CONTRIBUTED PAPER

Conservation Science and Practice
A journal of the Society for Conservation Biology

WILEY

Physiology as a tool for at-risk animal recovery planning: An analysis of Canadian recovery strategies with global recommendations

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Abstract

Many government organizations use recovery planning to synthesize threats, propose management strategies, and determine recovery criteria for threatened wildlife. Little is known about the extent to which physiological knowledge has been used in recovery planning, despite its potential to offer key biological information that could aid in recovery success. Using recovery strategies for at-risk animal species in Canada as a case study, we analyzed the prevalence, purpose, and type of physiological knowledge being used in recovery planning. We found that 73% of strategies contained mention of physiology and that incorporation of physiology has increased since 2006. Of the various types of physiological tools available, reference to stress, immune, thermal, and bioenergetic metrics appeared most frequently. Physiological information was more likely to be found in the background and threat assessment sections compared to action and future research sections, and less likely to be included in strategies for arthropods and birds compared to other taxonomic groups. By synthesizing our results with previous studies, we provide recommendations to encourage the application of physiological tools in recovery planning

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worldwide, such as increased incorporation of physiology in ongoing threat monitoring, critical habitat assessments, monitoring the success of recovery actions, and modeling responses to future environmental changes.

1 | TARGET AUDIENCE

We envision the target audience being comprised of conservation researchers interested generally in the recovery of imperiled species and/or integrative techniques for species recovery, researchers and practitioners interested in conservation physiology techniques, and conservation practitioners and planners involved in the listing and recovery of species at risk.

2 | INTRODUCTION

Globally, species are disappearing approximately 1000 times more quickly than pre-human rates of extinction (De Vos et al., 2015). Policies and legislation have been introduced in many regions to help protect and recover threatened wildlife. An important component of government-led action is recovery planning: a key preparative step preceding conservation action which typically involves a synthesis of evidence on threatened taxa including identification of threats, management priorities, and criteria that will be used to assess recovery (Bottrill et al., 2011; Foin et al., 1998; Schwartz, 2008). Once completed, recovery planning documents are used to inform, guide, and coordinate the recovery of imperiled species (Hoekstra et al., 2002).

It is necessary that recovery planning incorporates sufficient biological information to inform conservation agendas. Examples of relevant biological information include characteristics such as habitat use, population biology, life history, behavior, genetics, and general ecology (Clark & Harvey, 2002; Mair et al., 2018; Moore & Wooller, 2004; Troyer & Gerber, 2015). Many have advocated that a more effective integration of key biological information in recovery planning is essential to improving global conservation success (Clark et al., 2002; Clark & Harvey, 2002; Gerber & Schultz, 2001; Mahoney et al., 2018; Moore & Wooller, 2004). A quantitative assessment of Endangered Species Act (ESA) recovery plans in the United States revealed that the inclusion of biological information in the recovery planning process has increased through time, and that plans for species characterized as "improving" more frequently include a very clear biological basis for selection of recovery criteria (e.g., reference to relevant biological data or characteristics) compared to other species (Gerber & Hatch, 2002).

The conservation toolbox has generally been expanded by a variety of mechanistic techniques, spanning behavior, genetics and genomics, and physiology, which provide greater insight into the causes behind population declines compared to traditional demographic monitoring in isolation (Carey, 2005; Cooke & O'Connor, 2010; Madliger, Franklin, Love, & Cooke, 2021; Seebacher & Franklin, 2012). In comparison to conservation behavior and conservation genetics, the discipline of conservation physiology is more recently defined (Cooke et al., 2013; Wikelski & Cooke, 2006) but has become increasingly established and is contributing to solving diverse conservation challenges across animal taxa (Madliger, Franklin, Love, & Cooke, 2021). Conservation physiology draws on information and techniques, including, but not limited to immune function and health, stress and reproductive physiology, nutrition, toxicology, and bioenergetics (Cooke et al., 2013). Birnie-Gauvin, Walton, et al. (2017) provide examples of how physiological information can be incorporated in the recovery planning process for threatened and endangered species, citing particularly valuable applications in threat assessment (e.g., determining the underlying causes of population decline), as well as aiding in recovery actions such as health and stress monitoring or captive breeding and release. The use of physiological information has also proved successful when it comes to monitoring responses to habitat restoration and other management techniques (Cooke et al., 2020; Coristine et al., 2014; Mahoney et al., 2018), controlling invasive species (Lennox et al., 2015; Mahoney et al., 2018), determining tolerances and habitat requirements for translocation projects (Birnie-Gauvin, Walton, et al., 2017; Tarszisz et al., 2014), and supporting future scenario modeling and vulnerability assessments (e.g., to emerging stressors or climate change) (Ames et al., 2020; Birnie-Gauvin, Walton, et al., 2017; Evans et al., 2015)—all of which support the recovery process. For example, physiological information has contributed to lion and hyena population increases

through the development of a thermostable vaccine against rinderpest for domestic cattle (Dobson, Holdo, & Holt, 2011), supported the recovery of the peregrine falcon (*Falco peregrinus*) by revealing the mechanisms of dichlorodiphenyltrichloroethane's (DDT) detrimental effects on raptor populations (Ratcliffe, 1970), and identified ideal supplemental feeding formulations to support the critically endangered kākāpō (*Strigops habroptilus*) recovery program (see summary in Birnie-Gauvin, Peiman, et al., 2017). Although physiological information has well-established potential to aid in species recovery, in many jurisdictions, little is known about whether and how physiological information is being used in the recovery planning process. Understanding the answers to these questions is key to determining whether physiological information and tools are being used to their full potential in recovery planning and could reveal opportunities where an increased application would make recovery planning more effective.

In 2002, Canada passed the Species at Risk Act (SARA), which is intended to protect and recover at-risk species in Canada. The listing process under SARA begins with an independent advisory panel recommending a given Designatable Unit (i.e., species, subspecies, or population) for listing (SARA, 2002). If, based on this recommendation, a Designatable Unit is added to the official list of wildlife species at risk (SARA Schedule 1), recovery and action planning documents are developed to guide its protection and management (SARA, 2002). For Designatable Units determined to be "extirpated" (no longer existing in the wild in Canada, but still found elsewhere), "endangered" (at imminent risk of extirpation or extinction), or "threatened" (likely to become endangered without management), this includes the preparation of a recovery strategy. Recovery strategies identify the major threats to at-risk populations, define their critical habitat, and outline objectives for their recovery (Government of Canada, 2021; SARA, 2002). These documents provide directives for action planning and are thus highly influential in guiding the active management of imperiled species in Canada. Work has been done to elucidate trends associated with identified threats in SARA recovery strategies (McCune et al., 2013), taxonomic biases associated with recovery strategy publication (Creighton & Bennett, 2019), the number of eligible species with finalized recovery strategies (Bird & Hodges, 2017; Mooers et al., 2010), and the percentage of species with critical habitat identified in their recovery strategies (Bird & Hodges, 2017). However, little work has been done to identify how key biological information is incorporated and used in SARA recovery strategies, including physiology.

To determine the extent to and ways in which physiology has been used in the recovery planning of at-risk species in Canada, we ask six questions: (1) How has the prevalence of physiology in recovery strategies changed over time? (2) Which types of physiological information are most commonly incorporated into recovery strategies? (3) How is physiology being used in recovery strategies (i.e., background information, threat assessment, recovery actions, and/or future study suggestions)? (4) Is physiology more likely to be included for some taxonomic groups compared to others? (5) Are Designatable Units facing certain threats more likely to have physiology included in their strategies? (6) Are Designatable Units with certain threat statuses more likely to have physiology in their strategies? We limit our study to animal species, as our collective expertise is in animal conservation and physiology. The six questions we have outlined reflect some major unknowns about trends and biases associated with the use of physiological data in at-risk species conservation (Lennox & Cooke, 2014; Mahoney et al., 2018). With more than 50% of Canadian wildlife species in decline (WWF, 2017), learning to meaningfully incorporate new conservation tools like physiology into the recovery process represents a valuable opportunity to improve recovery rates for Canada's most imperiled populations. While we aim to provide insights as to how physiology can be more effectively incorporated into future recovery planning in Canada, we also outline lessons and recommendations that are broadly applicable to other jurisdictions around the globe.

3 | METHODS

3.1 | Data

We obtained recovery strategies for all at-risk animal species published up until April 2021 from the Government of Canada's *Species at risk public registry* (Government of Canada, 2021). The oldest strategies recovered in our search were published in 2006. We only considered strategies that were finalized, meaning that any strategies published as drafts or undergoing their public review period were excluded from our study. We included only the most recent version of each strategy (i.e., only one version per Designatable Unit was included in our dataset), leading to a final database of 189 documents.

For each recovery strategy in our database, we made a record of: whether the strategy pertained to a single species or multiple species, the year the strategy was published, the threat statuses of Designatable Units covered by the strategy (threatened, endangered, or extirpated),

and the taxonomic group of interest (amphibian, arthropod, bird, fish, mammal, mollusk, or reptile).

To search for physiological information within the recovery strategies, we compiled a list of 112 physiological terms based on our own knowledge and through contact with other physiologists (see Acknowledgments). The terms spanned all physiological subdisciplines and covered common metrics measured by conservation physiologists (Madliger et al., 2018). We used truncated terms where necessary to avoid missing similar terms (e.g., "metabol" was included to ensure we would find both "metabolic" and "metabolism"). The full list of search terms can be found in the Supporting Information. To determine which terms were included in each strategy and the number of times they were mentioned, we used the pdfsearch text extraction package (LeBeau, 2019) in R. Using the generated list of terms identified in a given strategy, we then manually searched for each instance of a term to confirm that it indeed related to physiology. Upon confirmation, we recorded a description of the physiological metric and its broad physiological subdiscipline (biochemical, bioenergetic, cardiorespiratory, general (i.e., no subdiscipline indicated or inferable), immunological, neurophysiological/sensory, nutritional, reproductive, stress, thermal, or toxicological). We also noted the purpose of including the physiological metric by recording which of the four recovery strategy sections the information was mentioned in: background information (includes a description of the species and population/populations of interest and information on their assessment, status, distribution, and life history), threat delineation/assessment, suggestion of future study (knowledge gaps/information need), or action/recovery item. Physiological data were collected by CLM, KBG, RJL, GDR, and SJC. Prior to beginning the full data extraction process, we performed a validation to ensure that all participating authors were collecting similar data by coding the same three randomly selected recovery strategies and comparing the output. We found no discrepancies across authors.

To obtain data on threat classifications, we reviewed each recovery document and recorded whether the Designatable Units they covered were affected by threats encompassed by each of the following 11 threat categories: residential and commercial development, agriculture and aquaculture, energy production and mining, transportation and service corridors, biological resource use, human intrusions and disturbance, natural system modifications, invasive and other problematic species and genes, pollution, geological events, and climate change and severe weather (Salafsky et al., 2008). Threats that were explicitly identified as having "negligible" or "unknown" effects were not recorded in our dataset. Salafsky et al. (2008) provide further detail on the specific threat types covered by each of the 11 threat categories referenced here.

3.2 | Statistical analyses

Data were analyzed using R version 4.0.5 (R Core Team, 2021).

3.2.1 | How has the prevalence of physiology in recovery strategies changed over time?

To assess how the incorporation of physiological data has changed over time, we fit a generalized linear model with a binomial distribution using the lme4 package in R (Bates et al., 2014). In this model, the response was the proportion of strategies containing mention of physiology published each year. This proportional response was entered into our model using the "cbind" function in R where the sum of the number of strategies published in a given year with mention of physiology was regarded as the number of "successes" and the number of "fails" was calculated as the number of strategies published without mention of physiology. Year (2006–2020) was entered as a fixed effect. Strategies published in 2021 were not included in this analysis as our dataset only contained data from the first four months of the year. We checked model assumptions and fit by plotting residuals versus the fitted values. Residual plots and analyses with the Diagnostics for Hierarchical Regression Models (DHARMa) R package (Hartig, 2017) indicated acceptable model fits.

3.2.2 | Which types of physiological information are most common?

To test which types of physiological information (e.g., bioenergetic, stress, reproductive) were most frequently included in strategies, we ran a series of one-tailed Fisher's exact tests using the "fisher. test" function implemented in R (R Core Team, 2021). For each physiological subdiscipline, we asked whether the frequency of strategies with mentions was either greater or less than expected given the typical frequency of mentions reported for other physiological subdisciplines. We used a sequential Bonferroni correction (Holm, 1979) for p-values, to account for multiple comparisons (i.e., 11 physiological subdisciplines).

3.2.3 | How is physiology being included in strategies?

To determine how the inclusion of physiology varied across recovery strategy sections, we conducted a series of one-tailed Fisher's exact tests. For each of the four recovery strategy sections (i.e., background, threat assessment, recovery actions, and future study information), we asked whether the frequency of presence of physiological information was either greater or less than expected given the typical frequency with which physiological information appeared in the other three sections. The p-values from these tests were adjusted using the sequential Bonferroni correction (Holm, 1979) to account for multiple comparisons (i.e., four recovery strategy sections).

3.2.4 | Is physiology more likely to be applied to certain taxa, threats, or threat statuses?

When testing whether mention of physiology was biased by taxonomic group, threats, or threat status, we restricted analyses to single-species recovery strategies to avoid the possibility that strategies covering multiple species were disproportionately more likely to contain mention of physiology, if for example, covering a broader range of taxa increases the pool of physiological knowledge and data available for reference. Multi-species strategies can also contain Designatable Units from different taxonomic groups, with different threats, and with different threat statuses (i.e., our variables of interest) in the same strategy making it unclear how to summarize these variables for analyses where individual strategies are the level of observation. Extirpated taxa were also removed from these analyses given they represented a small number of Designatable Units ($n = 12$) compared to threatened ($n = 101$) and endangered ($n = 61$) Designatable Units, and since it is difficult to compare threat data documented for these taxa to those documented for other Designatable Units given that they cannot be studied in their Canadian range. One single-species strategy for the red knot (*Calidris canutus*) covered populations of the same species with differing threat statuses and was thus removed, leaving us with a total of 162 strategies for analyses. To limit the total number of comparisons, we focused on the five most common threat categories identified for at-risk animals in Canada which were determined to be: residential and commercial development (61% of Designatable Units), natural system modifications (78%), invasive and other problematic species and genes (69%), pollution (65%), and climate change and severe weather (64%).

Prior to testing them independently against physiology mentions, we considered the possibility that taxonomic grouping, threat category, and threat status could be confounded (e.g., particular taxonomic groups being more likely than others to be assigned a particular threat status). Therefore, prior to our main analyses, we used Fisher's exact tests (2x2) and Fisher–Freeman–Halton tests (>2x2) to determine if each of our variables of interest were significantly associated with one another. We found that threat status shared no significant association with taxonomic group or any threat category; however, we did find that three of our five threat categories were significantly associated with taxonomic grouping (see Table S1). Given that all three variables were not intercorrelated, we opted to test taxonomic group, threats, and threats status independently against measures of physiology cognizant of the fact that further analyses would be required if both taxonomic group and threat category were significantly associated with the mention of physiology.

To determine whether recovery strategy mentions of physiology were disproportionately associated with Designatable Units belonging to particular taxonomic groups, associated with common threats, or assigned to particular threat statuses, we ran a series of Fisher's exact tests. We tested whether the frequency of physiology mentions in recovery strategies for each taxonomic group was greater or less than the frequency of mentions across all other taxonomic groups. We corrected each set of p-values using a sequential Bonferroni (Holm, 1979) to account for multiple comparisons among the seven taxonomic groups. For each threat category, we tested whether the frequency of physiology mentions differed for Designatable Units affected by a given threat category versus Designatable Units not affected by that threat category. Finally, to assess whether threat status was associated with the use of physiology, we tested whether the frequency of physiology mentions differed for recovery strategies covering threatened versus endangered Designatable Units.

4 | RESULTS

4.1 | How has the prevalence of physiology in recovery strategies changed over time?

The proportion of animal recovery strategies with mentions of physiology increased significantly from 2006 to 2020: for each passing year, the odds of a published strategy containing a mention of physiology (as opposed to not containing a mention of physiology) increased by a
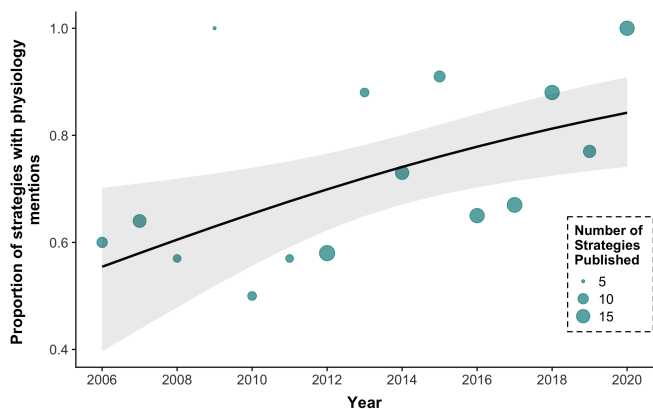
FIGURE 1 Proportion of SARA recovery strategies with mention of physiology versus year (2006 to 2020). Points show raw values where point size indicates the number of finalized strategies published during a given year. Trendline estimated from a generalized linear model including standard error shaded in gray (see methods for model setup)

factor of 1.110 (i.e., the odds ratio) (ß [95% CI] = 0.104 [0.027–0.180]; $p = .008$; Figure 1; Table S2).

4.2 | Which types of physiological information are most common?

The average (hereafter, all reported averages are taken as the geometric mean) number of physiological subdisciplines referenced in a single SARA recovery strategy was 2 (range: 0–6). Physiological metrics falling into the subdisciplines of stress ($p < .001$), immune function ($p < .001$), bioenergetics ($p < .001$), and thermal ($p = .030$) were most common across SARA recovery strategies (Figure 2; Table S3). Metrics that were mentioned least frequently across recovery strategies were those associated with biochemical ($p < .001$), neuro/sensory ($p < .001$), nutritional ($p < .001$), reproductive ($p = .002$), and cardiorespiratory ($p = .024$) physiology (Figure 2; Table S3). Physiological metrics falling into the subdisciplines of toxicological and general physiology were not mentioned more or less frequently than expected when compared to all other types of physiology (Figure 2; Table S3).

4.3 | How is physiology being included in strategies?

Of the 189 recovery strategies, 73% included at least one mention of physiology (average: 2.6 mentions/strategy; range: 0–15 mentions). Mention of physiology was significantly more likely to be made in the background and

threat assessment sections when compared to all other sections ($p = .001$ and $p < .001$, respectively; Figures 3 and 4; Table S4). Physiology was mentioned significantly less frequently in the sections about recovery actions and future study information in comparison to other sections ($p < .001$ in both cases; Figures 3 and 4; Table S4).

4.4 | Is physiology more likely to be applied to certain taxa, threats, or threat statuses?

Recovery strategies for reptiles were more likely to contain mention of physiology when compared to mentions across all other taxonomic groups ($p = .004$), while recovery strategies for birds and arthropods were less likely to contain mention of physiology ($p = .002$ and $p < .001$, respectively; Figure 5; Table S5). Strategies for amphibians were more likely to contain mention of physiology compared to other taxa, but not significantly so ($p = .081$; Figure 5; Table S5). Being impacted or not impacted by a different threat type did not affect the frequency at which physiology mentions were made across recovery strategies for at-risk Designatable Units (Table S6). Threat status (threatened versus endangered) similarly had no significant effect on the frequency with which strategies contained mention of physiology ($p = .369$).

5 | DISCUSSION

We found that 73% of published SARA recovery strategies contained at least one mention of physiology. There has been no worldwide investigation of the incorporation of physiology in at-risk species recovery planning. However, Mahoney et al. (2018) completed an analysis for United States Endangered Species Act recovery plans (2005 to 2016) and found that 93% of ESA plans included physiology, notably higher than what we found for Canada. We did find that the proportion of strategies containing physiological information appears to be trending upward. Conservation physiology was formally defined in 2006 (Wikelski & Cooke, 2006) and has since gained considerable growth as a discipline (Coristine et al., 2014; Madliger, Franklin, Love, & Cooke, 2021). This general increase in the application of physiological knowledge to conservation may be partially contributing to its uptake in Canadian recovery planning, perhaps due to an increased amount of physiology research, a greater number of formally trained conservation physiologists working to increase the accessibility of the discipline, less invasive options for physiological measurements, and a heightened and growing awareness of the field. The

FIGURE 2 Type of physiology (i.e., physiological subdiscipline) versus the proportion of all evaluated recovery strategies ($n = 189$) that contain at least one mention of that physiology type. The dotted line indicates the mean proportion of mentions across all types of physiology. *$p < .05$; **$p < .01$. Significance symbols indicate significance from Fisher's exact tests after applying Bonferroni correction to control for multiple comparisons. The "general" category refers to mentions of physiology that were too broad to be assigned to a subdiscipline
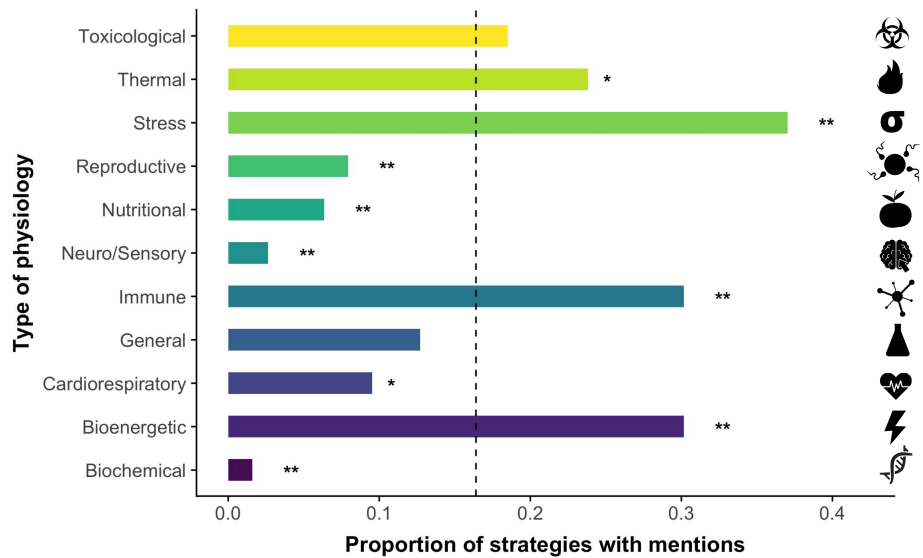
FIGURE 3 Section of recovery strategy versus the proportion of all evaluated recovery strategies ($n = 189$) with mention of physiology in that section. The dotted line indicates the mean proportion of mentions across all sections. **$p < .01$. Significance symbols indicate significance from Fisher's exact tests after applying Bonferroni correction to control for multiple comparisons
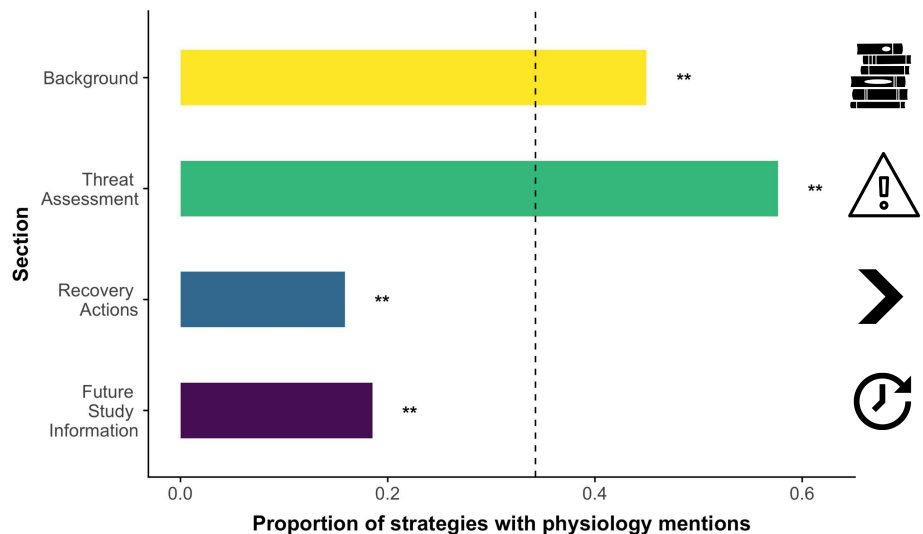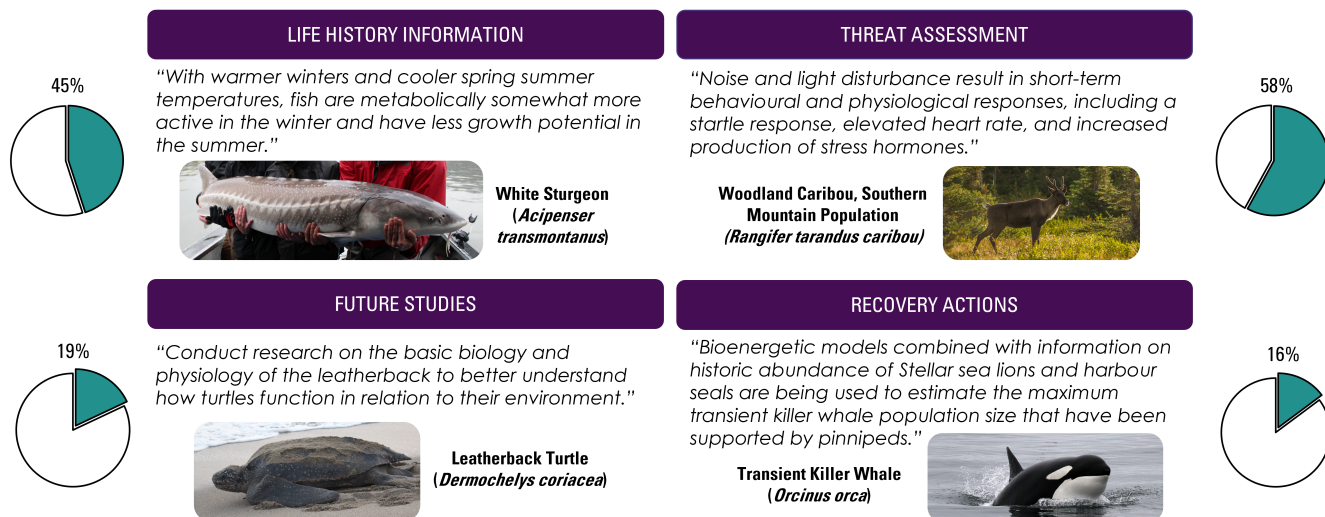
growth in the incorporation of physiological information and tools in recovery planning could also be related to increased funding and attention toward species at risk in Canada.

Notably, there is variation across strategies in the level of detail associated with the physiological information presented. In some cases, physiology is found throughout a strategy and is well-defined in terms of its application and the exact physiological metrics being used. For example, the strategy for the North Pacific humpback whale (*Megaptera novaeangliae*; 2013) clearly states how physiology contributes to toxin vulnerability, "When whales dive, blood is channeled to the heart and brain, potentially directing neurotoxins to vital areas. Limited blood flow to the liver and kidneys may slow metabolism and elimination of toxins during such dives." In other cases, reference to physiology is vague; 10% of strategies included a mention of "physiology" with no

reference to an exact metric, tool, or even broad physiological subdiscipline. For example, the eastern ribbon snake (*Thamnophis sauritus*; 2012) strategy states that "... climate change may also directly impact ribbon snake physiology", with no indication of the particular aspect of physiological functioning that may be affected. When it comes to recovery planning, action is time-sensitive, and finding ways to reduce the time it takes to incorporate new conservation tools like physiology, and increasing the overall clarity of the information included, increases the likelihood of success (e.g., Gerber & Hatch, 2002).

The incorporation of physiological information in recovery strategies did not appear to be associated with whether Designatable Units were affected by different threat types, or Designatable Unit threat status. However, recovery strategies for birds and arthropods were less likely to contain reference to physiology compared to other taxonomic groups. This could point to either (i) a

EXAMPLES OF PHYSIOLOGICAL INFORMATION IN RECOVERY STRATEGIES

LIFE HISTORY INFORMATION

45%

"With warmer winters and cooler spring summer temperatures, fish are metabolically somewhat more active in the winter and have less growth potential in the summer."

White Sturgeon
(*Acipenser transmontanus*)

THREAT ASSESSMENT

58%

"Noise and light disturbance result in short-term behavioural and physiological responses, including a startle response, elevated heart rate, and increased production of stress hormones."

Woodland Caribou, Southern Mountain Population
(*Rangifer tarandus caribou*)

FUTURE STUDIES

19%

"Conduct research on the basic biology and physiology of the leatherback to better understand how turtles function in relation to their environment."

Leatherback Turtle
(*Dermochelys coriacea*)

RECOVERY ACTIONS

16%

"Bioenergetic models combined with information on historic abundance of Stellar sea lions and harbour seals are being used to estimate the maximum transient killer whale population size that have been supported by pinnipeds."

Transient Killer Whale
(*Orcinus orca*)

FIGURE 4 Parts of recovery strategies that can include physiological information, the percentage of 189 strategies (2006 to 2020) that included physiology in those sections, and an example of each case. Photos: White sturgeon (Montana McLean); woodland caribou (CC BY-SA 4.0, ThartmannWiki); leatherback turtle (CC BY-SA 2.0; Alastair Rae); transient killer whale (CC BY-NC 2.0; Robin Agarwal)
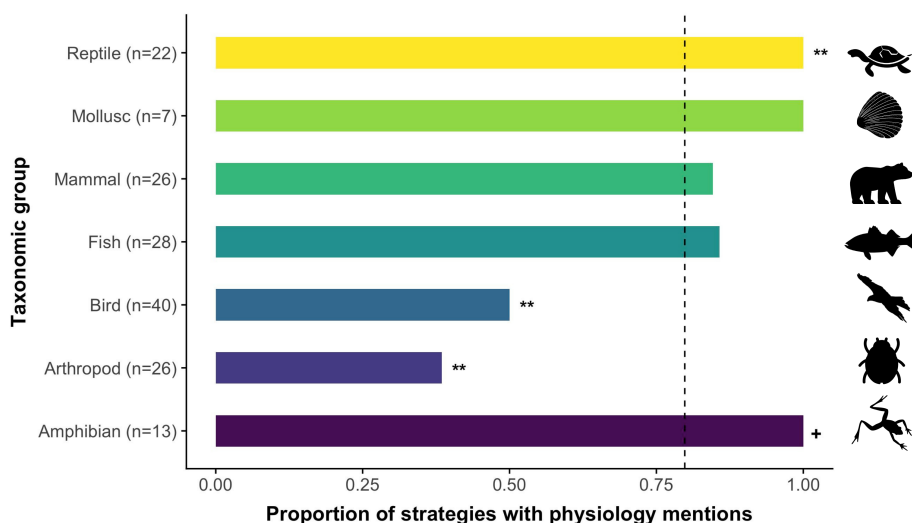
FIGURE 5 Taxonomic group versus the proportion of single-species recovery strategies containing mention of physiology. The total number of evaluated single-species strategies is 162 (see methods). The dotted line indicates the mean proportion of mentions across all taxonomic groups. $+p < .1$; $**p < .01$. Significance symbols indicate significance from Fisher's exact tests after applying Bonferroni correction to control for multiple comparisons

lack of relevant physiological information or tools available for these species, or (ii) that those involved in creating SARA recovery strategies are simply less likely to draw on physiological data and techniques for these taxonomic groups. In support of the first possibility, there is evidence that arthropods tend to be underrepresented in the conservation physiology literature overall (Lennox & Cooke, 2014; Madliger et al., 2018). In contrast, physiological information was more likely to be found in recovery strategies for reptiles compared to other taxonomic groups. Many reptile strategies included information related to thermal physiology in their background information. Being ectotherms, an important component of habitat requirements for daily use and overwintering relates to thermoregulatory maintenance, and many strategies further indicated that a variety of threats can create disruptions to thermoregulation (e.g., through loss of basking sites, destruction of hibernacula, or potential for mortality on roads while thermoregulating). In addition, despite not being statistically significant (due to the relatively small number of Designatable Units), all strategies for amphibians included mention of physiological information, with many mentions pertaining to water balance and referring to the susceptibility of different species to evaporative water loss and dehydration.

The data presented in Mahoney et al. (2018) indicate that birds, arthropods, and mammals had the lowest proportions of mentions of physiology across taxonomic

groups; however, this was not analyzed statistically in their study. As a result, taxonomic patterns in physiological mentions appear similar for SARA and ESA recovery documents and both point to inconsistencies in the use of physiology across different taxonomic groups. The reason that both SARA and ESA recovery documents for birds contain less physiological information compared to other taxonomic groups is not readily apparent but could be due to the availability of/reliance on long-term demographic datasets (e.g., Breeding Bird Survey, Christmas Bird Count) for decision-making or that recovery teams for birds are less likely to include members with a background in physiological techniques. Physiological tools may also be viewed as less validated in birds. For example, in an assessment of articles published in the journal *Conservation Physiology* that focused on validating physiological tools or proposing novel techniques, only 8% of studies were completed in birds (Madliger et al., 2018). Future work will be necessary to explore the underlying reasons for these taxonomic discrepancies across geographic spaces.

When looking at how physiological information is being used in recovery strategies, we found that mention of physiology was most likely to occur in descriptions of an organism's background/life history (45% of strategies) and when assessing its threats (58% of strategies). These sections of a strategy contain previously collected physiological data that act to improve the description of species and their tolerances, as well as delineate the threats that are likely to be causing declines and/or delaying their recovery (see Figure 4 for examples). Meanwhile, physiology was rarely identified in strategies as an actionable item (16%) or as an area for future study (19%) (see Figure 4 for examples). These sections are directly influential in determining which conservation actions are undertaken in the action planning stage of SARA (SARA, 2002). Thus, the lack of physiological information in these sections suggests that new physiological information is infrequently being used to guide or monitor recovery efforts, despite its capacity for filling in knowledge gaps (e.g., regarding potential or existing threats that are still poorly understood; Birnie-Gauvin, Walton, et al., 2017), monitoring population recovery (Cooke et al., 2013), and incorporating captive breeding and/or translocation as recovery options (Birnie-Gauvin, Walton, et al., 2017). These results are consistent with what has been reported in the United States, where physiology is more often included in the natural history information compared to action-oriented (i.e., research- and application based) sections of ESA recovery plans (Mahoney et al., 2018).

Stress, bioenergetic, thermal, and immune metrics were more commonly incorporated in recovery strategies than information from any other physiological sub-discipline, while biochemical, cardiorespiratory, neuro/sensory, reproductive, and nutritional metrics were least commonly incorporated. Stress-related physiological data (e.g., measures of glucocorticoids such as cortisol and corticosterone) are frequently published in the conservation physiology literature (Dantzer et al., 2014; Lennox & Cooke, 2014; Madliger et al., 2018) and assessing stress responses to external stimuli can be useful for identifying which threats are responsible for population declines (Wikelski & Cooke, 2006). It is, therefore, not surprising that stress-related physiological measures were common, particularly when many accounts of physiology appeared in the threat assessment section of strategies. Similarly, given that disease is an important precursor to mortality (an easily interpreted fitness metric for all conservation practitioners), it is perhaps unsurprising that immune-related metrics were more common. As discussed above, thermoregulatory physiology was an important component of the recovery strategies of ectotherms in terms of defining habitat requirements, thereby bolstering its use overall. However, we were surprised to find that reproductive physiology was not more commonly referenced, as these data are known to be informative for captive breeding, rehabilitation, and reproductive monitoring scenarios, all of which can support species recovery (Asa, 2010; Madliger, Franklin, Chown, et al., 2021).

6 | RECOMMENDATIONS

In Canada, species at risk rarely recover, with only 5.4% of species that have been assessed multiple times being reclassified as not at risk (Favaro et al., 2014). Therefore, there are likely to be opportunities to improve recovery success (Kraus et al., 2021). Physiological tools are known to benefit conservation (Cooke et al., 2013; Madliger, Franklin, Love, & Cooke, 2021; Wikelski & Cooke, 2006) and, if applied effectively, have potential to benefit the recovery process. We acknowledge that the advantages of incorporating physiology will need to be balanced against monetary and time costs and sensitivities associated with handling and that even basic information such as distributions, habitat use, and threats is lacking for many species. However, advancing technologies, smaller and less invasive sample requirements, and the existence of databases that contain baseline information necessary to understanding physiological functioning in undisturbed regions (e.g., HormoneBase; Vitousek et al., 2018) should serve to increase applicability over time. Therefore, considering our results along with those reported by Mahoney et al. (2018) for ESA recovery plans, we have compiled recommendations for the future use of
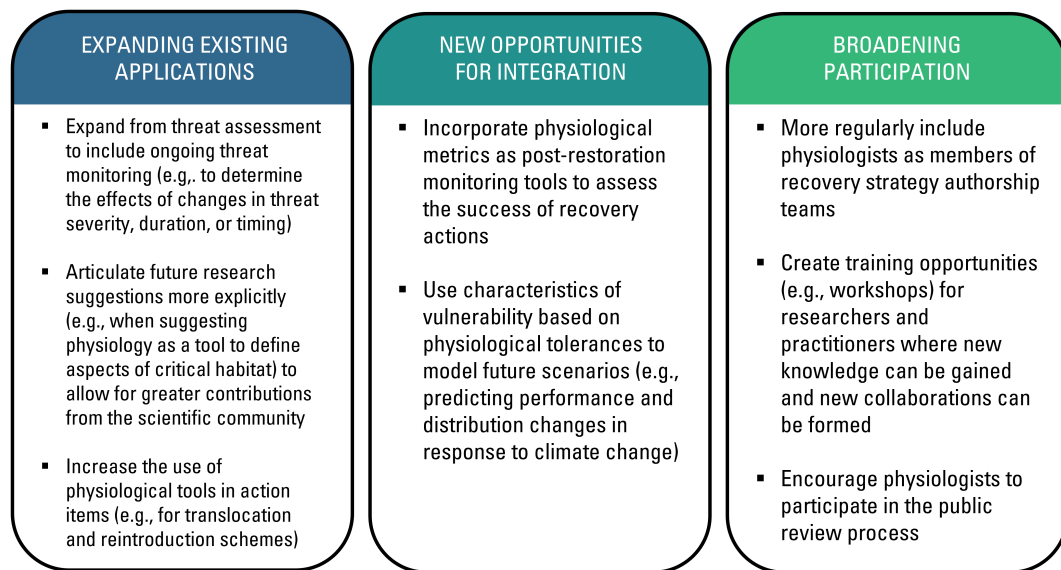
EXPANDING EXISTING APPLICATIONS	NEW OPPORTUNITIES FOR INTEGRATION	BROADENING PARTICIPATION
▪ Expand from threat assessment to include ongoing threat monitoring (e.g,. to determine the effects of changes in threat severity, duration, or timing) ▪ Articulate future research suggestions more explicitly (e.g., when suggesting physiology as a tool to define aspects of critical habitat) to allow for greater contributions from the scientific community ▪ Increase the use of physiological tools in action items (e.g., for translocation and reintroduction schemes)	▪ Incorporate physiological metrics as post-restoration monitoring tools to assess the success of recovery actions ▪ Use characteristics of vulnerability based on physiological tolerances to model future scenarios (e.g., predicting performance and distribution changes in response to climate change)	▪ More regularly include physiologists as members of recovery strategy authorship teams ▪ Create training opportunities (e.g., workshops) for researchers and practitioners where new knowledge can be gained and new collaborations can be formed ▪ Encourage physiologists to participate in the public review process

FIGURE 6 Summary of opportunities to expand and broaden the incorporation of physiology in species at risk recovery planning

physiology in global recovery planning (Figure 6). Given that there are at least 35 countries that have some form of legislation designed to prevent the extinction of wild species (Mooers et al., 2010), the recommendations we provide are designed to be useful for a range of recovery planning contexts.

6.1 | Expanding existing applications

There are ways that existing applications of physiology in recovery planning can be built upon and/or improved. We showed that physiology is clearly contributing to the initial assessment of threats (i.e., identifying which disturbances constitute a legitimate threat based on the measurement of a physiological response); therefore, an opportunity exists to incorporate physiological monitoring to verify whether certain threats continue to pose a risk (e.g., as they vary in severity, duration, or timing). We further identified that only 19% of SARA recovery strategies indicated physiology would be useful in future research scenarios. In some cases, the information is well articulated and clear. For example, in the whooping crane (*Grus americana*) strategy (2007), a future information need included "develop fecal corticosterone test to compare levels of stress associated with various management techniques in captivity." In contrast, other statements of information needs are less specific, such as the suggestion that researchers should "use laboratory studies to improve knowledge of wolffish physiology" (northern wolffish [*Anarhichas denticulas*] and spotted wolffish [*Anarhicas minor*] 2020). Further, while there was mention of physiology

in relation to critical habitat in the background of some strategies (e.g., thermoregulatory needs being an important factor of critical habitat for ectotherms), there was much less mention of physiology when critical habitat still needed to be defined for a species. A noticeable exception was the recovery strategy for leatherback turtles (*Dermochelys coriacea*) in Pacific Canadian waters which stated that "To determine the critical habitat of the leatherback in Canadian waters we must investigate the metabolic rate and food requirements." Physiological information (e.g., energy requirements and expenditure) can help test hypotheses as to which habitats are optimal and allow for the comparison of this data to occupancy and habitat selection processes (Cooke et al., 2013). This type of data can, therefore, identify underlying habitat needs, but also point to locations for restoration activities to increase the total availability of critical habitat. For instance, through an evaluation of energy use, Hasler et al. (2012) identified river reaches where migrating salmon were facing increased energy requirements, thereby pointing to prospective sites for restoration and increasing knowledge of necessary minimal flows. Therefore, consideration of physiological information could be beneficial in some cases for defining critical habitat and, in turn, potentially benefiting the overall recovery process, especially given that delays in the designation of critical habitat have been linked to continued species decline (Favaro et al., 2014). Overall, in instances where physiology is suggested as a tool to help fill a gap in knowledge, outlining the specific types of data that are needed would allow researchers to contribute more effectively to recovery goals.

Details regarding the suggested use of physiology in action-based items were more complete in comparison to those suggested in future research sections, with specific physiological metrics almost always being stated. For example, the demographic monitoring and inventory actions for the Vancouver Island marmot (*Marmota van-couverensis*) (2020) included the suggested use of trans-mitters that "record a pulse rate that can be correlated with body temperature...to determine whether an indi-vidual is alive during the active season, and whether they are active or hibernating in the spring and fall." There are certainly further opportunities for physiology to make actions in recovery documents more concrete, for instance by improving reintroduction or translocation suggestions by aiding in identifying ideal reintroduction sites, choosing candidates for release, monitoring and identifying ways to minimize capture and transport stress, determining risks following translocation, and monitoring post-release health and stress levels (Madliger, Franklin, Chown, et al., 2021; Tarszisz et al., 2014).

6.2 | New opportunities for integration

While there were a number of instances of physiological information being used to understand species' tolerances to temperature, pH, or toxins, the application of these data types to model how populations would change (see Bergman et al., 2019) was lacking. For instance, climate change is currently not considered explicitly in the recov-ery planning process for Canada (i.e., it is considered for some Designatable Units but not others), despite the immense threat it poses for many species and the poten-tial complexity it could impart for successful manage-ment (Kraus et al., 2021). Physiological assessments are highly relevant for understanding responses and vulnera-bilities to climate change (i.e., mechanistic distribution modeling; Dahlke et al., 2020; Madliger, Franklin, Chown, et al., 2021; Somero, 2010). Along with behav-ioral, genetic, and traditional demographic tools, physiol-ogy could represent a component of assessing climate change risk in recovery strategies.

We also did not document any use of physiology as a performance metric to assess recovery and/or the success of management actions. Physiological metrics can be employed as a variety of indicators including leading (to inform preventative actions), coincident (to measure current status), and lagging (to assess change resulting from actions) (sensu Kraus et al., 2021). For example, Alaux et al. (2017) found that honey bee (*Apis mellifera*) physiology (body fat and vitellogenin levels) reflected the positive effects of habitat restoration (increased flowering

catch crops and semi-natural habitats which lead to increased pollen diet diversity). Importantly, vitellogenin levels were linked to overwintering survival, indicating that monitoring physiology can provide insight on the fitness-related effects of habitat restoration. The measure-ment of reproductive hormones and fecal glucocorticoids has also been used to assess the effects of de-horning as a management strategy for the endangered white rhinoc-eros (*Ceratotherium simum*), providing evidence that this anti-poaching tactic does not have long-term effects on reproductive function or stress levels (Penny et al., 2020). Together, these examples illustrate the potential power of physiological approaches as post-management monitor-ing tools.

6.3 | Broadening participation

We also anticipate opportunities to generally broaden the participation of conservation physiologists in the recovery planning process. The majority of conservation physiolo-gists active in research currently hold academic positions (Madliger, Love, Nguyen, et al., 2021), so expanding authorship teams to include these individuals would likely change the content of recovery strategies. Besides writing the strategies, conservation physiologists could more actively participate in public reviews and com-menting periods for recovery strategies. It is possible that many physiologists who do not work directly with species at risk may be unaware that these review periods exist. Such information could be shared at national conferences or through newsletters or websites associated with scien-tific societies to raise awareness similar to how wildlife organizations such as the Canadian Wildlife Federation, Center for Biological Diversity, and The Wildlife Society regularly use news stories and/or press releases on their websites to share opportunities to contribute to public review processes. More training opportunities in physio-logical tools and techniques could also be offered to the species-at-risk community via workshops, courses, or other professional development opportunities. For exam-ple, many workshops that highlight physiological tools have been organized for conferences, conservation socie-ties, or special topics meetings that bring together govern-mental, academic, veterinary, and not-for-profit participants, such as the "Stable isotope analysis in stud-ies of marine mammal ecology and ecophysiology" work-shop (Society for Marine Mammalogy, 2017); "Mollusk health and disease" workshop (Freshwater Mollusk Con-servation Society, 2018); and the "Wildlife conservation physiology in a changing world workshop" (University of the Witwatersrand, 2022). These endeavors would not only increase awareness of conservation physiology but

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lead to the creation of new collaborations and dispel some of the negative connotations associated with physiology that are held by some conservation scientists (e.g., that physiological tools are too invasive) (Madliger, Love, Nguyen, et al., 2021). Starting in undergraduate settings, educating physiology students in conservation management principles and recovery planning, and educating conservation science students in physiology might similarly improve the integration between physiology and species-at-risk work long-term. Even in jurisdictions without a formal recovery strategy process, having people trained as diversely as possible could benefit species recovery projects.

7 | CONCLUSIONS

Our assessment of the role of physiology in SARA recovery strategies in Canada, when considered in combination with other literature, reveals opportunities for the integration of physiological information in recovery planning. We acknowledge that many data limitations exist for other aspects of species at risk biology (including distributions, habitat preferences, and demographics) and that not all species will be able to benefit meaningfully from a consideration of physiological knowledge and tools. Therefore, identifying cases based on our recommendations where physiological information would be particularly useful and feasible to obtain will be key to successful implementation. Although we focused on a Canadian case study for our analysis, our recommendations that physiology can be used to help (i) monitor ongoing threats or assess understudied emerging threats; (ii) improve descriptions of critical habitat; (iii) contribute to recovery actions, such as translocations; (iv) monitor the success of recovery actions; and (v) predict vulnerability to future environmental change (e.g., climate change) are useful for generally improving recovery planning globally. As techniques are developed, validated, and improved, the potential applications can only grow. Physiology represents a way to incorporate biological data more holistically into recovery planning, which is known to reduce time lags between listing and action. In turn, we anticipate increased certainty associated with threat designation and monitoring, an enhanced ability to predict responses to disturbance or management techniques, and the establishment of more diverse recovery actions.

CONFLICT OF INTEREST
The authors have no conflict of interest to declare.

DATA AVAILABILITY STATEMENT
The data used in this study are publicly available on Zenodo: https://doi.org/10.5281/zenodo.6383409.

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