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Perspective

An assessment of the US endangered species act recovery plans: using physiology to support conservation

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Applying physiology to help solve conservation problems has become increasingly prominent. It is unclear, however, if the increased integration into the scientific community has translated into the application of physiological tools in conservation planning. We completed a review of the use of animal physiology in the US Fish and Wildlife Service (USFWS) and National Marine Fisheries Service (NMFS) Endangered Species Act (ESA) recovery plans released between 2005 and 2016. Over those 11 years, 135 of the 146 recovery plans mentioned physiology, with 56% including it as background information on the natural history of the species and not as part of the recovery process. Fish and bird species had the lowest proportion of recovery plans to include physiology beyond the description of the natural history. When considering multiple sub-disciplines of physiology, immunology and epidemiology were incorporated as part of the recovery process most often. Our review suggests a disconnect between available physiological tools and the potential role of physiology in developing conservation plans. We provide three suggestions to further guide conservation scientists, managers and physiologists to work synergistically to solve conservation problems: (1) the breadth of knowledge within a recovery plan writing team should be increased, for example, through increased training of federal scientists in new physiology methodologies and tools or the inclusion of authors in academia that have a background in physiology; (2) physiologists should make their research more available to conservation scientists and federal agencies by clearly linking their research to conservation and (3) communication should be enhanced between government conservation scientists and physiologists.

Key words: Conservation physiology, Endangered Species Act, physiology, review

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Introduction

Conservation scientists and managers are constantly faced with new challenges when preserving and protecting habitats and mitigating threats to plant and animal populations. These challenges are compounded as the number of undisturbed habitats diminishes, while at the same time, the number of anthropogenic impacts increases (Javeline *et al.*, 2015).

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Scientists predict that approximately 21% of existing plant and animal species in threatened geographical areas will be extinct in the next 100 years (Javeline *et al.*, 2015). Although the field of conservation biology is integrative by including a wide range of economic, social and scientific fields, conservation scientist and managers have traditionally focused on measuring either demographic characteristics of populations or patterns of community dynamics to evaluate ecosystem function (Cooke *et al.*, 2013). Complex conservation problems require managers and scientists to use a variety of tools and information available to create innovative solutions. One potentially helpful field that has gained increasing interest in the conservation literature is physiology (Cooke *et al.*, 2013).

Conservation physiology is a sub-discipline of conservation biology, first defined in 2006 to help identify the important ways that physiological knowledge and tools can be used to help understand and solve conservation problems (Wikelski and Cooke, 2006). The field of conservation physiology includes areas of research such as bioenergetics and nutrition as well as toxicology, stress and reproductive physiology. Previous reviews of the field identify the potential sub-disciplines of physiology that can be used in conservation efforts, and provide examples of how conservation physiology can help inform some of the most commonly cited conservation and management concerns, such as climate change, habitat destruction, invasive species, pollution and disease (Wilcove *et al*.,. 1998; Wikelski and Cooke, 2006; Cooke *et al.*, 2013; Madliger and Love, 2015).

Although the sub-discipline has only recently been defined, using physiology for management purposes is not a new concept. In the past, physiological data has helped conservation biologists and law makers develop legislation and regulations to protect both vulnerable habitats and species. For example, the US Fish and Wildlife Service (USFWS) has been studying the physiological effects of lead poisoning from lead shot and lead sinkers on wildlife since the 1930s (USGS National Wildlife Health Center, 2016). Their research helped provide the scientific support for banning lead shot for waterfowl hunting in 1991 (USGS National Wildlife Health Center, 2016). Environmental toxicology studies on lead have also provided the scientific support for individual states such as Washington, Maine and New York to regulate or ban the use of lead fishing sinkers (USGS National Wildlife Health Center, 2016).

A key feature of using physiology in conservation planning is that it has the potential to help scientists understand how and why species respond and decline under varying environmental threats. Information such as reproductive physiology, stress physiology, immunology and epidemiology, and bioenergetics and nutritional physiology should be included as part of management and recovery plans of threatened and endangered species.

Species recovery plans developed and used by the US federal agencies are important tools for conservation, management and research of imperilled species. These plans are pursuant to the Endangered Species Act of 1973 (ESA), which its purpose is to provide 'a means whereby the ecosystems upon which endangered species depend may be conserved, to provide a program for the conservation of such endangered species and threatened species, and to take such steps as may be appropriate to achieve the purposes' of current and future international treaties and conventions (U.S. Congress House, 2003). As part of the ESA, USFWS and the National Marine Fisheries Service (NMFS) have been charged with the mandatory development of endangered species recovery plans that describe the current state, threats and intended steps for increasing endangered and threatened species population sizes. Each recovery plan must include a description of site-specific management actions, objective and measurable criteria that can be used to monitor the recovery of the species, criteria that must be met before the species can be removed from the endangered and threatened species list, and an estimate of the time required and costs to achieve the recovery plan's goals (U.S. Congress House, 2003). Within the act, endangered species are defined as 'any species which is in danger of extinction throughout all or a significant portion of its range other than a species of the Class Insecta determined by the Secretary [of the Interior] to constitute a pest whose protection under the provisions of the Act would present an overwhelming and overriding risk to man' (U.S. Congress House, 2003). A threatened species is also defined within the act as 'any species which is likely to become an endangered species within the foreseeable future throughout all or a significant portion of its range' (U.S. Congress House, 2003). The ESA recovery plans developed by the US federal agencies are the framework for future management of an endangered or threatened species, thus any potential monitoring tools or management recommendations should be included lest they not be considered.

Using a more holistic approach, that includes physiology, during the development of these recovery plans will help in developing strategic monitoring and management implementation plans aimed at increasing population sizes of threatened and endangered species (Birnie-Gauvin *et al.*, 2017). For example, an area of conservation physiology that has received considerable attention and has potential to affect management plans is the use of stress physiology as an early warning system for negative population responses to environmental changes. Managers respond to declining populations by changing management approaches without always clearly understanding the mechanism behind the population decline. However, population declines might be detected earliest by understanding the physiological responses of individuals. For example, in zebra finches (*Taeniopygia guttata*), increases in stress hormones early in life are correlated with decreased adult lifespans (Monaghan *et al.*, 2012). By monitoring individuals at the physiological level, researchers can provide mechanistic insight to help managers not only better detect, but also identify and predict species' responses to changing environments (Coristine *et al.*, 2014). This approach can be useful for both the monitoring of larger populations in areas of concern, and for monitoring how small threatened and endangered populations are responding to recovery measures already being implemented, such as monitoring their physiological response to habitat restoration.

Another potential technique to include in recovery plans is using physiological knowledge to help control invasive species (Cooke *et al.*, 2013). If invasive species are a concern, the recovery plan should include physiological information and tools that will help decrease threats the invasive species poses towards the species of concern. For example, researchers have found migratory and sex pheromones can be highly effective attractants in trap-based management of sea lamprey (*Petromyzon marinus*), an invasive species in the Great Lakes (Wagner *et al.*, 2006).

Since the sub-discipline of conservation physiology was defined, applying physiology to help solve conservation problems has become increasingly prominent in the field of conservation science (Cooke, 2014; Lennox and Cooke, 2014). The increasing interest in the field has prompted reviews that have used the scientific literature to categorize the ways physiology can be useful for conservation (Wikelski and Cooke, 2006; Cooke *et al.*, 2013; Madliger and Love, 2015). Additionally, a conceptual framework has been developed to guide conservation physiology and promote research cultivating conservation-motivated policy (Coristine *et al.*, 2014). It is unclear, however, if the increased integration into scientific literature has translated into the application of physiological tools in conservation planning and management. In light of this missing link, the purpose of this review was to analyze how physiological tools have been integrated into applied conservation by examining the US ESA recovery plans released between 2005 and 2016.

USFWS and NMFS ESA species recovery plans of federally-listed species are an excellent resource for examining if physiology has been integrated into conservation efforts. First, plans are developed by experts in the field of conservation and wildlife biology within the USFWS and NMFS. These plans are also routinely submitted to other federal and state agencies that have direct knowledge of the conservation problem, so that feedback can be provided to develop a thorough and accurate report and plan. Thus, these plans should provide accurate insight into the tools and information that conservation biologists and managers across the nation find most important and appropriate to use in conservation efforts. Second, the NMFS and USFWS created a joint document outlining the guidelines for developing and implementing recovery plans that all participating agencies must follow (National Marine Fisheries Service, 2010a). However, planners are given considerable discretion, and the guidelines clearly state that planners should view this discretion as an 'opportunity to use their creativity and ingenuity to craft the most effective and practical recovery program for each species in their care' (National Marine Fisheries Service (NMFS), 2010). Thus, all recovery plans follow similar outlines, but still show important variation, making them easy to compare. Finally, all the recovery plans are housed in a national database, making them easily accessible.

During our review of the ESA species recovery plans, we maintained four objectives: (1) identify the number of recovery plans that mentioned some aspect of physiology; (2) classify how physiology was applied to conservation efforts within each report; (3) evaluate the relative contribution of traditional population-level management techniques compared to physiological approaches and (4) examine what sub-disciplines of physiology were being used the most, and what taxa were being represented.

Methods

The USFWS and NMFS database of ESA recovery plans were analyzed for the use of physiology in final and draft plans released between 2005 and 2016. Although previous scientists have linked physiological regulations to an animal's ability to adapt to changing environments for decades (Carey, 2005), we selected the start year for our analysis based on the first time physiology was clearly articulated in the literature as an important conservation tool. This seminal publication by Carey (2005) suggested that 'physiological principles, concepts and methods that are rooted in traditional basic research in physiology, physiological ecology and evolutionary physiology are fundamentally important in understanding the causes of population declines and in conservation planning.' Although we focused solely on animals, conservation physiology can also be an important field for research and management plans focused on endangered plant species (Wikelski and Cooke, 2006). In cases where multiple species were included in a single report, each species was counted as an individual report.

To identify how many ESA species recovery plans included physiology (objective 1), each final or draft recovery plan released between 2005 and 2016 was read, and any portion that discussed one of the physiological sub-disciplines was highlighted (Wikelski and Cooke, 2006; Cooke *et al.*, 2013). The sub-disciplines included were: bioenergetics and nutritional physiology, cardio-respiratory physiology, chemical physiology, comparative physiology and biochemistry, environmental and ecological physiology, environmental toxicology, evolutionary physiology, immunology and epidemiology, locomotor performance physiology, neurophysiology and sensory biology, physiological genomics and reproductive physiology (Wikelski and Cooke, 2006; Cooke *et al.*, 2013). Common words we looked for included (but were not limited to): physiology, temperature, oxygen, toxins, pollutants, disease, parasite, reproduction, hormone, nutrition and stress. If one of these terms was found, further review was undertaken to confirm the use of the term while specifically discussing physiology.

To classify how physiology was applied to conservation (objective 2), we categorized all reports into three main classifications and the frequency of the three classifications was compared using a chi-square analysis. Our first classification was termed 'natural history' (Table 1). In this classification, physiology was used when describing the life history, natural history, or background of the species. For example, in the final recovery plan for the Mexican spotted owl (*Strix occidentalis lucida*), authors discuss the potential physiological impacts climate change may have on the species. They suggest if climate change results in increased periods of time where habitat temperatures exceed the lower or upper limit of the species, it will impact 'key physiological processes like thermoregulation and water balance' (U.S. Fish and Wildlife Service, 2012). Our last two classifications were termed 'research-based action' or 'application-based action' (Table 1). A research-based action is when a recovery plan clearly stated that continued physiological research was required for the species of concern. For example, in the recovery plan for the ocelot (*Leopardus pardalis*), authors discuss the need for baseline physiological data. As part of the recovery strategy, they recommend establishing a protocol for physiological assessment and identification (U.S. Fish and Wildlife Service, 2016b). Another example of a research-based action comes from the draft recovery plan for the laurel dace (*Chrosomus saylori*). The authors suggest the need for research on how changes in habitat quality (e.g. water temperature, dissolved oxygen, water pH) will affect the physiology of the species (U.S. Fish and Wildlife Service, 2016a). If a recovery plan included an application-based action, it included a plan to use a physiological tool to help in the recovery or monitoring of the species. In the recovery plan of the Wyoming toad, the authors suggest the use of hormonal priming and *in vitro* fertilization for captive populations (U.S. Fish and Wildlife Service, 2015b). In these examples, the research-based actions differs from the application-based action in that the former two examples specifically identify the need for new protocols or research to be established, which would include collecting baseline information from individuals that may potentially be used later to help monitor a population's health, whereas, the latter is already using reproductive physiology knowledge and methodologies to increase reproductive success.

All reports were analyzed for how the term 'stress' was used to evaluate the relative contribution of traditional population-level management techniques compared to physiological approaches (objective 3). Environmental stress, or stressors, can be defined as aversive stimulus (Romero, 2004; Dantzer *et al.*, 2014), whereas, the physiological stress response of an individual is a 'suite of physiological and behavioural mechanisms to cope with the stressor' (Wikelski and Cooke, 2006). If recovery plans recognize different environmental stressors as threats to different species, and try to establish the link between cause and effect of the stressors at the physiological level, effects can be measured and monitored to act like an early warning system against future environmental and anthropogenic changes that may cause population declines. We classified reports on if the link between stressors and the physiological response was or was not made apparent. If the link was not made, then that supports the idea that there is a disconnection between the authors of the reports and available physiological techniques and approaches. For example, in the recovery plan for the Preble's meadow jumping mouse (*Zapus hudsonius preblei*), the authors include a list of potential stressors for the mouse, but never connect their threats to the physiological implications of the stressors (U.S. Fish and Wildlife Service, 2016c).

To further examine the connection between the use of the word stress and its connection to physiology, we also examined how often the word stress was used in conjunction with an action-based use of physiology (objective 3). For example, in the recovery plan for the polar bear (*Ursus maritimus*), authors discuss many potential stressors for polar bears and identify the link between physiology and stress in their conservation and recovery actions. The authors identify the need to improve their 'understanding of the physiological response of polar bears to environmental and anthropogenic stressors and develop methods for monitoring those responses' (U.S. Fish and Wildlife Service, 2015a). They also suggest the need to 'characterize the physiological stress response of polar bears relative to life history, physiological states and environmental conditions, and determine if a relationship exists between stress responses and measures of body condition and reproduction' (U.S. Fish and Wildlife Service, 2015a).

Information about what sub-disciplines of physiology were used the most in recovery plans and for which taxa could be important for helping physiologists decide where they should focus their research to best inform conservation

Table 1: Classification of the US Endangered Species Act recovery plans to indicate the manner in which physiology was mentioned

Classification	Criteria
Natural History (NH)	Physiological concepts included when discussing the natural history of the species.
Action-based Physiology	
Application-based Action (ABA)	Current physiological tools and methodologies included when developing the recovery or monitoring actions for the species.
Research-based Action (RBA)	Suggestions for additional research on either how stressors affect an organism on the physiological level, or research on how current or new physiological methodologies can be modified or developed for a specific organism to aid in the recovery or monitoring process.

efforts. For our fourth objective, we further examined all plans classified as action-based. We separated the plans using the sub-disciplines described in Cooke *et al.* (2013) and Wikelski and Cooke (2006) (see Supplemental material). The frequency of use of the sub-disciplines was compared using a chi-square analysis. We also organized our data by taxonomic order to compare where physiology is used most often.

Results

Out of the total 146 recovery reports that were released between 2005 and 2016, 135 (93%) included physiology. Of those that did include physiology, 56% used physiology in the form of describing the natural history of the species, but not an action-based form (Fig. 1). Of the 135 reports including physiology, the number of reports focusing on natural history was significantly greater than the number of reports including an action-based focus ($\chi^2 = 91.934$, $P < 0.0001$). Of the 135 reports that included physiology, 96% used a natural history form of physiology, 44% used at least one action-based form, 32% used at least one research-based action and 17% used at least one application-based action. In some instances, recovery reports used a combination of all three forms (Fig. 1). When comparing the 60 reports that used an action-based form of physiology (44% of reports including physiology), research-based actions were used significantly more than application-based actions ($\chi^2 = 12.428$, $P = 0.0004$; Fig. 1), such that research-based actions were used in 72% of reports and application-based actions were used in 38% of reports.

The term 'stress' was used with clear physiological meaning in 63% of reports that included the term (Fig. 2). An example of using stress with clear physiological meaning comes from the Kemp's Ridley sea turtle (*Lepidochelys kempii*) recovery plan, where authors discuss how being entangled in fishing gear, and forcibly submerged in water causes 'respiratory and metabolic stress that can lead to severe disturbance of their biochemistry' National Marine Fisheries Service *et al.* (2011). An example of using stress with no clear physiological meaning comes from the recovery plan for the St. Andrew's beach mouse (*Peromyscus polionotus peninsularis*), where authors identified each potential threat to the species as a stressor without ever identifying the physiological effects of those stressors on an individual (U.S. Fish and Wildlife Service, 2010).

When we examined how often the word stress was used in conjunction with an action-based form of physiology we discovered 23% of all recovery plans using the terms stress or stressor proceeded to describe a physiological action-based plan to manage the said threat (Fig. 2).

Of the 11 sub-disciplines of physiology defined as important to conservation, only eight were in an action-based form for all the recovery plans. There was a significant difference in the frequency of the sub-disciplines ($\chi^2 = 162.650$, $P < 0.0001$). The sub-discipline immunology and epidemiology

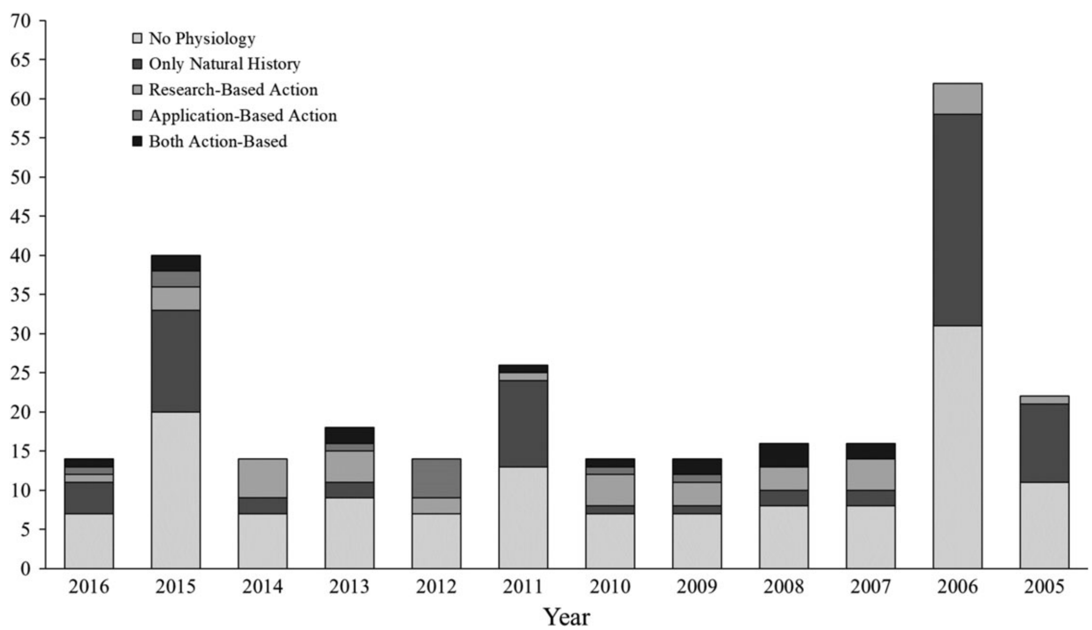

Figure 1: A breakdown of how physiology has been used in US Endangered Species Act recovery plans across years (2005–16). Each column total is equal to the total number of recovery plans released that year. The bottom of each stack represents the number of recovery plans that did not mention any form of physiology, and the total of the remaining stacks in each column equals the number of recovery plans released in a specific year that mentioned physiology in one form or another.

was used the most (63% of reports), followed by reproductive physiology (31% of reports; Fig. 3).

Of the 146 recovery plans we reviewed, 11 taxonomic groups were mentioned (Table 2). Birds were represented the most with 42 recovery plans (29%), followed closely by mammals (21%) and fishes (16%). In all three taxa, over 80% of the recovery plans included physiology; however, less than 50% of the bird and fish taxa included plans with action-based physiology (37% and 45% respectively; Table 2).

Discussion and conclusions

In the past decade, applying physiology to help solve conservation problems has become increasingly prominent in the field of conservation biology. Even so, it is unclear if the increased integration into the scientific community has translated into the actual application of physiological tools in conservation planning. By reviewing the USFWS and NMFS database of recovery plans, we have provided insight into how managers and conservation scientists are using physiology. During the review process, we discovered a major deficit of knowledge being used by federal agency authors assigned to write recovery plans. We identified three main recommendations to further guide conservation scientists, managers and physiologists to work synergistically to solve conservation problems: (1) the breadth of knowledge within a recovery plan writing team should be increased by, for example, increased training of federal agency scientists in new physiological techniques and research or the inclusion of authors with academic affiliations that study physiology; (2) physiologists should make their research more available to conservation scientists and federal agencies by clearly linking their research to conservation, and developing thorough reviews and (3) communication should be enhanced between government conservation scientists and physiologists.

The importance of physiology for understanding species–environment interactions needs to be communicated to recovery plan authors prior to, or during, the peer-review process. Written input on how current environmental stressors affect an individual at the physiological level, and thus potentially lead to a cascade of other effects at the population level would be beneficial. We recognize that the lack of physiological tools being used can originate from either a scarcity of knowledge passing between research scientists and writers, or from federal agency writers not understanding the importance of diversifying their methodologies to include new techniques that incorporate physiology. However, the shortage of expert input is supported by the fact that although the use of physiology was seen in most recovery plans, it was mainly found in the portion of the plan describing the natural history of the species. Further, the portions of the reports describing the actions required for the recovery of the species rarely used physiological tools or methodologies. The absence of awareness could be resolved by forming interdisciplinary teams to ensure that both recovery plans undergoing updates and future plans connect the terms ‘stress’ or ‘stressors’ to an action-based use of physiology. Recovery plan writing teams might include university-based scientists with specialized expertise pertaining to physiology. Another source of scientists for recovery plan writing teams includes

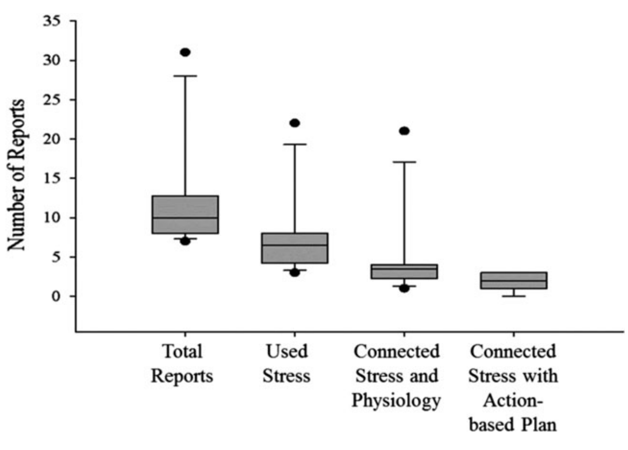

Figure 2: A breakdown of how the term stress was used within the US Endangered Species Act recovery plans, averaged across the 11 year review period (2005–16). ‘Total Reports’ represent the average number of reports written each year. The category ‘Used Stress’ was defined as any recovery plan that used the term stress. ‘Connected Stress and Physiology’ was defined as any report that connected the term stress with physiology. ‘Connected Stress with Action-Based Plan’ was defined as any recovery plan that connected the term stress with either a research-based action or application-based action.

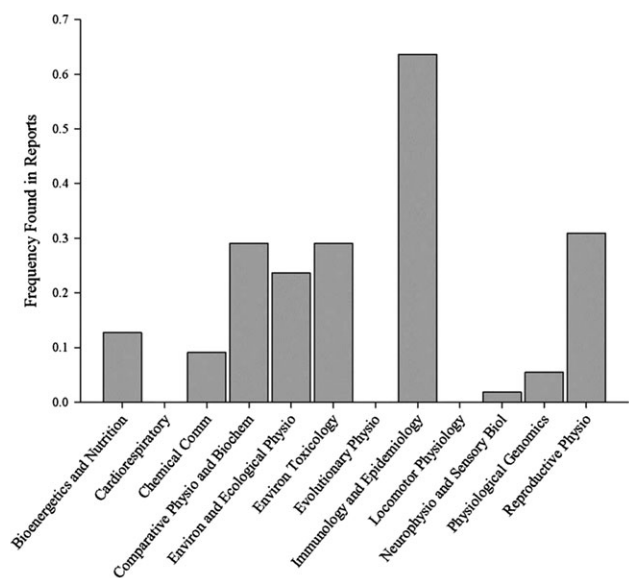

Figure 3: The frequency of physiology sub-disciplines used in the animal subset of US Endangered Species Act recovery plans (2005–16). Only action-based forms of physiology (research-based and application-based) were counted.

Table 2: A breakdown by taxa of the number of the US Endangered Species Act recovery plans that mentioned physiology and of those the number that incorporated an action-based form of physiology (i.e. research-based action [RBA] or application-based action [ABA]; see Supplemental material for details on the recovery plans evaluated)

Taxonomic class	Number of recovery plans	Recovery plans mentioning physiology	Recovery plans with action-based physiology (RBA, ABA)
Bivalvia	2	2	2 (2,0)
Gastropoda	11	11	5 (5,1)
Branchiopoda	4	4	0
Malacostraca	1	1	0
Arachnids	7	7	0
Insecta	13	9	1 (1,0)
Osteichthyes	23	22	10 (7,3)
Amphibians	10	10	3 (2,2)
Reptilia	3	3	3 (3,1)
Aves	42	40	15 (10,7)
Mammalia	30	25	17 (12,8)

the federal agency's own research scientists. If federal agency scientists are actively doing research involving physiology, they should be invited to join recovery plan writing teams as an important source of knowledge for current physiological methodologies and tools.

Previous analysis of the process and success of recovery plans suggests that increasing training for writing ESA recovery plans in federal agencies would increase quality and efficacy of these plans (Clark *et al.*, 2002). Recommendations by the Society for Conservation Biology's recovery plan project pointed out that recovery plans underused modern conservation biology tools (Clark *et al.*, 2002). They also suggested that underutilization was partially due to the tools being relatively new, and the tools had been developed by biologists outside the USFWS. Because the tools were researched and created outside of the federal agencies, federal employees often lacked the current training to know how to effectively use the tools (Clark *et al.*, 2002). An example of a physiological tool that may require specialized training is the collection and interpretation of glucocorticoid levels, or stress hormone levels, in endangered and threatened species (Dantzer *et al.*, 2014). There are many mediums that can be used to collect physiological stress data, and when and how to use each technique may require specific training (Dantzer *et al.*, 2014).

Diversifying the authorship of the recovery plans by engaging individuals with academic affiliations or federal agency scientists conducting physiological research can also increase the breadth of physiological tools and knowledge available to the writing teams. According to the 'Interim Endangered and Threatened Species Recovery Planning Guidance,' federal agencies have the option of assembling recovery teams to write recovery plans; and, there have been multiple reviews and analyses of recovery plans that suggest diverse teams make the best and most productive recovery plans (Boersma *et al.*, 2001; Gerber and Schultz, 2001; Clark *et al.*, 2002). By including at least one author with an academic affiliation and/or physiological background, the number of recovery plans examining the cause and effect relationships between physiology and environmental stressors may increase. In fact, one review examining how authorship influences the biology used in recovery plans found that teams with at least one academic author were more likely to clearly link the biology of the species with recovery criteria and monitoring strategies (Gerber and Schultz, 2001).

The relationship between physiologists and the field of conservation biology should be reciprocal in nature. The time requirements for someone with academic affiliations actively participating as a member of a recovery plan writing team may be extensive, causing potential conflicts between responsibilities. However, there are also many advantages to being a part of a writing team such as having access to knowledge of new potential research topics and new avenues for funding (Lennox and Cooke, 2014).

Another possible argument for the lack of physiology in recovery plans is that there just has not been enough relevant physiological research on endangered and threatened species to be of current use for recovery plans. Lennox and Cooke (2014) estimated that between 2006 and 2012, there was only 2% integration between current physiological research and conservation research in 16 prominent conservation and biodiversity, animal physiology, plant physiology and ecology journals. The lack of integration is supported by our analysis, which indicates that more research-based actions were suggested than application-based actions in the recovery plans. These results suggest that even when authors understood the importance of incorporating physiology, they required more information about a particular method or how to use a tool for a particular species before the authors could suggest that a method or tool be applied.

As part of the lack of integration between physiological research and conservation, recovery plan authors may find identifying useful resources difficult. For example, in some instances, the use of physiology in conservation efforts may be frowned upon due to the invasive nature of collecting physiological data (Lennox and Cooke, 2014). Many recovery plans even stipulate the need to better regulate the use of endangered and threatened species for research purposes, such as in the recovery plan for the Mojave population of the desert tortoise (*Gopherus agassizii*). The authors specify that they will only permit research that may 'result in infrequent injury or mortality' (U.S. Fish and Wildlife Service, 2011). They go on to discuss how invasive procedures associated with obtaining physiological data can cause significant stress and possible death for individuals (Berry *et al.*, 2002; U.S. Fish and Wildlife Service, 2011). However, if the resources describing the many noninvasive methods for collecting physiological data were made more accessible, more action-based research may be included in recovery plans. Examples of such tools include: fur and feathers (molted or new) can be used to analyze stable isotopes and stress response (i.e. corticosterone or cortisol) (Bortolotti *et al.*, 2008; Richards *et al.*, 2008; Carlitz *et al.*, 2016), and faecal samples can be used for analyzing stress and reproduction (Millspaugh and Washburn, 2004; Schwarzenberger, 2007).

Our second recommendation is that physiology researchers should link their research to conservation more clearly to help recovery plan writers identify available physiological data, tools and methods. By examining previous reviews on the use of physiology in conservation, physiologists can get a better idea of what type of research is useful for recovery plans (Wikelski and Cooke, 2006; Cooke *et al.*, 2013). To go one step further, our results specifically show recovery plan authors most often use the following sub-disciplines: immunology and epidemiology, comparative physiology, environmental toxicology, environmental and ecological physiology, and reproductive physiology. Our results also identified that the reptile and mammal classes had the highest proportion of recovery plans including action-based physiology and the avian and fish classes had the lowest. Seven out of the ten action-based recovery plans for fish included only research-based actions. In addition, upon review of fish species recovery plans, most of the plans included at least a brief mention of increasing water temperatures negatively affecting the species, but in many cases, there was no further discussion of what the physiological range of the species is. This suggests the need for additional physiological research on fish, and the development of new methodologies for monitoring fish populations.

Physiological data can be helpful for conservation recovery and management plans, but there is also a need for tool refinement to improve physiological sampling methods and tools for increased applicability (Madliger and Love, 2015). Increased conservation physiology research may not be followed by increased use in recovery plans if the writers are not aware of the new methods and tools available to them. Thus, physiologists should also increase accessibility of knowledge by composing thorough reviews of methods and tools. Such reviews can be thought of as 'one-stop shopping' for writers where they can find a plethora of information in one location.

The burden of increasing the amount of relevant conservation physiology research should not solely be placed on the shoulders of university-based researchers. In addition to writing recovery plans, federal agencies also conduct their own conservation and management research. Thus, federal agencies should be encouraging their scientists to incorporate an interdisciplinary approach in their research. Such an approach would not only diversify conservation techniques, but also expose federal scientists to a broader array of scientific research. Currently, the USFWS National Conservation Training Center does not mention physiology in their course guide. Adding a Conservation Physiology course under the Wildlife Biology and Field Techniques category is a potential way to increase the awareness of Department of Interior employees that physiology can be an important tool for conservation.

For the solutions discussed above to be successful, they must all share a common denominator—communication. Thus, our final recommendation is that for recovery plans to be successful, physiologists, conservation biologists and federal agencies need to communicate with each other. For physiologists to produce useful research for conservation they need to have a clear understanding of what is needed from them; and for agencies to do their due diligence for the ESA recovery plans, they need to continue to incorporate new and useful tools and methods in their plans.

Although communication between federal agency employees and external scientists can be difficult, there are avenues that can ease the barrier. For example, one important avenue of communication is for both federal and academic scientists to attend professional meetings and conferences such as the Society for Conservation Biology, Society for Integrative and Comparative Biology and Society for Experimental Biology. Such conferences provide unique environments for conservation biologist to seek input on physiological methodologies, and for physiologist to find relevant applications for their research through new collaborations with conservation biologists (Madliger *et al.* 2017). Another potential area for collaboration is for federal agencies to develop more research agreements with universities. For example, the US Department of Agriculture, National Wildlife Research Center has had a cooperative agreement with North Dakota State University since the late 1970s for red-winged blackbird research. Their agreement has included graduate student projects that examine blackbird stress physiology in response to predators and unmanned aerial systems (Klug, 2017). An example of this research includes an examination on how stress during the breeding season negatively affects female physiology and reproduction (Mahoney *et al.* 2016). Such agreements are beneficial to all parties—where the federal agencies provide unique opportunities for budding conservation physiologists and in return receive high-quality research and publications and an avenue for direct communication with those in academia. Other areas of communication include increasing publications, attending one-on-one meetings and participating in the recovery plan review process.

Conservation physiology is a relatively new field, and has great potential for helping solve and monitor conservation issues. It can be beneficial for helping connect the cause and effect relationships between the changes in the environment and variations in species' population sizes. However, thus far, conservation plans have sorely underutilized the tools and techniques from the field of physiology. This disconnect may be due to a deficit of knowledge about physiology from the authors of the recovery plans. By increasing the breadth of knowledge within writing teams, using tool refinement to make physiological research more available to conservation scientists and federal agencies, and by improving the modes of communication between conservation scientists, federal agencies, and physiologists, conservation physiology can be used to its full potential in recovery and other management plans in the future.

Supplementary

Supplementary material is available at *Conservation Physiology* online.

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