, Cavey JF, Garrett LJ, Kimberley M, Lowenstein F, Nuding A, Olson LJ, Turner J *et al.* (2014) Effectiveness of the International Phytosanitary Standard ISPM No. 15 on reducing wood borer infestation rates in wood packaging material entering the United States. *PLoS ONE* 9: e96611.
- Hammerschlag N, Gallagher AJ, Wester J, Luo JG, Ault JS (2012) Don't bite the hand that feeds: assessing ecological impacts of provisioning ecotourism on an apex marine predator. *Funct Ecol* 26: 567–576.
- Haydon DT, Randall DA, Matthews L, Knobel DL, Tallents LA, Gravenor MB, Williams SD, Pollinger JP, Cleaveland S, Woolhouse MEJ *et al.* (2006) Low-coverage vaccination strategies for the conservation of endangered species. *Nature* 443: 692–695.
- Hayes TB, Case P, Chui S, Chung D, Haeffele C, Haston K, Lee M, Mai VP, Marjuoa Y, Parker J *et al.* (2006) Pesticide mixtures, endocrine disruption, and amphibian declines: Are we underestimating the impact? *Environ Health Perspect* 114: 40–50.
- Hayes TB, Anderson LL, Beasley VR, de Solla SR, Iguchi T, Ingraham H, Kestemont P, Kniewald J, Kniewald Z, Langlois VS *et al.* (2011) Demasculinization and feminization of male gonads by atrazine: consistent effects across vertebrate classes. *J Steroid Biochem* 127: 64–73.
- Health Canada (2011) Proposed Re-evaluation of Decision PRVD2011-14 Chlorothalonil. Health Canada Pest Management Regulatory Agency. http://publications.gc.ca/collections/collection_2012/sc-hc/H113-27-2011-14-eng.pdf.
- Hecker M, Hollert H (2011) Endocrine disruptor screening: regulatory perspectives and needs. *Environ Sci Europe* 23: 1–14.
- Hindmarsh JT, Lyon AW (1996) Strategies to promote rational clinical chemistry test utilization. *Clin Biochem* 29: 291–299.
- Hocking MD, Reynolds JD (2011) Impacts of salmon on riparian plant diversity. *Science* 331: 1609–1612.
- Honan P (2008) Notes on the biology, captive management and conservation status of the Lord Howe Island Stick Insect (*Dryococelus australis*) (Phasmatodea). *J Insect Conserv* 11: 399–413.
- Horváth G, Kriska G, Malik P, Robertson B (2009) Polarized light pollution: a new kind of ecological photopollution. *Front Ecol Environ* 7: 317–325.
- Hubert TD (2003) Environmental fate and effects of the lampricide TFM: a review. *J Great Lakes Res* 29: 456–474.

- Hultine KR, Bean DW, Dudley TL, Gehring CA (2015) Species introductions and their cascading impacts on biotic interactions in desert riparian ecosystems. *Integr Comp Biol* 55: 587–601.
- Hunt KE, Moore MJ, Rolland RM, Kellar NM, Hall AJ, Kershaw J, Raverty SA, Davis CE, Yeates LC, Fauquier DA *et al.* (2013) Overcoming the challenges of studying conservation physiology in large whales: a review of available methods. *Conserv Physiol* 1: doi:10.1093/conphys/cot006.
- IPPC (2009) International Standards for Phytosanitary Measures Revision of ISPM No. 15 Regulations of Wood Packaging Material in International Trade. International Plant Protection Convention (IPPC) Secretariat, Food and Agriculture Organization (FAO), United Nations. http://www.tis-gdv.de/tis_e/verpack/holz/export/ispm15.pdf.
- Janetski DJ, Chaloner DT, Tiegs SD, Lamberti GA (2009) Pacific salmon effects on stream ecosystems: a quantitative synthesis. *Oecologia* 159: 583–595.
- Jobling S, Sheahan D, Osborne JA, Matthiessen P, Sumpter JP (1996) Inhibition of testicular growth in rainbow trout (*Oncorhynchus mykiss*) exposed to estrogenic alkylphenolic chemicals. *Environ Toxicol Chem* 15: 194–202.
- Jobling S, Nolan M, Tyler CR, Brighty G, Sumpter JP (1998) Widespread sexual disruption in wild fish. *Environ Sci Technol* 32: 2498–2506.
- Joly K, Wasser SK, Booth R (2015) Non-invasive assessment of the inter-relationships of diet, pregnancy rate, group composition, and physiological and nutritional stress of barren-ground caribou in late winter. *PLoS ONE* 10: e0127586.
- Jordan LK, Mandelman JW, McComb DM, Fordham SV, Carlson JK, Werner TB (2013) Linking sensory biology and fisheries bycatch reduction in elasmobranch fishes: a review with new directions for research. *Conserv Physiol* 1: doi:10.1093/conphys/cot002.
- Kidd KA, Blanchfield PJ, Mills KH, Palace VP, Evans RE, Lazorchak JM, Flick RW (2007) Collapse of a fish population after exposure to a synthetic estrogen. *Proc Natl Acad Sci USA* 104: 8897–8901.
- Klem D (2009) Avian mortality at windows: the second largest human source of bird mortality on earth. In Rich TD, Arizendi C, Demarest D, Thompson C, eds. *Tundra to Tropics: Proceedings of the Fourth International Partners in Flight Conference*. Partners in Flight, McAllen, Texas, USA, pp 244–251.
- Klem D, Saenger PG (2013) Evaluating the effectiveness of select visual signals to prevent bird-window collisions. *Wilson J Ornithol* 125: 406–411.
- Klem D, Farmer CJ, Delacretaz N, Gelb Y, Saenger PG (2009) Architectural and landscape risk factors associated with bird-glass collisions in an urban environment. *Wilson J Ornithol* 121: 126–134.
- Krueger CC, Jones ML, Taylor WW (1995) Restoration of lake trout in the Great Lakes: challenges and strategies for future management. *J Great Lakes Res* 21: 547–558.
- Kuvlesky WP, Brennan LA, Morrison ML, Boydston KK, Ballard BM, Bryant FC (2007) Wind energy development and wildlife conservation: challenges and opportunities. *J Wildlife Manage* 71: 2487–2498.
- Lennox R, Cooke SJ (2014) State of the interface between conservation and physiology: a bibliometric analysis. *Conserv Physiol* 2: doi:10.1093/conphys/cou003.
- Lennox RJ, Choi K, Harrison PM, Paterson JE, Peat T, Ward T, Cooke SJ (2015) Improving science-based invasive species management with physiological knowledge, concepts, and tools. *Biol Invasions* 17: 2213–2227.
- Lewin N, Treidel LA, Holekamp KE, Place NJ, Haussmann MF (2015) Socioecological variables predict telomere length in wild spotted hyenas. *Biol Lett* 11: 20140991.
- Lien J, Guigne J, Chopin F (1989) *Development of Acoustic Protection for Fixed Fishing Gear to Minimise Incidental Catches of Marine Mammals*. Fisheries Innovation and Industrial Support Program, St John's, Newfoundland, pp 24.
- Lloret J (2010) Environmental impacts of recreational activities on the Mediterranean coastal environment: the urgent need to implement marine sustainable practices and ecotourism. In Krause A, Weir F, eds, *Ecotourism: Management, Development and Impact*. Nova Science Publishing, Inc., Hauppauge, NY, pp 135–157.
- Loh RK, Daehler CC (2007) Influence of invasive tree kill rates on native and invasive plant establishment in a Hawaiian forest. *Restor Ecol* 15: 199–211.
- Loh RK, Daehler CC (2008) Influence of woody invader control methods and seed availability on native and invasive species establishment in a Hawaiian forest. *Biol Invasions* 10: 805–819.
- Loh R, McDaniel S, Benitez D, Schultz M, Palumbo D, Ainsworth A, Smith K, Tunison T, Vaidya M (2007) Rehabilitation of seasonally dry 'ōhi'a woodlands and mesic koa forest following the broomsedge fire, Hawaii Volcanoes National Park. Technical report no. 147, Honolulu, HI, pp 21.
- Loh R, Ainsworth A, Tunison T, D'Antonio C (2009) Testing native species response to fire at Hawaii Volcanoes National Park. Technical report no. 167, Honolulu, HI, pp 30.
- Lohmann KJ, Witherington BE, Lohmann CM, Salmon M (1997) Orientation, navigation, and natal beach homing in sea turtles. In Lutz PL, Musick JA, eds, *The Biology of Sea Turtles, Volume I*. CRC Press, Boca Raton, FL, pp 107–136.
- Loss SR, Will T, Loss SS, Marra PP (2014) Bird–building collisions in the United States: estimates of annual mortality and species vulnerability. *Condor* 116: 8–23.
- McDaniel S, Loh R, Dale S, Smith K, Vaidya M (2008) Rehabilitation of 'ōhi'a-swordfern (*metrosideros polymorpha-nephrolepis multiflora*) woodlands following the kupukupu fire, Hawaii Volcanoes National Park. Technical report no. 160, Honolulu, HI, pp 29.
- McDonald P, Edwards RA, Greenhalgh JFD, Morgan CA (2002) *Animal Nutrition*, Ed 6. Prentice-Hall, London.
- McDowell LR (1989) *Vitamins in Animal Nutrition*. Academic Press, New York.
- McMahon TA, Halstead NT, Johnson S, Raffel TR, Romansic JM, Crumrine PW, Boughton RK, Martin LB, Rohr JR (2011) The fungicide chlorotha-

- Ionil is nonlinearly associated with corticosterone levels, immunity, and mortality in amphibians. *Environ Health Perspect* 119: 1098–1103.
- McMahon TA, Halstead NT, Johnson S, Raffel TR, Romansic JM, Crumrine PW, Rohr JR (2012) Fungicide-induced declines of freshwater biodiversity modify ecosystem functions and services. *Ecol Lett* 15: 714–722.
- McMahon TA, Sears BF, Venesky MD, Bessler SM, Brown JM, Deutsch K, Halstead NT, Lentz G, Tenouri N, Young S *et al.* (2014) Amphibians acquire resistance to live and dead fungus overcoming fungal immunosuppression. *Nature* 511: 224–227.
- Madliger CL (2012) Toward improved conservation management: a consideration of sensory ecology. *Biodivers Conserv* 21: 3277–3286.
- Madliger CL, Love OP (2014) The need for a predictive, context-dependent approach to the application of stress hormones in conservation. *Conserv Biol* 28: 283–287.
- Madliger CL, Love OP (2015) The power of physiology in changing landscapes: considerations for the continued integration of conservation and physiology. *Integr Comp Biol* 55: 545–553.
- Mariner JC, House JA, Mebus CA, Sollod AE, Chibeu D, Jones BA, Roeder PL, Admassu B, Van't Klooster GGM (2012) Rinderpest eradication: appropriate technology and social innovations. *Science* 337: 1309–1312.
- Martin GR (2011) Understanding bird collisions with man-made objects: a sensory ecology approach. *Ibis* 153: 239–254.
- Martin GR, Crawford R (2015) Reducing bycatch in gillnets: a sensory ecology perspective. *Global Ecol Conserv* 3: 28–50.
- Martin LB, Hopkins WA, Mydlarz LD, Rohr JR (2010) The effects of anthropogenic global changes on immune functions and disease resistance. *Ann NY Acad Sci* 1195: 229–148.
- Menzie CM, Hunn JB (1976) Chemical control of the sea lamprey: the addition of a chemical to the environment. *Environ Qual Saf* 5: 1–14.
- Miller KM, Li S, Kaukinen KH, Ginther N, Hammill E, Curtis JMR, Patterson DA, Sierocinski T, Donnison L, Pavlidis P *et al.* (2011) Genomic signatures predict migration and spawning failure in wild Canadian salmon. *Science* 331: 214–217.
- Mills EL, Leach JH, Carlton JT, Secor CL (1994) Exotic species and the integrity of the great lakes – lessons from the past. *BioScience* 44: 666–676.
- Müllner A, Linsenmair KE, Wikelski M (2004) Exposure to ecotourism reduces survival and affects stress response in hoatzin chicks (*Opisthocomus hoazin*). *Biol Conserv* 118: 549–558.
- Newsome D, Dowling RK, Moore SA (2005) *Wildlife Tourism*. Channel View Publications, Clevedon.
- New York City Audubon Society, Inc. (2007) Bird-Safe Building Guidelines, 59 pp.
- Noatch MR, Suski CD (2012) Non-physical barriers to deter fish movements. *Environ Rev* 20: 71–82.
- Orr BK, Leverich GT, Diggory ZE, Dudley TL, Hatten JR, Hultine KR, Johnson MP, Orr DA (2014) Riparian restoration framework for the upper Gila River in Arizona. Prepared for the Gila Watershed Partnership of Arizona.
- Palka DL, Rossman MC, Vanatten A, Orphanides CD (2008) Effect of ping-ers on harbour porpoise (*Phocoena phocoena*) bycatch in the US Northeast gillnet fishery. *J Cetacean Res Manage* 10: 217–226.
- Philippart JC (1995) Is captive breeding an effective solution for the preservation of endemic species? *Biol Conserv* 72: 281–295.
- Pierre JP, Norden WS (2006) Reducing seabird bycatch in longline fisheries using a natural olfactory deterrent. *Biol Conserv* 130: 406–415.
- Pimentel D, Lach L, Zuniga R, Morrison D (2000) Environmental and economic costs of nonindigenous species in the United States. *BioScience* 50: 53–65.
- Quinones RM, Grantham TE, Harvey BN, Kiernan JD, Klasson M, Wintzer AP, Moyle PB (2014) Dam removal and anadromous salmonid (*Oncorhynchus* spp.) conservation in California. *Rev Fish Biol Fisher* 25: 195–215.
- Raby GD, Donaldson MR, Hinch SG, Patterson DA, Lotto AG, Robichaud D, English KK, Willmore WG, Farrell AP, Davis MW *et al.* (2012) Validation of reflex indicators for measuring vitality and predicting the delayed mortality of wild coho salmon bycatch released from fishing gears. *J Appl Ecol* 49: 90–98.
- Raffel TR, Halstead NT, McMahon T, Romansic JM, Venesky MD, Rohr JR (2013) Disease and thermal acclimation in a more variable and unpredictable climate. *Nature Clim Change* 3: 146–151.
- Ramos R, Garnier R, Gonzalez-Solis J, Boulonier T (2014) Long antibody persistence and transgenerational transfer of immunity in a long-lived vertebrate. *Am Nat* 184: 764–776.
- Randall DA, Marino J, Haydon DT, Sillero-Zubiri C, Knobel DL, Tallents LA, Macdonald DW, Laurenson MK (2006) An integrated disease management strategy for the control of rabies in Ethiopian wolves. *Biol Conserv* 131: 151–162.
- Ricciardi A, Rasmussen JB (1999) Extinction rates of North American freshwater fauna. *Conserv Biol* 13: 1220–1222.
- Robertson BA, Rehage JS, Sih A (2013) Ecological novelty and the emergence of evolutionary traps. *Trends Ecol Evol* 28: 552–560.
- Rohr JR, McCoy KA (2010) A qualitative meta-analysis reveals consistent effects of atrazine on freshwater fish and amphibians. *Environ Health Perspect* 118: 20–32.
- Rohr JR, Raffel TR (2010) Linking global climate and temperature variability to widespread amphibian declines putatively caused by disease. *Proc Natl Acad Sci USA* 107: 8269–8274.
- Rohr JR, Sager T, Sesterhenn TM, Palmer BD (2006) Exposure, postexposure, and density-mediated effects of atrazine on amphibians: breaking down net effects into their parts. *Environ Health Perspect* 114: 46–50.
- Rohr JR, Raffel TR, Romansic JM, McCallum H, Hudson PJ (2008a) Evaluating the links between climate, disease spread, and amphibian declines. *Proc Natl Acad Sci USA* 105: 17436–17441.

- Rohr JR, Raffel TR, Sessions SK, Hudson PJ (2008b) Understanding the net effects of pesticides on amphibian trematode infections. *Ecol Appl* 18: 1743–1753.
- Rohr JR, Schotthoefer AM, Raffel TR, Carrick HJ, Halstead N, Hoverman JT, Johnson CM, Johnson LB, Lieske C, Piwoni MD *et al.* (2008c) Agrochemicals increase trematode infections in a declining amphibian species. *Nature* 455: 1235–1239.
- Rohr JR, Raffel TR, Halstead NT, McMahon TA, Johnson SA, Boughton RK, Martin LB (2013) Early-life exposure to a herbicide has enduring effects on pathogen-induced mortality. *Proc Biol Sci* 280, 20131502.
- Salmon M (2006) Protecting sea turtles from artificial night lighting at Florida's oceanic beaches. In Rich C, Longcore T, eds, *Ecological Consequences of Artificial Night Lighting*. Island Press, Washington, DC, pp 141–168.
- San Francisco Planning Commission (2011) Standards for Bird-Safe Buildings. 42 pp.
- Sancha E, van Heezik Y, Maloney R, Alley M, Seddon P (2004) Iodine deficiency affects hatchability of endangered captive kaki (black stilt, *Himantopus novaeseelandiae*). *Zoo Biol* 23: 1–13.
- Schlaepfer MA, Runge MC, Sherman PW (2002) Ecological and evolutionary traps. *Trends Ecol Evol* 17: 474–480.
- Seebacher F, Franklin CE (2012) Determining environmental causes of biological effects: the need for a mechanistic physiological dimension in conservation biology. *Philos Trans R Soc Lond B Biol Sci* 367: 1607–1614.
- Semiñuk CA, Rothley KD (2008) Costs of group-living for a normally solitary forager: effects of provisioning tourism on southern stingrays *Dasyatis americana*. *Mar Ecol-Prog Ser* 357: 271–282.
- Semiñuk CA, Speers-Roesch B, Rothley KD (2007) Using fatty-acid profile analysis as an ecologic indicator in the management of tourist impacts on marine wildlife: a case of stingray-feeding in the Caribbean. *Environ Manage* 40: 665–677.
- Semiñuk CA, Bourgeon S, Smith SL, Rothley KD (2009) Hematological differences between stingrays at tourist and non-visited sites suggest physiological costs of wildlife tourism. *Biol Conserv* 142: 1818–1829.
- Semiñuk CAD, Haider W, Cooper A, Rothley KD (2010) A linked model of animal ecology and human behaviour for the management of wildlife tourism. *Ecol Model* 221: 2699–2713.
- Shafroth PB, Cleverly JR, Dudley TL, Taylor JP, van Riper III C, Weeks EP, Stuart JN (2005) Control of *Tamarix* spp. In the western US: implications for water salvage, wildlife use, and riparian restoration. *Environ Manage* 35: 231–246.
- Snyder NFR, Derrickson SR, Beissinger SR, Wiley JW, Smith TB, Toone WD, Miller B (1996) Limitations of captive breeding in endangered species recovery. *Conserv Biol* 10: 338–348.
- Southwood A, Fritsches K, Brill R, Swimmer Y (2008) Sound, chemical, and light detection in sea turtles and pelagic fishes: sensory-based approaches to bycatch reduction in longline fisheries. *Endanger Species Res* 5: 225–238.
- Stevenson RD, Tuberty SR, Wingfield JC (2005) Ecophysiology and conservation: the contribution of endocrinology and immunology—introduction to the symposium. *Integr Comp Biol* 45: 1–3.
- Stoot LJ, Cairns NA, Cull F, Taylor JJ, Jeffrey JD, Morin F, Mandelman JW, Clark TD, Cooke SJ (2014) Use of portable blood physiology point-of-care devices for basic and applied research on vertebrates: a review. *Conserv Physiol* 2: doi:10.1093/conphys/cou011.
- Stuart SN, Chanson JS, Cox NA, Young BE, Rodrigues ASL, Fischman DL, Waller RW (2004) Status and trends of amphibian declines and extinctions worldwide. *Science* 306: 1783–1786.
- Suski CD, Killen SS, Morrissey M, Lund SG, Tufts BL (2003) Physiological changes in largemouth bass caused by live-release angling tournaments in southeastern Ontario. *N Am J Fish Manage* 23: 760–769.
- Sutherland WJ, Pullin AS, Dolman PM, Knight TM (2004) The need for evidence-based conservation. *Trends Ecol Evol* 19: 305–308.
- Tallis H, Lubchenco J (2014) Working together: a call for inclusive conservation. *Nature* 515: 27–28.
- Thiel D, Jenni-Eiermann S, Braunisch V, Palme R, Jenni L (2008) Ski tourism affects habitat use and evokes a physiological stress response in capercaillie *Tetrao urogallus*: a new methodological approach. *J Appl Ecol* 45: 845–853.
- Thrall MA, Weiser G, Allison R, Campbell TW (2012) *Veterinary hematology and clinical chemistry*. John Wiley & Sons, Inc., Ames, Iowa, USA.
- Tracy CR, Nussear KE, Esque TC, Dean-Bradley K, Tracy CR, DeFalco LA, Castle KT, Zimmerman LC, Espinoza RE, Barber AM (2006) The importance of physiological ecology in conservation biology. *Integr Comp Biol* 46: 1191–1205.
- Underwood EJ (1977) *Trace Elements in Human and Animal Nutrition*. Academic Press, New York.
- US Fish and Wildlife Service (2011) *Revised Recovery Plan for the Mojave Population of the Desert Tortoise (Gopherus agassizii)*. US Fish and Wildlife Service, Pacific Southwest Region, Sacramento, CA, pp 222.
- US Geological Survey (2011) Protecting Black-Footed Ferrets and Prairie Dogs Against Sylvatic Plague. pp 2.
- US Green Building Council (2015) Leadership in Energy and Environmental Design Version 4 Bird collision deterrence. <http://www.usgbc.org/node/4561982?return=/credits>.
- Venesky MD, Raffel TR, McMahon TA, Rohr JR (2014) Confronting inconsistencies in the amphibian-chytridiomycosis system: implications for disease management. *Biol Rev Camb Philos Soc* 89: 477–483.
- Vilà M, Espinar JL, Hejda M, Hulme PE, Jarošík V, Maron JL, Pergl J, Schaffner U, Sun Y, Pyšek P (2011) Ecological impacts of invasive alien plants: a meta-analysis of their effects on species, communities and ecosystems. *Ecol Lett* 14: 702–708.
- Vitousek PM, D'Antonio CM, Loope LL, Rejmanek M, Westbrooks R (1997) Introduced species: a significant component of human-caused global change. *New Zeal J Ecol* 21: 1–16.

- Vos JG, Dybing E, Greim HA, Ladefoged O, Lambre C, Tarazona JV, Brandt I, Vethaak AD (2000) Health effects of endocrine-disrupting chemicals on wildlife, with special reference to the European situation. *Crit Rev Toxicol* 30: 71–133.
- Vynne C, Booth RK, Wasser SK (2014) Physiological implications of landscape use by free-ranging maned wolves (*Chrysocyon brachyurus*) in Brazil. *J Mammal* 95: 696–706.
- Wang JH, Fisler S, Swimmer Y (2010) Developing visual deterrents to reduce sea turtle bycatch in gill net fisheries. *Mar Ecol Prog Ser* 408: 241–250.
- Ward-Paige CA, Davis B, Worm B (2013) Global population trends and human use patterns of *Manta* and *Mobula* rays. *PLoS ONE* 8: e74835.
- Wasser SK, Cristobal-Azkarate JA, Booth RN, Hayward L, Hunt K, Ayres K, Vynne C, Gobush K, Canales-Espinosa D, Rodriguez-Luna E (2010) Non-invasive measurement of thyroid hormone in feces of a diverse array of avian and mammalian species. *Gen Comp Endocrinol* 168: 1–7.
- Wasser SK, Keim JL, Taper ML, Lele SR (2011) The influences of wolf predation, habitat loss, and human activity on caribou and moose in the Alberta oil sands. *Front Ecol Environ* 9: 546–551.
- Weimerskirch H (2004) Diseases threaten Southern Ocean albatrosses. *Polar Biol* 27: 374–379.
- Wikelski M, Cooke SJ (2006) Conservation physiology. *Trends Ecol Evol* 21: 38–46.
- Wilcove DS, Rothstein D, Dubow J, Phillips A, Losos E (1998) Quantifying threats to imperiled species in the United States. *BioScience* 48: 607–615.
- Williams WI, Friedman JM, Gaskin JF, Norton AP (2014) Hybridization of an invasive shrub affects tolerance and resistance to defoliation by a biological control agent. *Evol Appl* 7: 381–393.
- Young JL, Hinch SG, Cooke SJ, Crossin GT, Patterson DA, Farrell AP, Van Der Kraak G, Lotto AG, Lister A, Healey MC *et al.* (2006) Physiological and energetic correlates of en route mortality for abnormally early migrating adult sockeye salmon (*Oncorhynchus nerka*) in the Thompson River, British Columbia. *Can J Fish Aquat Sci* 63: 1067–1077.
- Young RC, Kitaysky AS, Barger CP, Dorresteijn I, Ito M, Watanuki Y (2015) Telomere length is a strong predictor of foraging behavior in a long-lived seabird. *Ecosphere* 6: doi:10.1890/ES14-00345.1.