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On the relevance of animal behavior to the management and conservation of fishes and fisheries

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Abstract There are many syntheses on the role of animal behavior in understanding and mitigating conservation threats for wildlife. That body of work has inspired the development of a new discipline called conservation behavior. Yet, the majority of those synthetic papers focus on non-fish taxa such as birds and mammals. Many fish populations are subject to intensive exploitation and management and for decades researchers have used concepts and knowledge

from animal behavior to support management and conservation actions. Dr. David L. G. Noakes is an influential ethologist who did much foundational work related to illustrating how behavior was relevant to the management and conservation of wild fish. We pay tribute to the late Dr. Noakes by summarizing the relevance of animal behavior to fisheries management and conservation. To do so, we first consider what behavior has revealed about how fish respond to

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key threats such as habitat alteration and loss, invasive species, climate change, pollution, and exploitation. We then consider how behavior has informed the application of common management interventions such as protected areas and spatial planning, stock enhancement, and restoration of habitat and connectivity. Our synthesis focuses on the totality of the field but includes reflections on the specific contributions of Dr. Noakes. Themes emerging from his approach include the value of fundamental research, management-scale experiments, and bridging behavior, physiology, and ecology. Animal behavior plays a key role in understanding and mitigating threats to wild fish populations and will become more important with the increasing pressures facing aquatic ecosystems. Fortunately, the toolbox for studying behavior is expanding, with technological and analytical advances revolutionizing our understanding of wild fish and generating new knowledge for fisheries managers and conservation practitioners.

Keywords Ethology · Fish behavior · David Noakes · Conservation behavior

Introduction

The study of animal behavior (including both ethology and behavioral ecology) has a long history, but it was not until Konrad Lorenz, Niko Tinbergen, and Karl von Frisch were awarded the 1973 Nobel Prize in Physiology and Medicine for their research on individual and social behavior patterns that animal behavior was widely embraced as a formal discipline (Moreno and Muñoz-Delgado 2007; Goodenough et al. 2009). Notably, Tinbergen's famous four questions, which serve as categories of explanation for animal behaviors (Tinbergen 1963), have withstood

the test of time and still represent the dominant paradigm in animal behavior scholarship (Bateson and Laland 2013; Burkhardt 2014). The field has further developed with effort focused on understanding the fundamentals and foundations of animal behavior (Houck and Drickhamer 1996) and an emphasis on animal-environment interactions (i.e., behavioral ecology; Owens 2006). Yet, animal behavior also has applications in quantifying and enhancing animal welfare (Mench 1998), increasing production in agri/aquaculture (Baxter 1983), training of companion animals (Horwitz 2008), and for informing the conservation and management of wildlife (Sutherland 1998). The latter application — conservation and management of wildlife — has developed into its own discipline known as conservation behavior (Blumstein and Fernández-Juricic 2004) (Fig. 1).

Conservation behavior was formally acknowledged as a discipline beginning in the 1990s and early 2000s with the publication of several conceptual papers (Sutherland 1998; Buchholz 2007; Caro and Sherman 2011; Caro 2016) and books (Caro 1998; Blumstein and Fernández-Juricic 2004; Berger-Tal and Saltz 2016) that illustrated the benefits of animal behavior research for addressing conservation and management problems. This acknowledgement was followed by articles that took a more pessimistic view towards the interface of behavior and conservation (see Caro 2007; Angeloni et al. 2008), as well as the publication of a conceptual framework (Berger-Tal et al. 2011). Today, many examples demonstrate how animal behavior has helped us understand how humans affect wildlife (Tuomainen and Candolin 2011; Wong and Candolin 2015) and how animal behavior is increasingly used to improve conservation and management interventions (Blumstein 2015). However, existing syntheses on conservation behavior contain few examples with fishes, while examples with birds, mammals, herpetofauna, and even invertebrates are featured prominently. We regard this lack of focus on fishes to be a simple oversight given the taxonomic foci of most of the authors of conservation behavior synthesis papers.

Fishes are the most speciose group of vertebrates (Helfman et al. 2009). They can be found from high elevation freshwater lakes to the abyss of ocean basins and from the Amazon River to under the Antarctic Ice Shelf. Global marine and freshwater fish populations face a number of threats. Indeed, there is

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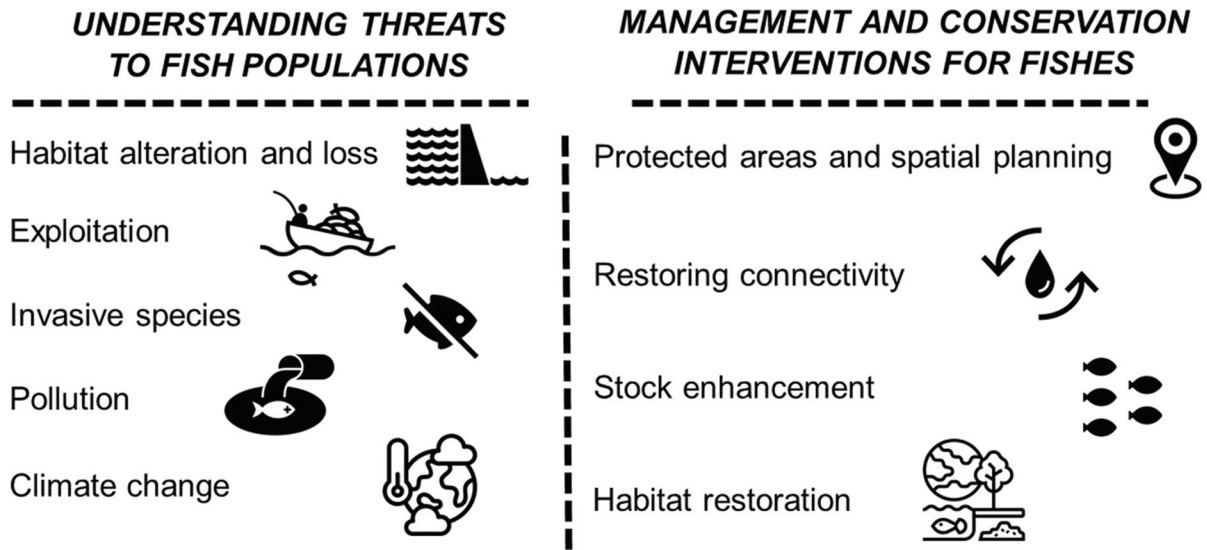


Fig. 1 Graphical depiction of the ways in which animal behavior is relevant to understanding threats to fish populations and informing the conservation and management of fishes

ample evidence documenting widespread population declines linked to various threats (Arthington et al. 2016; Gordon et al. 2018; Reid et al. 2019) and the identification and mitigation of key threats is urgently needed so that fish populations can be conserved or restored. Moreover, for fish populations that are doing well, there is a need to ensure that management actions are effective. Fish provide numerous ecosystem services including some with direct benefit to humans by supporting nutritional security (Islam and Berkes 2016), and livelihoods and cultures (Holmlund and Hammer 1999; Lynch et al. 2016), which provide compelling examples of why fish populations need to be managed sustainably. Underpinning the contemporary science-based management and conservation of fishes is an evidence base that brings together stock assessment data and knowledge of fish biology, physiology, genetics, and behavior.

Many researchers who study the behavior of fishes do so with the goal of generating knowledge that can be used by decision makers to achieve conservation and management objectives. Over the years, there have been a few highly focused reviews, such as applications of behavior in freshwater fisheries (O’Hara 1986), in stock assessment (Fréon et al. 1993), or on applications of acoustic telemetry

tracking data to management (Crossin et al. 2017). The only synthesis on the relevance of animal behavior to fisheries and fish conservation (i.e., Shumway 1999) was published two decades ago in *Environmental Biology of Fishes* as part of a special issue on behavior and fish conservation (see Volume 55, Issue 1–2; Helfman 1999). This topic was of great interest to the late Dr. David L. G. Noakes — the long serving Editor of *Environmental Biology of Fishes*, as well as our friend, colleague, and mentor. Dr. Noakes was an influential behaviorist (see Muir 2022) who did foundational work illustrating how behavior was relevant to the management and conservation of wild fishes. Here, we pay tribute to Dr. Noakes by summarizing the relevance of animal behavior to fisheries management and conservation, with a focus on key threats to fishes, as well as common management interventions. This synthesis focuses on the totality of the field, but we also include a section where we summarize some of the unique contributions of Dr. Noakes and reflect on some of the themes that emerged from his work. Our synthesis spans freshwater and marine systems and is intended to be a resource for those with an interest in the application of behavioral tools, concepts, and knowledge to managing and conserving wild fish populations.

On the functional links between behavior, fitness and populations

To contextualize why those responsible with managing and conserving fishes should be concerned with fish behavior, we first provide a brief summary of the functional links between behavior and fitness with links to population-level processes. Behavior is fundamental to the organism-environment relationship (Owens 2006) whereby the environment can both constrain or stimulate behaviors, often operating through physiological mechanisms (e.g., energetics, locomotion, endocrinology; Ricklefs and Wikelski 2002). The behavior of individuals can affect their fitness (i.e., survivorship and lifetime reproductive success; Sutherland 1996). For example, activities such as foraging, social interactions and antipredator behavior are involved in the demographic performance of individuals via their influence on growth, condition, and reproductive rate/output (Sumpter and Broomhead 2001). Individual behavioral decisions (e.g., if and when to migrate, which habitats to occupy, when to forage vs seek refuge) can influence population parameters such as recruitment, population abundance, age at maturity, number of reproductively active adults, and mortality rates, among others (McNamara and Houston 1986). Conservation practitioners and resource managers tend to be primarily concerned with population-level processes (e.g., are they increasing, decreasing, stable), yet it is individual-level behavior (and physiology) that directly connects animals (including fishes) to their environment (Cooke et al. 2014; Horodysky et al. 2015; Bailey et al. 2022) and at times, their vulnerability to harvest/exploitation (e.g., Horodysky et al. 2015; Sbragaglia et al. 2022). As such, it is through the environment that stressors are often applied and realized on behavior and fitness (Killen et al. 2013). Behavior can vary greatly among individuals in the same population with individuals and groups responding differently to natural and anthropogenic threats and management actions (Goss-Custard and Sutherland 1997, Villegas-Ríos et al. 2022) and thus, contributing to variation in fitness across multiple scales (Smith and Blumstein 2008).

Relevance of animal behavior to understanding threats to fish populations

Habitat alteration and loss

Fishes have evolved a rich diversity of behaviors that allow them to exploit the environment and habitats around them to ultimately maximize their fitness. Whether a fish requires thousands of kilometers of riverine habitat, or a single cave within a coral reef, intact habitats and corridors among habitat patches are critical to sustain fish behaviors and life histories. In recent decades, habitat alteration and loss have intensified within aquatic ecosystems, particularly the degradation of lotic systems to support various human uses (e.g., energy production, flood control, irrigation, agriculture, sand mining; Tickner et al. 2020). As habitat is altered or lost, the fitness benefits associated with that habitat are altered, changing the way that fish behave in those environments. Indeed, fish behavior is dynamic and substantial plasticity in behavioral responses to environmental change is evident (Pitcher 1992).

Understanding of the behavioral ecology of fishes, and the interactions between fishes and their environments, can provide important insights into the effects of habitat loss and alteration on fish species (Scherer 1992). Many tools exist to study the behavior of fish in altered and fragmented landscapes (e.g., telemetry, mark-recapture, direct/video observation; Hussey et al. 2015). Regardless of the tool employed, the premise is that changes in fish behavior resulting from habitat change are a useful indicator of the influence of those impacts on the individual fish. As such, it is critical that the behavior of fish is compared to that of fish unimpacted by habitat alteration. As an example, in South America, migratory fish in dammed river reaches are generally unable to move upstream beyond dams, and they also tend to avoid the slow, lentic habitat associated with the reservoirs upstream of dams (Pelicice et al. 2015). Similarly, low-head barrier dams that were installed or maintained to limit migrating adult invasive sea lamprey (*Petromyzon marinus*) from accessing spawning habitat in rivers flowing into the Laurentian Great Lakes also restrict the upstream movement and reduce the biodiversity of desirable (non-target) species (see Table 1; Porto et al. 1999; Dodd et al. 2003; McLaughlin et al. 2006). In Lake Erie, one of the Great Lakes,

Table 1 David Noakes' contributions to the behavior, management, and conservation of fishes

Category	Sub-category	Findings	References
Threats	<i>Habitat alteration and loss</i>	Fish biomass and production is lower in channelized than in natural stream sections	Portt et al. 1986
		Brook Trout (<i>Salvelinus fontinalis</i>) are less reactive to disturbance in habitats with abundant habitat structure	Grant and Noakes 1987
		Young Brook Trout seek out velocity refuges to save on swimming costs without affecting foraging rate	McLaughlin and Noakes 1998
		Spawning areas for Brook Trout were positively associated with areas of groundwater discharge, which protected redds from ice	Curry and Noakes 1995; Curry et al. 1995
		Short-term variability in discharge caused by hydroelectricity peaking regimes could have negative effects on natural groundwater supply around Brook Charr redds	Curry et al. 1994
	<i>Invasive species</i>	Low head barrier dams used to restrict the upstream movements of sea lamprey in streams have negative effects on the movement and biodiversity of non-target species	Porto et al. 1999; Dodd et al. 2003; McLaughlin et al. 2006
		Non-native male Chinook Salmon (<i>Oncorhynchus tshawytscha</i>) interfere with the reproduction of Atlantic Salmon impeding re-introduction efforts in Lake Ontario	Scott et al. 2003; Scott et al. 2005c
		Non-native juvenile Chinook Salmon and Brown Trout (<i>Salmo trutta</i>) negatively affect the behavior of re-introduced Atlantic Salmon	Scott et al. 2005b
	<i>Pollution</i>	Non-native Atlantic Salmon are able to navigate using the geomagnetic field, perhaps facilitating their invasion of novel habitats	Scanlan et al. 2018
		Brook Trout alevins avoid low pH and elevated concentrations of aluminum, facilitating survival in acidifying waters	Gunn and Noakes 1986
Pulse exposure to acidic Aluminum-rich water has negative effects on the fitness of Lake Trout embryos		Gunn and Noakes 1987	

Table 1 (continued)

Category	Sub-category	Findings	References
Management interventions	<i>Protected areas and spatial planning</i>	Territorial behavior limits population density and potentially regulates population abundance of stream-dwelling Salmonids	Cole and Noakes 1980; McNicol and Noakes 1981; McNicol and Noakes 1984; Grant et al. 1989
		Aggressiveness, mobility and trophic specialization are inherited traits of juvenile Charrs, which facilitates adaptation to diverse habitats and ecological speciation	Ferguson and Noakes 1982; Ferguson and Noakes 1993
		Magnetic maps are inherited traits of Salmonids, facilitating their migratory life history patterns	Putman et al. 2014b
	<i>Restoring connectivity</i>	Removal of barriers promotes the movement of stream fishes and increases upstream species richness	Porto et al. 1999; Dodd et al. 2003
		Glass eels use two forms of locomotor behavior, active swimming and vertical climbing which facilitate their swimming into rivers and then over barriers	Linton et al. 2007
	<i>Habitat restoration</i>	Rainbow Trout held in high-density conditions suffered from higher levels of physiological stress than those at lower densities	Noakes and Leatherland 1977
		Reproductive behavior of captive-bred Atlantic Salmon is sufficiently natural to expect some success of restoration programs	Scott et al. 2005a
		Salmonids imprint on their natal magnetic fields, so rearing Salmonids in locations with unnatural fields may hinder attempts to stock or reintroduce populations	Putman et al. 2013; Putman et al. 2014a
		Exposing Salmon embryos to the olfactory signature of sites for future stocking may improve reintroduction success	Scanlan et al. 2018
		The success of restoration programs for Charrs will depend on the strengths of competition and predation in target fish community	Noakes and Curry 1995

hypoxic bottom layers caused by agricultural nutrient input displaced benthic fishes, changing the vertical distribution of prey fishes to the benefit of walleye (*Sander vitreus*), a key fishery target species (Brandt et al. 2011). Behavioral changes such as these are a clear indication of the impacts that habitat loss and alteration can have on fish fitness, and for species

with specific niches or habitat requirements, large-scale habitat alterations can result in a complete loss of lifetime fitness (e.g., Pacific salmon *Oncorhynchus* spp.; Groot and Margolis 1991). With the staggering amount of fish movement and habitat use data generated by fish telemetry tracking, it seems likely that in the near future we will see many powerful examples

of how those data can be used to quantify the effects of habitat change and loss on the behavior of fishes.

Exploitation

Somewhat ironically, exploitation (and overfishing) of fish stocks has been, in part, supported by our ever-growing understanding of the behavior of fishes (including traditional and Indigenous ecological knowledge), with early fishing settlements forming around accessible areas where fish aggregate in high abundance (e.g., kelp forest, coral reefs; Steneck and Pauly 2019), along migration routes, or at spawning sites (Sahrhage and Lundbeck 2012). Through the industrialization of fishing, the spatial extent and magnitude of exploitation has increased, leading to regional extirpation and ultimately the collapse of some fisheries. Indeed, exploitation is the most important threat to at-risk marine fishes in Dr. Noakes' home country of Canada (Woo-Durand et al. 2020). While information is less certain for inland systems and smaller fisheries (Deines et al. 2017; Hilborn et al. 2020; Ovando et al. 2021), exploitation ranks as the 4th most important major threat to freshwater fishes in Canada (Woo-Durand et al. 2020) and Dr. Noakes' adopted country of the USA (Wilcove et al. 1998). While the diversity of fishes and fish behavior was a driving force behind the range of capture methods that have been developed (Wardle 1986), the more formal study of fish behavior in the context of improving fisheries and fishing technology did not arise until the 1950s (Fréon and Misund 1999). This quickly expanded, however, to also develop more effective stock assessment and habitat or population protections to reduce exploitation and work within more tractable catch limits.

In addition to exploitation reducing the size and persistence of a fish stock, it may also alter the life history or behavior of the fishes that remain within the population by preferentially selecting for behavioral phenotypes that reduce catchability, which can lead to fisheries-induced evolution (Kuparinen and Merila 2007; Uusi-Heikkilä et al. 2008). For example, passive fishing approaches (e.g., gill nets, trapping, angling) preferentially catch bold, aggressive, or more active individuals, while more active gear (e.g., trawling, seining) captures shy or social individuals (Biro and Post 2008; Arlinghaus et al. 2017; Monk et al. 2021). In the former case, bias in capture

can result in exploitation-induced timidity syndrome, whereby individuals that remain in a population may struggle to maintain social groupings, fail to reach their spawning grounds, or exhibit overall reductions in their dispersal and movement (Arlinghaus et al. 2017). Given the documented correlation between some behaviors (e.g., boldness or aggressiveness) and life history parameters (e.g., size at maturity or growth; reviewed in Biro and Stamps 2008), selection for specific behaviors within populations may result in lower yield, smaller stock sizes, or reduced catchability (Jørgensen et al. 2007; Arlinghaus et al. 2017; Guerra et al. 2020). Alternatively, behavioral diversity can provide resilience to a stock, such as Pearly Razorfish (*Xyrichtys novacula*) in Mallorca; Alos et al. (2015) found that daytime chronotypes of the Razorfish were most vulnerable to fishing but this phenotype was not heritable, so nighttime chronotype fish could evade capture and replenish the population, a behavioral buffer to overexploitation.

Considering protection of diverse behavior and life history phenotypes (see Shumway 1999) remains a conceptual and pragmatic challenge for fisheries managers. Management options may include temporal or spatial restrictions on fishing or adjustments in the type of fishing gear, but regardless of the method, the approach should aim to protect the portfolio of observed variation in behavior of the targeted species (Olsen et al. 2012). Sound management practices can support the recovery of overexploited stocks and prevention of exploitation of stocks that are currently stable (Hilborn et al. 2020), and a species' behavioral ecology will be essential in informing the development of such practices. Animal behavior (often alongside sensory physiology; Elmer et al. 2021) can also be exploited to develop bycatch mitigation strategies such as those that reduce bycatch by identifying how to spatio-temporally focus fishing efforts on target species (O'Keefe et al. 2014) or that involve study of gear types to identify opportunities for avoiding bycatch (Parsons et al. 2012; Martin and Crawford 2015).

Invasive species

Behavior plays an essential role in mediating species invasions, including the traits of species that determine their invasiveness, as well as those of native organisms that enable species invasions (Holway and

Suarez 1999; Weis and Sol 2016) and developing and implementing control or eradication methods (e.g., Bravener and McLaughlin 2013). Species invasions are also a dynamic multi-stage process where behavioral interactions change, often resulting in alterations to the behavioral tendencies of both native and invasive species (Ruland and Jeschke 2020). Synthesizing the role of behavior in species invasions, Sol and Weis (2019) concluded that invaders generally exhibit high levels of behavioral plasticity that facilitate their success in novel environments and that behavior is linked with many traits that affect invasiveness, including life history traits. Invaders often experience high resource availability and low predation pressure, which may contribute to more bold, aggressive, and highly dispersive behavioral phenotypes relative to native counterparts or even invaders in longer established areas (Myles-Gonzalez et al. 2015). However, this is not always the case based on a study of pumpkinseed in their native and introduced range where native fish were more bold (Ashenden et al. 2017). Bold, aggressive behavioral characteristics can also help invaders to outcompete native species that occupy a similar niche and drive invasion expansion through intraspecific competition (Hudina et al. 2014). For example, Noakes and colleagues suggested that inter-specific competition from non-native brown trout *Salmo trutta* and Pacific salmon were impeding the attempts to restore Atlantic salmon *Salmo salar* to Lake Ontario (Scott et al. 2003, 2005b, c; Table 1). Predator release often occurs due to behavioral factors, where native predators are present with the physical capacity to prey on the invader, but the predators fail to adapt to a new prey source because they do not recognize it as prey or lack the hunting tactics to effectively prey upon them (Sih et al. 2010). Similarly, prey species can also fail to detect, recognize and avoid novel invasive predators and experience high predation rates.

In the context of management, knowledge of species traits, including behavior, can help identify high-risk invaders and proactive steps to reduce the potential for their introduction and spread (Kolar and Lodge 2001). In cases where invasive species have become established, the behavioral responses of predators and prey often determine the longer-term role of the invader and changes to community structure in non-native ecosystems. For example, Round Goby (*Neogobius melanostomus*) have

become hyper-abundant in established areas of the Great Lakes basin of North America. Further, Round Goby have become important prey for many predators, such as Smallmouth Bass (*Micropterus dolomieu*), resulting in increased growth rates and abundance (Steinhart et al. 2004; Morissette et al. 2018). Efforts may also be undertaken to help to condition native predators to effectively prey upon novel invasive species, such as culling invasive Lionfish (*Pterois* spp.) by helping sharks and groupers learn that lionfish are potential prey (Diller et al. 2014). However, in most instances, behavioral conditioning is unlikely to be a stand-alone solution to controlling or mitigating an established invasive species and its impacts.

Understanding the invasion potential of species to reduce their introduction is the only known and highly effective means of combatting the negative effects of introduced species. Indeed, once established, invasive species are nearly impossible to eradicate and expensive to control. For example, low-head barriers have been critical to the control of invasive Sea Lamprey in the Laurentian Great Lakes, North America. The barriers reduce the amount of tributary spawning habitat that Sea Lamprey can access and the amount of larval rearing habitat that is treated with chemical lampicides (Hrodey et al. 2021). However, as Noakes and his students have shown, these barriers also restrict the movement of native fishes (Porto et al. 1999), impact habitat (Dodd et al. 2003), and affect the distribution and abundances of native species (McLaughlin et al. 2006; see Table 1). Thus, our need to control invasions must also be balanced with our need to conserve native species. Once established, species invasions are dynamic and the behavioral characteristics of both invaders and native species change through time, which can have cascading effects on ecosystem structure and vulnerability to subsequent invasions (Ehrenfeld 2010). Knowledge of the behavior of invasive fishes derived from telemetry studies (reviewed in Lennox et al. 2016) is increasingly revealing opportunities for control by identifying areas of aggregation where control measures can be applied (e.g., identifying tributary use of Grass Carp [*Ctenopharyngodon idella*] in Lake Erie to guide the deployment of nets and electrofishing used to catch and remove the carp; Harris et al. 2021).

Pollution

A variety of pollutants (e.g., acidity, metals, pesticides, pharmaceuticals) can have detrimental consequences for aquatic species and ecosystems (Gunn and Noakes 1986, 1987; Saaristo et al. 2018). Measurements of physiology and fitness are commonly used when assessing the effects of aquatic pollution (e.g., Gunn and Noakes 1987). In contrast, the measurement of behavioral change associated with pollutants has garnered less attention (Jacquin et al. 2020), despite its proposed use in ecotoxicology dating back over 50 years (Warner et al. 1966) and the recent emergency of behavioral ecotoxicology (Ford et al. 2021). The earliest suggestions of why behavioral indicators have the capacity to be used as indices of sub-lethal toxicity still stand true (Dell’Omo 2002): they are an integrated result of many biochemical and physiological responses, tend to be sensitive, and can be obtained non-invasively (Warner et al. 1966). Avoidance responses of brook trout alevins in redds were crucial to their ability to survive pulses of low-pH conditions (Gunn and Noakes 1987; Table 1). Beyond avoidance responses, pollutants can alter much more complex forms of behavior. Acidification, herbicides, and thermal effluent can interfere with fish reproduction by influencing nest-building activity, courtship, offspring defence, and parental care (Jones and Reynolds 1997). More recently, attention has also been placed on the behavioral effects of non-chemical pollutants such as light and noise. For example, light pollution was shown to increase overall activity levels and disrupt the circadian rhythm of activity in nesting Smallmouth Bass, with potential consequences for energy use during a highly demanding life history stage (Foster et al. 2016). Pollution can similarly interfere with group behaviors. Groups of juvenile Seabass (*Dicentrarchus labrax*) exposed to playbacks of marine pile-driving are less able to coordinate their movements, showing less correlated directional and speed-related changes, cohesiveness, and directional ordering (Herbert-Read et al. 2017). Reproductive ecology could also be affected in organisms such as Burbot (*Lota lota*) which use drumming muscles on their swim bladder to generate noises coincident with their under-ice spawning (Cott et al. 2014). This

intimate communication could be compromised by ice-road noise in northern regions (Cott et al. 2012).

Collectively, mounting evidence shows that behavioral responses to pollutants form an important link in understanding how pollutants influence individual fitness, population persistence, and ecosystem health, and therefore, the level of threat a pollutant poses (Jacquin et al. 2020). As links between sublethal behavioral effects and fitness are established, there will be potential to incorporate behavioral assays as more formal components of overall threat assessment and decision-making for fish populations in relation to a broad suite of pollution types (Jones and Reynolds 1997). By understanding how responses may change with varying levels of pollution, behavior also permits researchers and managers to predict the outcomes of pollution episodes and prioritize mitigation efforts (Jacquin et al. 2020). Understanding how pollutants impact avoidance and exploration behavior also has applications for determining how larger-scale processes in wild populations, such as migration or habitat selection, may be affected by increasing pollution levels (Malik et al. 2020).

While the application of behavior to the management of fishes facing pollution is gaining more traction, a number of research areas are ripe for further attention. First, much of the information we have about the influence of pollution on fish populations comes from studies investigating a single pollutant at a time. However, many individuals can be impacted by multiple types of pollution simultaneously, requiring studies that take a multi-stressor approach (McCarthy et al. 2008; Jacquin et al. 2020). Second, measuring multiple behavioral traits to gain more complete information on how fishes are responding to different forms of pollution can be a valuable approach. For example, marine noise pollution can affect swimming, shoaling, exploration, predator avoidance, nest attendance, territoriality, and sheltering behaviors, but rarely has more than one behavior been measured in the same study (Di Franco et al. 2020). Lastly, we still lack understanding on the level of inter-population variability in behavioral responses to pollutants (Jacquin et al. 2020). For instance, in the Laurentian Great Lakes, cleanup of many heavily polluted areas of concern (AOCs) has resulted in recolonization by fishes such as Lake Sturgeon (*Acipenser fulvescens*) and Lake Whitefish (*Coregonus clupeaformis*). While the exact mechanism is unknown, enhanced water

quality is hypothesized to be a factor (Manny et al. 2015). However, this variation is highly relevant to determining how susceptible different populations may be to specific pollutants, and therefore how to best predict changes and manage them.

Climate change

Behavioral variation in fishes complicates our ability to project how they will respond to global climate warming, especially for species that live in thermally heterogeneous environments. Behavioral thermoregulation has long been studied in fishes (Keenleyside and Hoar 1954; Ferguson 1958; Magnuson et al. 1979) and some species clearly are adept at using temperature variability to their advantage. For example, Dogfish (*Scyliorhinus canicula*) make diel vertical migrations along a north-temperate sea mount to rest in deeper, cooler waters at night — a behavior that was conclusively motivated by a bioenergetic benefit rather than being caused by prey availability or predation risk (Sims et al. 2006). Bonefish (*Albula vulpes*), a species of the coastal tropics, shifted their foraging behavior to avoid what was otherwise a preferred nearshore foraging habitat when nearshore water temperatures reached upper extremes (Brownscombe et al. 2017). Temperate freshwater fishes experience dynamic temperatures. For example, habitat use by Lake Trout (*Salvelinus namaycush*) shifts seasonally as the thermal profile of lakes change, with concomitant changes in energy transfer and effects on prey fish communities (Guzzo et al. 2017). Knowledge about how fishes thermoregulate in the field can be useful for bioenergetic modeling to project future variability in growth and reproductive output. In Lake Erie, water temperature appears to at least partially drive an annual basin-wide migration of Walleye (*Sander vitreus*; Kershner et al. 1999, Raby et al. 2018). Knowing the temperature thresholds that cause fish to migrate or shift habitats could be useful from a fisheries planning standpoint, because fish movement can affect fisheries prosecution, assessment, and management (Sims et al. 2004; Crossin et al. 2017). It might be possible to use data now widely being generated with electronic tags (e.g., biologging and biotelemetry) to develop spatially and temporally explicit bioenergetic models that consider within and among individual variation in body temperature (Brownscombe et al. 2017), as long as appropriate

bioenergetic calibrations are available for the species and sensor types being deployed.

The terrestrial ecology literature is replete with examples of how climate warming can cause phenological mismatches, whereby behaviors (e.g., migration) are either set based on photoperiod, and therefore, inflexible to changes in temperature, or triggered by temperature in ways that can be maladaptive when temperature regimes change dramatically (Robinson et al. 2009). In fishes, there are fewer examples, but the same types of behavioral problems can occur in response to a changing climate. Sockeye Salmon (*Oncorhynchus nerka*) have a relatively fixed schedule for their spawning migration. With the aid of geomagnetic imprinting (Putman et al. 2013; Table 1), migration begins hundreds or thousands of kilometers from river entry and ends in streams and rivers that drain into lakes upstream of the marine environment (Farrell et al. 2008). The relative inflexibility in timing of these migrations has up to now, appeared to be a problem, particularly for fish migrating upstream in summer that are encountering warmer temperatures, sometimes causing high en route mortality (Martins et al. 2011). Even if summer-run stocks were to shift their migration timing to late summer or early fall when temperatures are cooler, that would reduce among-stock diversity in spawn timing which in turn makes fisheries management more difficult (Schindler et al. 2010). Unlike Salmon, Sims et al. (2004) found that the timing of Flounder (*Platichthys flesus*) migration is sensitive to thermal variation, with profound implications for fisheries planning.

Apart from movement and migration, the thermal choices of fish in the laboratory can be used to predict their ecologically optimal temperature range in the wild. A variety of behavioral arena designs have been used to do so over the years (Christensen et al. 2021). In most cases, laboratory experiments are the only way to assess the ‘true’ thermal preferences of fishes (because other influences like food and predators can be controlled in the lab), but thermal preference behavioral tests have not proliferated widely (e.g., unlike the use of CTmax, or respirometry, to assess thermal performance), perhaps because the experiments are time-consuming and technically challenging (Speers-Roesch and Norin 2016). Animal-borne electronic tags with temperature sensors, in thermally mapped environments, can in some cases provide clear signals about what temperatures fishes prefer or

avoid (Peat et al. 2016). Extensive mapping of thermal macro- and micro-habitat can be challenging, especially at biologically meaningful scales where secondary inputs and seeps can provide thermal refuge at difficult-to-measure scales. Nevertheless, effective examples exist, such as in a Canadian lake that became isothermal and reached supra-optimal temperature for Lake Trout. Here, telemetry-tracked Lake Trout congregated in the cold water plume from a groundwater discharge site that provided thermal refuge (Snucins and Gunn 1995). In Atlantic Salmon parr, conspecific chemical cues appear to help fish locate thermal refuge during severe heat waves (Elvidge et al. 2017). Spawning Brook Trout prefer to spawn in areas of groundwater discharge, which protect redds from the increasing variation in temperature that will accompany climate change (Curry and Noakes 1995; Curry et al. 1995; Table 1). Ultimately, understanding a given species' behavioral preferences and tendencies around temperature is useful for mapping available habitat and projecting future changes, both of which can be useful for conservation planning and mitigation.

Relevance of animal behavior to management and conservation interventions for fish

Protected areas and spatial planning

Spatial management of fisheries has historically been an essential component of the management toolbox (Hyrenbach et al. 2000; Suski and Cooke 2007), which necessarily draws on fish ethology. Unlike terrestrial systems where ecotones and species distributions are relatively well-defined, underwater spatial management poses a greater challenge (Lennox et al. 2019). The aquatic realm is dynamic with currents, fronts, eddies, and clines that can form invisible boundaries for fish or alternatively be exploited to save energy and move, thereby maximizing bioenergetic efficiency. Animal behavior has advanced rapidly with the increasing availability of electronic tags to remotely observe fish underwater, which has allowed us to estimate the paths of individual fish and estimate their space use. Resulting locational data contribute to estimating migration timing, range size, and residency time in certain areas as well as fidelity to specific habitats, resource selection, fishing

and predation vulnerability, and landscape energetics (Hussey et al. 2015). These metrics are essential for testing the robustness of boundaries drawn for spatial management (noting that political and socio-economic factors also tend to be determinants for planning), which can include protected areas as well as zoning limits for aquatic infrastructure (e.g., fish farms, tidal energy, shipping) that limit disturbance to critical species and habitats.

With movement metrics, spatial management measures can be evaluated and refined. For example, areas that are too small to protect fish from fishing can be revealed by tracking behavior of individuals. Tracking may occur before implementation of spatial management in order to draw effective boundaries or after delineation to evaluate performance. Tracking animals within a protected area can provide data to evaluate their home range, core area use, or network dimensions based on relocations of the individual (e.g., Filous et al. 2017). Poorly situated protected areas can be revealed by matching detections to habitat types and assessing resource or step selection from a random subset of alternative habitats in the area (Griffin et al. 2021). If critical habitats are not included in a protected area, fish will not be well protected and spatial management will fail (e.g., Martin et al. 2020). Lea et al. (2016) specifically showed that marine protected area boundaries needed to expand in the Seychelles to properly cover shark habitat use. In the future, spatial management of fish resources may become more dynamic based on knowledge of fish presence and absence, as well as other species such as sea turtles (*Cheloniidae* spp.) that may be vulnerable to bycatch. Telemetry will continue to play a key role in ascertaining where and when fish move including testing performance of protected areas and other spatial management schemes. However, visual (e.g., baited underwater video; Whitmarsh et al. 2017) or auditory monitoring of fish with hydrophones (Luczkovich et al. 2008) may soon become more common non-invasive tools for tracking individual movement via spatial-capture-recapture to track presence and absence of fish and estimate space use within and beyond protected areas.

Restoring connectivity

Loss of habitat connectivity is one of the most pervasive threats to fish movement (Dudgeon et al. 2006;

Reid et al. 2019). Restoring and improving connectivity is thus one of the biggest challenges for fisheries conservation and management. For connectivity enhancement to be meaningful and effective however, it should be informed by knowledge of fish behavior. For example, knowing the distance of upriver migration can provide information for prioritizing barrier removal, or where fish passes may be constructed to be most effective (Branco et al. 2014). Noakes and colleagues illustrated this point in a study of the upstream migration of glass eels in Iceland (Table 1). At water temperatures above 4.5 °C, glass eels exhibited swimming behavior, which facilitated their entry into rivers during the early summer (Linton et al. 2007). However, climbing behavior only occurs at the warmer temperatures encountered in streams, which allows the eels to bypass natural barriers and proceed further upstream (Linton et al. 2007). Information on the timing and phenology of migration (and other movements) can help managers refine hydropower operations to improve passage during peak migration (Aarestrup et al. 2018; Birnie-Gauvin et al. 2019). While great effort is devoted to enhancing connectivity for migratory species, connectivity is also necessary for species generally viewed as non-migratory (Brevé et al. 2014; Benitez et al. 2018). Many fishes still move within freshwaters as they feed, reproduce, or seek refuge. Identifying where and when these various events occur can help managers decide where and when connectivity is most needed. Behavior can also be used to evaluate the effectiveness of connectivity enhancement projects (e.g., fishways, barrier removal) by evaluating differences in behavior before and after connectivity measures have been implemented.

Various approaches can be used to explore the behavior of fishes within the context of connectivity, with telemetry being one of the most common approaches used (Hussey et al. 2015). For example, acoustic telemetry showed that threatened Silver Perch (*Bidyanus bidyanus*) in the Murray River, south-eastern Australia occupied large areas that extended over hundreds of kilometers and over multiple habitat types, demonstrating that connectivity across these habitat types was important to prevent further population declines of this imperiled species (Koster et al. 2021). In another study, environmental DNA (eDNA) was used to monitor spawning migrations of Danube Bleak (*Alburnus mento*) and Vimba

Bream (*Vimba vimba*). Specifically, daily counts were highly correlated to eDNA signals when flow was accounted for, providing managers with a non-invasive method to study fish behavior (Thalinger et al. 2019). Regardless of the method used, a greater understanding of fish behavior is necessary to focus efforts aimed at restoring connectivity for greatest benefit to fishes.

Habitat restoration

Habitat refers to the three-dimensional spatial units in which organisms reside that contain the physical, chemical, and biological attributes (Brind'Amour and Boisclair 2006) that facilitate survival and reproduction of individuals in a population. Habitat requirements differ across species and can vary over time in response to ontogenetic changes in the behavior and physiology of organisms, seasonal changes in habitat availability or suitability, and ecosystem instability. With aquatic ecosystems across the globe suffering from extensive habitat loss and degradation (Dudgeon et al. 2006; Arthington et al. 2016), ecological restoration has the potential to protect biodiversity (Bernhardt et al. 2005). Indeed, the United Nations has declared 2021–2030 the “Decade on Ecosystem Restoration,” which aims to improve habitat and combat climate change (UNEA 2019). Underpinning efforts with a holistic understanding of behavior across all phases of restoration (i.e., planning, executing, and monitoring; see Hobbs and Norton 1996) is fundamental to maximizing restoration effectiveness (Caro 2007).

Habitat restoration can occur on a variety of spatial scales. For example, in aquatic ecosystems, habitat restoration has included interventions like liming of acidified lakes (e.g., Nyberg 1984; Booth et al. 1986), control and removal of invasive species (e.g., Frazer et al. 2012; Siefkes et al. 2013), dam removal (e.g., Catalano et al. 2007), and construction of artificial spawning reefs (e.g., Clark and Edwards 1999; Marsden et al. 2016). Regardless of spatial scale, the goal of habitat restoration intervention is to establish and conserve self-sustaining populations of target organisms, but often this goal is not met. Hale et al. (2020) proposed a framework highlighting how knowledge of animal behavior can be used to improve habitat restoration, centering on two critical questions that should be considered

prior to, during, and after undertaking a restoration project: (1) do animals colonize restored habitat?, and (2) does the restored habitat meet the target animal's habitat requirements? Addressing these questions requires an understanding of how and why animals select specific habitats, including but not limited to mechanisms of navigation and cues used to locate habitat, characteristics of preferred habitat, resource requirements, and intra and inter-species interactions (Hale et al. 2020). Phenotypic variability in behavior (e.g., partial migration, see Bajer et al. 2015) within a population is another important consideration in habitat restoration, and restoration plans that accommodate and promote behavioral diversity (e.g., portfolio effect, see Schindler et al. 2015) may help increase the resilience of the target population to future perturbations.

Descriptive studies of behavior of fishes in the wild (e.g., Bergstedt et al. 2012; Binder et al. 2018) can help managers gain insight into the habitat preferences of species, but controlled experimental studies in both the laboratory and field tend to be better at identifying specific habitat cues, preferences, and behavioral mechanisms. For example, discrete choice experiments are commonly used to identify habitat preferences (e.g., Casterlin and Reynolds 1977; Brooker et al. 2013) and habitat-locating cues (e.g., Sorensen et al. 2005; Armstrong et al. *In Press*) in fishes. That said, results of laboratory studies should be applied to restoration projects with caution, as behaviors and preferences derived from controlled laboratory studies do not always translate to the wild. For example, Lake Trout in the field typically reside in water temperatures that are several degrees cooler than laboratory-derived thermal optima (Marsden et al. 2021). In general, a good approach may be to treat laboratory-based observations as hypotheses, and where time and resources allow, test them in the wild before initiating a restoration project. Behavioral studies can be costly and time and labor intensive, and often there is pressure to act immediately on restoration projects. However, failure to understand the behavioral ecology of a population in relation to habitat selection, especially colonization behavior and habitat preferences, could result in counterproductive or ineffective restoration efforts that could be even more costly in the long run.

Stock enhancement

Hatchery-based programs consisting of captive breeding or rearing of juvenile fishes for release to enhance or replace fish stocks for conservation or fisheries enhancement purposes have been applied throughout the northern hemisphere for well over a century, particularly with Salmonids (Naish et al. 2007). Despite considerable effort and investment, the effectiveness of stock enhancement programs at maintaining viable, naturally reproducing populations has been highly variable among species and systems (Fraser 2008). Hatchery rearing conditions can strongly influence the development of individual phenotypes, and one of the first experimental demonstrations of this phenomenon was the association between rearing density and physiological stress levels (Noakes and Leatherland 1977).

The epigenetic link between rearing conditions and phenotype spawned a thriving field of research into hatchery enrichment (Huntingford 2004). In general, enriched hatchery conditions offering greater structural complexity (Cogliati et al. 2019a), live prey in addition to commercial fish feed (Brown et al. 2003), realistic flow characteristics (Pedersen et al. 2008), and exposure to the outdoor environment under semi-natural conditions (Hatanpää et al. 2020) may provide valuable “life skills” training (Brown and Laland 2001; Hawkins et al. 2008) to fish prior to release. Enriched rearing has been associated not only with greater rates of survival (Alioravainen et al. 2018), growth (Vainikka et al. 2010), and performance (Hatanpää et al. 2020), but also migratory tendencies and phenologies more closely matching those of wild conspecifics (Hyvärinen and Rodewald 2013; Pedersen et al. 2008). Hatchery exposure to site-specific factors like biofilm communities and associated water chemistry may allow fish to “imprint” on their intended habitat and increase stocking success (Dittman et al. 2015; Putman et al. 2014a; Ueda 2011). Although fish released in better condition and at larger sizes generally experience higher survival rates and hatchery feeding regimes often allow individuals to reach satiation, food restriction immediately prior to release favors subsequent smoltification over precocious maturation in Atlantic Salmon (*Salmo salar*) parr (Vainikka et al. 2012).

Beyond hatchery influences on phenotypes of captive-reared Salmonids, behavioral interactions

with other fish species at stocking sites can influence performance and survival of different phenotypes or strains of stocked fishes (Noakes and Curry 1995). Predation (Greenberg et al. 1997; Álvarez and Nicieza 2003; Kellison et al. 2003; Brokordt et al. 2006; Ochwada et al. 2009; Jackson and Brown 2011) and competition with both native (Miranda and Raborn 2013) and introduced (Scott et al. 2003) species, as well as between hatchery-origin and wild conspecifics (Yamamoto et al. 2008; Laffaille 2011), both negatively impact the success of stocking efforts and when they do not, stocked fish may impact the native population and community (Vehanen et al. 2009).

Collectively, conservation stocking studies have identified the importance of matching captive rearing conditions as closely as possible to natural conditions the fish will experience following release while limiting both rearing growth to ecologically realistic rates and competition for natural-type feed. This comes with the caveat that overfeeding and providing “too comfortable” an upbringing may mitigate the benefits of more enlightened rearing approaches. Despite the large body of work on this topic, long-term survival and fitness of stocked fishes remain largely unknown but the adoption of biologging and telemetry technologies (Ebner and Thiem 2009), as well as genetic techniques (Wilson et al. 2007; Fraser 2008) for long-term outcome tracking present great possibilities for future research. Further, more refined, genetically informed captive breeding programs (Lemopoulos et al. 2019) may be beneficial to both conservation-oriented stocking, as well as stock augmentations for recreational and subsistence fisheries (Dunham et al. 1986; Redpath et al. 2010; Blackwell et al. 2021; Vainikka et al. 2021).

The contributions of Dr. Noakes to fish behavior, conservation and management

Professor David Noakes was a pioneer in the behavior, ecology, and conservation of fishes. An extensive portion of the research contributions he made over five decades embodied the spirit of conservation behavior — with many of these contributions made well before the concept of conservation behavior was formalized. Consistent with Tinbergen’s integrated set of explanations of behavior, Dr. Noakes research

combined the principles and practices of animal behavior, endocrinology, physiology, ecotoxicology, morphology, genetics, and evolution to improve our understanding of fundamental questions about the biology of fishes in general, and salmonid fishes in particular (see Muir, this issue). Perhaps his greatest contributions, and most relevant to the theme of the current paper, came from Dr. Noakes’ unyielding encouragement to integrate behavioral principles, practices, and understanding into management-scale studies exploring how fish populations respond to anthropogenic threats and identifying management interventions that could mitigate these threats.

As an ecologist and conservation behaviorist, Noakes’ research on threats to native wild fish populations had mainly to do with such factors as habitat alteration or loss, effects of invasive species, and pollution (Table 1). His work on habitat alteration or loss tended to focus on how Salmonids used cover and natural areas of heterogeneity while foraging (Grant and Noakes 1986; McLaughlin and Noakes 1998), or during reproduction (Curry and Noakes 1995; Curry et al. 1995), and ultimately how these areas could be affected negatively by loss (Portt et al. 1986) or processes related to anthropogenic disturbance (Curry et al. 1994). Noakes and colleagues were also interested in understanding the impacts of pollution (Gunn and Noakes 1986, 1987) and invasive species on native biodiversity and the movement (Porto et al. 1999; Dodd et al. 2003; McLaughlin et al. 2006), spawning behavior (Scott et al. 2005b, c; Scanlan et al. 2018), and reproduction (Scott et al. 2003, 2005a) of natural populations. For example, he contributed early work demonstrating that Brook Charr (*Salvelinus fontinalis*) alevins showed behavioral avoidance of low pH and elevated aluminum levels and suggested that these behavioral mechanisms could impart an advantage in systems experiencing acidification (Gunn and Noakes, 1986).

From a management perspective, Noakes focused his research interests on management interventions that involved spatial planning and protected areas, restoring connectivity, and habitat and population restoration. For example, Noakes and colleagues investigated the effects of barriers on species richness (Porto et al. 1999; Dodd et al. 2003), and further, tested how eels use different locomotor behavior to overcome such obstacles (Linton et al. 2007). Additional work considered how Salmonids inherit magnetic maps to

facilitate migration (Putman et al. 2014b) as well as aggressiveness, mobility, and trophic specialization to facilitate adaptation to diverse habitats and eventually, speciation (Ferguson and Noakes 1982, 1993; Skúlason et al. 1993). In other studies, Noakes investigated how behaviors, such as territoriality, limit population density and play a role in regulating the abundance of stream-swelling Salmonids (Cole and Noakes 1980; McNicol and Noakes 1981, 1984; Grant et al. 1989). Lastly, Noakes made significant contributions towards understanding how rearing conditions, captive-breeding, sensory biology, and fish community dynamics could influence population restoration efforts of Salmonids under diverse conditions (Noakes and Leatherland 1977; Noakes and Curry 1995; Scott et al. 2005a; Putman et al., 2013, 2014b; Dittman et al. 2015).

The contributions of David Noakes extend to most branches of fisheries biology and his accomplishments, particularly with respect to Salmonid ecology and biology are widespread. Much of his work has had a lasting impact on the fields of conservation behavior and animal behavior and will likely continue to do so for years to come.

The future of applied fish behavior through the lens of Dr. Noakes

Below, we briefly identify research directions that develop these approaches on subject areas close to Dr. Noakes' heart. We do so knowing that Dr. Noakes would actively argue for more integrative studies of conservation behavior in fishes that explore Tinbergen's four levels of explanation using novel conceptual and technical methods that on their own, or in combination with existing methods, reveal both greater and deeper understanding of behavior, and its connections to the life histories, ecology, and management for fish species of conservation concern.

Engaging in management scale experiments

One of the most common criticisms of research involving applied fish behavior and conservation behavior research more broadly (Caro 2007) is that the research is conducted at scales that are not relevant to managers. Because managers focus their efforts at the level of the population, and often across

an entire waterbody, catchment, or land/sea-scape, studies that are exclusively conducted in the laboratory on a small number of fish without scaling up to field settings often fail to provide the information needed to influence policy and practice (Walters and Holling 1990). Even when work is done in the field, for example using telemetry, sample sizes are often small and may not be representative of the population (Brownscombe et al. 2017). As Director at the Oregon Hatchery Research Centre for the past decade, Dr. Noakes and his collaborators led a number of management scale experiments intended to support management and conservation decisions regarding fish. That work tested novel hypotheses, developed creative new tools, and gained insights into current fish management concerns largely associated with hatchery practices for conservation and hatchery production of wild Salmonid phenotypes (Cogliati et al. this issue). Prominent examples include research on early-life rearing (e.g., Cogliati et al. 2019a, b, c), breeding (e.g., Auld et al. 2021), imprinting (Dittman et al. 2015), and homing (e.g., Putman et al. 2013). These projects, some which continue today, involved extensive collaboration with management agencies and in situ testing of hypotheses relevant to native Salmonid conservation in the Pacific northwest. The scale of all of these studies was impressive in that they often combined laboratory studies with large sample sizes followed by releasing and tracking large numbers of tagged animals throughout their spawning migrations. Such work that bridges the lab and the field with large sample sizes and studies fish across large spatial scales over time are essential to generate actionable knowledge. This type of experimentation is also an important step for moving from a more descriptive applied fish behavior to a more predictive one that can inform management decisions. The work of Dr. Noakes provides a model for others to follow.

Conducting integrative research that bridges behavior and physiology

David Noakes appreciated that his two academic specialty areas, behavior and ecology, are essentially a seamless extension of an animal's physiology and anatomy. Physiological factors and mechanisms are the basis for motivating, controlling, and fueling behaviors (Breed and Sanchez 2010; Horodysky et al. 2015) (as a Ph.D. student Dr. Noakes was the

teaching assistant in a class titled “Chemical Mediation”). Further, physiology along with anatomy is the basis for how a species determines its own ecological niche as described by Hutchinson (1958). It is therefore not surprising that his studies often included physiology. This research is relevant to a multitude of management and conservation topics. Physiological aspects of Dr. Noakes’ research ranged from understanding physiological mechanisms driving or resourcing, i.e., bioenergetics (Cogliati et al. 2019c), behavior to whole animal physical and behavioral performance. The following are some examples to illustrate the depth and breadth of David’s studies that had a physiological component. Much of his work centered around understanding movement of fish, often with a focus on migration and habitat selection. His approach working at the mechanistic level includes looking at downstream movement of juvenile Pacific salmonids as it relates to a fish’s preference to be in salt water. That, of course, entails a shift in osmoregulatory physiology as the fish goes from a hydrating to a dehydrating environment. His ongoing projects involve clinical assessment of smoltification as they relate to movement behavior. Ion regulatory ability is key and can be influenced by stress that could affect behavior (Stewart et al. 2016, 2017). Visual isolation, as a consequence of structure in an environment, could also affect how fish respond to stressors and hence behavior (Cogliati et al. 2019b). Other studies explored how physiology is involved in fish social behavior (Noakes and Leatherland 1977). Physiology at the whole animal level includes questions such as how growth might be involved in juvenile salmon development and ultimately how that might affect migratory behavior (Self et al. 2018a, b). Studies concerning growth also have a strong bearing on conservation (Noakes et al. 1999). In addition, survival of out migrant salmonids appears to be different between the sexes (Thompson et al. 2015). In this regard, climate change and global warming potentially could affect sexual development in the fish (Cole et al. 2021). Acclimation temperature plays a role in how fish behave regarding different temperatures (Munakata et al. 2017). Orientation by adult anadromous salmonids concerns olfaction (Dittman et al. 2015). Upstream movement behavior in salmonids also involve gonadal factors; David’s Master’s student Eva Schemmel (Schemmel 2009) found that castrated steelhead had the same homing behavior as

intact fish; swimming energetics was also not affected by castration. Whole animal response to contaminants reflects sensory physiology as well as behavior (Gunn and Noakes 1986). Whole animal physiology is also obviously also inherent in the research related to fish anesthetics mentioned earlier. Further, Dr. Noakes’ studies related to magnetism as a guide for homing (Putman et al. 2013, 2014a, 2014b; Scanlan et al. 2018; Naisbett-Jones et al. 2020) is seminal both scientifically and for conservation and management. David assiduously contributed to our understanding of behavior and ecology by understanding that they could not be investigated on their own, but rather were best understood more holistically when physiology was included in his investigations.

Using technology to study applied fish behavior in the field

Technological advances and tool development in fields such as genetics/genomics (Hohenlohe et al. 2020), telemetry (Crossin et al. 2017), and electromagnetism (Klimley et al. 2021) have, and continue to, contribute to our understanding of animal behavior and in turn develop ideas and create solutions for many of the applied fisheries and conservation-based issues discussed in this paper. Dr. Noakes routinely pushed the frontiers of applied fish behavior using technology and was a champion for the development of tools that enabled behavior studies to be conducted in the field. Examples from early in his career included the validation and use of tissue concentrations of DNA, RNA, and proteins, and otolith ageing, to assess the growth rates of fish displaying different foraging tactics in the field and the nature of phenotypic selection acting on the fish (Locke 1995; McLaughlin et al. 1995, 1999). Today, advances in the field of genomics are creating opportunities to gain insight into the genetic makeup and relatedness of large numbers of individuals with greater accuracy and at a fraction of previous costs (e.g., De Coster et al. 2021). These advances have provided increasing insight into population genetics (Hohenlohe et al. 2020), animal movement, and migration (Cooke et al. 2008), and mating (Auld et al. 2019, 2021), which are all integral to the successful management and conservation of fish and fisheries. In the future, the complex and cumulative effects of anthropogenic stressors will make the use of these tools in isolation insufficient to

address the fish, fishery, and conservation issues of the day. To deal with these issues, we need far-reaching collaborative and transdisciplinary studies involving trophic ecology, fish movement, and behavior as well as socio-economic and other human dimensions affecting fish and fisheries. Given the vast amount of data generated by new technologies, the challenge will be ensuring that it is analyzed in ways that will inform fisheries management and conservation decisions. Dr. Noakes was not a technology junkie — rather, he used the tool appropriate for the task at hand and always kept an open mind about how new tools could enable him to better address questions in applied fish behavior.

Conclusions

Our objectives herein were twofold, first to synthesize the knowledge and relevance of animal behavior to fishery management and conservation and second to view the current state of the disciplines through the lens of the late Prof. David L. G. Noakes, an influencer who advanced the field. It is clear that animal behavior has become a common and trusted tool in informing the management and conservation of fishes. Although such examples are rarely celebrated in the conservation behavior literature, they are well represented in the vast fisheries literature. Although once neglected (*sensu* Shumway 1999), behavioral tools and concepts are being used to understand the threats faced by fishes and to identify and refine management and conservation strategies. David Noakes was on the forefront of conservation behavior and proactive in incorporating fish behavior in management and management planning. His vision was remarkable, tackling many issues well before their time including the conflict between barriers for invasive species control in the Laurentian Great Lakes and their unintended consequences for native species and habitat connectivity—a critical global fishery issue now recognized as the connectivity conundrum (Zielinski et al. 2020). Likewise, his leadership at the Oregon Hatchery Research Center to confront the challenge of producing wild phenotypes in the hatchery is now beginning to change hatchery practices in the Pacific Northwest and has gained traction elsewhere. The primary behavioral research areas relevant to understanding threats to fish populations

synthesized herein—habitat alteration and loss; exploitation; invasive species; pollution; climate change; protected areas and spatial planning; restoring connectivity; habitat restoration; and stock enhancement—are actively being pursued by a strong lineage of trainees mentored by Dr. David Noakes and his colleagues around the world. Noakes helped many find their niche in the science community; upon getting a manuscript rejected, he once said “just find a better journal.” In his dry, witty sense of humor, this meant you need to work harder to figure out where you and your work fit into the bigger picture and true to his mentoring style, he would facilitate the appropriate connections to make that happen. His passion, inspiration, teachings, and fortuitous (or cleverly engineered) introductions have led to a global network that continues to advance animal behavior and conservation behavior in fishery management and management planning. Looking forward, we submit that behavior is no longer neglected (Shumway 1999) when it comes to fish conservation and management which is in no small part to the work of Dr. David L.G. Noakes.

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References

- Aarestrup K, Birnie-Gauvin K, Larsen MH (2018) Another paradigm lost? Autumn downstream migration of juvenile brown trout: evidence for a pre-smolt migration. *Ecol Freshw Fish* 27:513–516. <https://doi.org/10.1111/eff.12335>
- Alioravainen N, Hyvärinen P, Kortet R, Härkönen L, Vainikka A (2018) Survival of crossbred brown trout under experimental pike predation and stocking in the wild. *Boreal Environ Res* 23:267–281
- Alos J, Palmer M, Rossello S, Arlinghaus R (2015) Fast and behavior-selective exploitation of a marine fish targeted by anglers. *Sci Rep* 6:38093. <https://doi.org/10.1038/srep38093>
- Álvarez D, Nicieza AG (2003) Predator avoidance behavior in wild and hatchery-reared brown trout: the role of experience and domestication. *J Fish Biol* 63:1565–1577. <https://doi.org/10.1111/j.1095-8649.2003.00267.x>
- Angeloni L, Schlaepfer MA, Lawler JJ, Crooks KR (2008) A reassessment of the interface between conservation and behavior. *Anim Behav* 75:731–737. <https://doi.org/10.1016/j.anbehav.2007.08.007>
- Arlinghaus R, Laskowski KL, Alós J, Klefoth T, Monk CT, Nakayama S, Schröder A (2017) Passive gear-induced timidity syndrome in wild fish populations and its potential ecological and managerial implications. *Fish and Fish* 18:360–373. <https://doi.org/10.1111/faf.12176>
- Armstrong ME, Minkoff D, Dittman AH, May D, Moody EK, Quinn TP, Atema J, Ardren WR (In Press) Evidence of an olfactory imprinting window in embryonic Atlantic salmon. *Ecol Freshw Fish*. <https://doi.org/10.1111/eff.12628>
- Arthington AH, Dulvy NK, Gladstone W, Winfield IJ (2016) Fish conservation in freshwater and marine realms: status, threats and management. *Aquat Conserv* 26:838–857. <https://doi.org/10.1002/aqc.2712>
- Ashenden T, Rooke AC, Fox MG (2017) Boldness and dispersal tendency of native and invasive pumpkinseed (*Lepomis gibbosus*): is spatial sorting creating superior invaders? *Aquat Invasions* 12(3). <https://doi.org/10.3391/ai.2017.12.3.05>
- Auld HL, Jacobson DP, Rhodes AC, Banks MA (2021) Differences in mate pairings of hatchery- and natural-origin coho salmon inferred from offspring genotypes. *Integr Org Biol* 3:obab020. <https://doi.org/10.1093/iob/obab020>
- Auld HL, Noakes DL, Banks MA (2019) Advancing mate choice studies in salmonids. *Rev Fish Biol Fish* 29:249–276. <https://doi.org/10.1007/s11160-019-09551-5>
- Bajer PG, Parker JE, Cross TK, Venturelli PA, Sorensen PW (2015) Partial migration to seasonally-unstable habitat facilitates biological invasions in a predator-dominated system. *Oikos* 124(11):1520–1526
- Bailey LA, Childs AR, James NC, Winkler A, Potts WM (2022) Links between behaviour and metabolic physiology in fishes in the Anthropocene. *Rev Fish Biol Fish* 00:000–000
- Bateson P, Laland KN (2013) Tinbergen's four questions: an appreciation and an update. *Trends Ecol Evol* 28:12–718. <https://doi.org/10.1016/j.tree.2013.09.013>
- Baxter MR (1983) Ethology in environmental design for animal production. *Appl Anim Ethol* 9:207–220. [https://doi.org/10.1016/0304-3762\(83\)90001-9](https://doi.org/10.1016/0304-3762(83)90001-9)
- Benitez JP, Dierckx A, Matondo BN, Rollin X, Ovidio M (2018) Movement behaviors of potamodromous fish within a large anthropised river after the reestablishment of the longitudinal connectivity. *Fish Res* 207:140–149. <https://doi.org/10.1016/j.fishres.2018.06.008>
- Berger-Tal O, Polak T, Oron A, Lubin Y, Kotler BP, Saltz D (2011) Integrating animal behavior and conservation biology: a conceptual framework. *Behav Ecol* 22:236–239. <https://doi.org/10.1093/beheco/arq224>
- Berger-Tal O, Saltz D (2016) Conservation behavior: applying behavioral ecology to wildlife conservation and management. Cambridge University Press, Cambridge
- Bergstedt RA, Argyle RL, Krueger CC, Taylor WW (2012) Bathythermal habitat use by strains of Great Lakes-and Finger Lakes-origin lake trout in Lake Huron after a change in prey fish abundance and composition. *Trans Am Fish* 141:263–274. <https://doi.org/10.1080/0002487.2011.651069>
- Bernhardt ES, Palmer MA, Allan JD, Alexander G, Barnas K, Brooks E, Carr J et al (2005) Synthesizing U. S. river restoration efforts. *Science* 308:636–637. <https://doi.org/10.1126/science.1109769>
- Binder TR, Farha SA, Thompson HT, Holbrook CM, Bergstedt RA, Riley SC, Bronte CR, He J, Krueger CC (2018) Fine-scale acoustic telemetry reveals unexpected lake trout, *Salvelinus namaycush*, spawning habitats in northern Lake Huron, North America. *Ecol Freshw Fish* 27:594–605. <https://doi.org/10.1111/eff.12373>
- Birnie-Gauvin K, Franklin P, Wilkes M, Aarestrup K (2019) Moving beyond fitting fish into equations: Progressing the fish passage debate in the Anthropocene. *Aquatic Conserv* 29:1095–1105. <https://doi.org/10.1002/aqc.2946>
- Biro PA, Post JR (2008) Rapid depletion of genotypes with fast growth and bold personality traits from harvested fish populations. *PNAS* 105:2919–2922. <https://doi.org/10.1073/pnas.0708159105>
- Biro PA, Stamps JA (2008) Are animal personality traits linked to life-history productivity? *Trends Ecol Evo* 23:361–368. <https://doi.org/10.1016/j.tree.2008.04.003>
- Blackwell BG, Ward MJ, Kaufman TM (2021) Angling of hybrid sunfish from a hatchery pond with potential implications for community fisheries. *Aquac Fish*. <https://doi.org/10.1016/j.aaf.2021.08.001>
- Blumstein DT (2015) Prioritizing conservation behavior research: a comment on Wong and Candolin. *Behav Ecol* 26:674–674. <https://doi.org/10.1093/beheco/aru208>
- Blumstein DT, Fernández-Juricic E (2004) The emergence of conservation behavior. *Conserv Biol* 18:1175–1177. <http://www.jstor.org/stable/3588984>. Accessed 4 Jan 2022
- Booth GM, Hamilton JG, Molot LA (1986) Liming in Ontario: short-term biological and chemical changes. *Water Air Soil Pollut* 31:709–720. <https://doi.org/10.1007/BF00284221>

- Branco P, Segurado P, Santos JM, Ferreira MT (2014) Prioritizing barrier removal to improve functional connectivity of rivers. *J Appl Ecol* 51:1197–1206. <https://doi.org/10.1111/1365-2664.12317>
- Brandt SB, Costantini M, Kolesar S, Ludsins SA, Mason DM, Rae CM, Zhang H (2011) Does hypoxia reduce habitat quality for Lake Erie walleye (*Sander vitreus*)? A bioenergetics perspective. *Can J Fish Aquat Sci* 68:857–879. <https://doi.org/10.1139/f2011-018>
- Bravener GA, McLaughlin RL (2013) A behavioral framework for trapping success and its application to invasive sea lamprey. *Can J Fish Aquat Sci* 70:1438–1446. <https://doi.org/10.1139/cjfas-2012-0473>
- Breed M, Sanchez L (2010) What functions of living systems underlie behavior? *Nat Educ Knowl* 3:67
- Brevé NW, Buijse AD, Kroes MJ, Wannings H, Vriese FT (2014) Supporting decision-making for improving longitudinal connectivity for diadromous and potamodromous fishes in complex catchments. *Sci Total Environ* 496:206–218. <https://doi.org/10.1016/j.scitotenv.2014.07.043>
- Brind'Amour A, Boisclair D (2006) Effect of the spatial arrangement of habitat patches on the development of fish habitat models in the littoral zone of a Canadian Shield lake. *Can J Fish Aquat Sci* 63:737–753. <https://doi.org/10.1139/f05-249>
- Brokordt KB, Fernández M, Gaymera CF (2006) Domestication reduces the capacity to escape from predators. *J Exp Mar Biol Ecol* 329:11–19. <https://doi.org/10.1016/j.jembe.2005.08.007>
- Brooker RM, Munday PL, Mcleod IM, Jones GP (2013) Habitat preferences of a corallivorous reef fish: predation risk versus food quality. *Coral Reefs* 32:613–622. <https://doi.org/10.1007/s00338-013-1057-6>
- Brown C, Davidson T, Laland K (2003) Environmental enrichment and prior experience of live prey improve foraging behavior in hatchery-reared Atlantic salmon. *J Fish Biol* 63:187–196. <https://doi.org/10.1111/j.1095-8649.2003.00208.x>
- Brown C, Laland K (2001) Social learning and life skills training for hatchery reared fish. *J Fish Biol* 59:471–493. <https://doi.org/10.1111/j.1095-8649.2001.tb02354.x>
- Brownscombe JW, Cooke SJ, Danylchuk AJ (2017) Spatiotemporal drivers of energy expenditure in a coastal marine fish. *Oecologia* 183:689–699. <https://doi.org/10.1007/s00442-016-3800-5>
- Buchholz R (2007) Behavioral biology: an effective and relevant conservation tool. *Trends Ecol Evol* 22:401–407. <https://doi.org/10.1016/j.tree.2007.06.002>
- Burkhardt RW Jr (2014) Tribute to Tinbergen: putting Niko Tinbergen's 'Four Questions' in historical context. *Ethology* 120:215–223. <https://doi.org/10.1111/eth.12200>
- Caro T (1998) Behavioral ecology and conservation biology. Oxford University, Oxford
- Caro T (2007) Behavior and conservation: a bridge too far? *Trends Ecol Evol* 22:394–400. <https://doi.org/10.1016/j.tree.2007.06.003>
- Caro T (2016) Behavior and conservation, conservation and behavior. *Curr Opin Behav Sciences* 12:97102. <https://doi.org/10.1016/j.cobeha.2016.09.008>
- Caro T, Sherman PW (2011) Endangered species and a threatened discipline: behavioral ecology. *Trends Ecol Evol* 26:111–118. <https://doi.org/10.1016/j.tree.2010.12.008>
- Casterlin ME, Reynolds WW (1977) Aspects of habitat selection in the mosquitofish *Gambusia affinis*. *Hydrobiologia* 55:125–127. <https://doi.org/10.1007/BF00021053>
- Catalano MJ, Bozek MA, Pellett TD (2007) Effects of dam removal on fish assemblage structure and spatial distributions in the Baraboo River, Wisconsin. *N Am J Fish Manag* 27:519–530. <https://doi.org/10.1577/M06-001.1>
- Christensen EAF, Andersen LEJ, Steffensen JF, Killen SS (2021) Shuttle-box systems for studying preferred environmental ranges by aquatic animals. *Conserv Physiol* 9:coab028. <https://doi.org/10.1093/conphys/coab028>
- Clark S, Edwards AJ (1999) An evaluation of artificial reef structures as tools for marine habitat rehabilitation in the Maldives. *Aquat Conserv* 9:5–21
- Cogliati KM, Herron CL, Noakes DLG, Schreck CB (2019a) Reduced stress response in juvenile Chinook Salmon reared with structure. *Aquaculture* 504:96–101
- Cogliati KM, Unrein JR, Schreck CB, Noakes DLG (2019b) Rearing environment affects spatial learning in juvenile Chinook salmon *Oncorhynchus tshawytscha*. *J Fish Biol* 95:870–880. <https://doi.org/10.1111/jfb.14083>
- Cogliati KM, Unrein JR, Sealey WM, Barrows FT, Hakanson O, Chitwood R, Noakes DLG, Schreck CB (2019c) Low lipid diets fed at reduced ration: effects on growth, body composition, and survival of juvenile Chinook Salmon. *J Fish Wildl Manag* 10:500–508. <https://doi.org/10.3996/062018-JFWM-059>
- Cole KS, Noakes DLG (1980) Development of early social behavior of rainbow trout, *Salmo gairdneri* (Pisces, Salmonidae). *Behav Process* 5:97–112. [https://doi.org/10.1016/0376-6357\(80\)90059-5](https://doi.org/10.1016/0376-6357(80)90059-5)
- Cole KS, Noakes DLG, Thompson N, Blouin M, Morrison B, Couture RB, O'Neil J, Schreck CB (2021) Effects of temperature on sexual development in steelhead, *Oncorhynchus mykiss*. *Environ Biol Fish* 104:229–238
- Cooke SJ, Hinch SG, Farrell AP, Patterson DA, Miller-Saunders K, Welch DW, Donaldson MR et al (2008) Developing a mechanistic understanding of fish migrations by linking telemetry with physiology, behavior, genomics and experimental biology: an interdisciplinary case study on adult Fraser River sockeye salmon. *Fisheries* 33:321–339. <https://doi.org/10.1577/1548-8446-33.7.321>
- Cooke SJ, Blumstein DT, Buchholz R, Caro T, Fernandez-Juricic E, Franklin CE, Metcalfe J, St. O'Connor CM, Clair CC, Sutherland WJ, Wikelski M (2014) Physiology, behavior, and conservation. *Physiol Biochem Zool* 87(1):1–14
- Cott PA, Hawkins AD, Zeddies D, Martin B, Johnston TA, Reist JD, Gunn JM, Higgs DM (2014) Song of the burbot: under-ice acoustic signaling by a freshwater gadoid fish. *J Great Lakes Res* 40:435–440
- Cott PA, Mann DA, Higgs DM, Johnston TA, Gunn JM (2012) Assessing disturbance from under-ice noise on fishes in boreal lakes. In: Popper AN, Hawkins A (eds) Effects of Noise on Aquatic Life. Springer, New York, pp 363–366
- Crossin GT, Heupel MR, Holbrook CM, Hussey NE, Lowerre-Barbieri SK, Nguyen VM, Raby GD, Cooke SJ (2017)

- Acoustic telemetry and fisheries management. *Ecol App* 27:1031–1049
- Curry RA, Gehrels J, Noakes DLG, Swainson R (1994) Effects of river flow fluctuations on groundwater discharge through brook trout, *Salvelinus Fontinalis*, Spawning and Incubation Habitats. *Hydrobiologia* 277:121–134. <https://doi.org/10.1007/Bf00016759>
- Curry RA, Noakes DLG (1995) Groundwater and the selection of spawning sites by brook trout (*Salvelinus fontinalis*). *Can J Fish Aquat Sci* 52:1733–1740. <https://doi.org/10.1139/F95-765>
- Curry RA, Noakes DLG, Morgan GE (1995) Groundwater and the incubation and emergence of brook trout (*Salvelinus fontinalis*). *Can J Fish Aquat Sci* 52:1741–1749. <https://doi.org/10.1139/F95-766>
- De Coster W, Weissensteiner MH, Sedlazeck FJ (2021) Towards population-scale long-read sequencing. *Nat Rev Genet* 22:572–587. <https://doi.org/10.1038/s41576-021-00367-3>
- Deines AM, Bunnell DB, Rogers MW, Bennion D, Woelmer W, Sayers MJ, Grimm AG, Shuchman RA et al (2017) The contribution of lakes to global inland fisheries harvest. *Front Ecol Environ* 15:293–298. <https://doi.org/10.1002/fee.1503>
- Dell’Omo G (2002) Behavioral ecotoxicology. Wiley, Chichester
- Di Franco E, Pierson P, Di Iorio L, Calò A, Cottalorda JM, Derijard B et al (2020) Effects of marine noise pollution on Mediterranean fishes and invertebrates: a review. *Mar Pollut Bull* 159:111450. <https://doi.org/10.1016/j.marpollbul.2020.111450>
- Diller JL, Frazer TK, Jacoby CA (2014) Coping with the lionfish invasion: evidence that naïve, native predators can learn to help. *J Exp Mar Biol Ecol* 455:45–49. <https://doi.org/10.1016/j.jembe.2014.02.014>
- Dittman AH, Pearsons TN, May D, Couture RB, Noakes DLG (2015) Imprinting of hatchery-reared salmon to targeted spawning locations: a new embryonic imprinting paradigm for hatchery programs. *Fisheries* 40:114–123. <https://doi.org/10.1080/03632415.2015.1007206>
- Dodd HR, Hayes DB, Baylis JR, Carl LM, Goldstein JD, McLaughlin RL, Noakes DLG, Porto LM, Jones ML (2003) Low-head sea lamprey barrier effects on stream habitat and fish communities in the Great Lakes Basin. *J Great Lakes Res* 29:386–402. [https://doi.org/10.1016/S0380-1330\(03\)70502-4](https://doi.org/10.1016/S0380-1330(03)70502-4)
- Dudgeon D, Arthington AH, Gessner MO, Kawabata ZI, Knowler DJ, Lévêque C et al (2006) Freshwater biodiversity: importance, threats, status and conservation challenges. *Biol Rev* 81:163–182. <https://doi.org/10.1017/S1464793105006950>
- Dunham RA, Smitherman RO, Goodman RK, Kemp P (1986) Comparison of strains, crossbreeds and hybrids of channel catfish for vulnerability to angling. *Aquaculture* 57:193–201. [https://doi.org/10.1016/0044-8486\(86\)90197-3](https://doi.org/10.1016/0044-8486(86)90197-3)
- Ebner BC, Thiem JD (2009) Monitoring by telemetry reveals differences in movement and survival following hatchery or wild rearing of an endangered fish. *Mar Freshw Res* 60:45–57. <https://doi.org/10.1071/MF08027>
- Ehrenfeld JG (2010) Ecosystem consequences of biological invasions. *Annu Rev Ecol Evol Syst* 41:59–80. <https://doi.org/10.1146/annurev-ecolsys-102209-144650>
- Elmer LK, Madliger CL, Blumstein DT, Elvidge CK, Fernández-Juricic E, Horodysky AZ et al (2021) Exploiting common senses: sensory ecology meets wildlife conservation and management. *Conserv Physiol* 9(1):coab002
- Elvidge CK, Cooke ELL, Cunjak RA, Cooke SJ (2017) Social cues may advertise habitat quality to refuge-seeking conspecifics. *Can J Zool* 95:1–5. <https://doi.org/10.1139/cjz-2016-0144>
- Farrell AP, Hinch SG, Cooke SJ, Patterson DA, Crossin GT, Lapointe M, Mathes MT (2008) Pacific salmon in hot water: applying aerobic scope models and biotelemetry to predict the success of spawning migrations. *Physiol Biochem Zool* 81:697–708. <https://doi.org/10.1086/592057>
- Ferguson MM, Noakes DLG (1982) Genetics of social behavior in charrs (*Salvelinus* species). *Animal Behav* 30:128–134. [https://doi.org/10.1016/S0003-3472\(82\)80247-9](https://doi.org/10.1016/S0003-3472(82)80247-9)
- Ferguson MM, Noakes DLG (1993) Movers and stayers: Genetic analysis of mobility and positioning in hybrids of lake charr, *Salvelinus namaycush*, and brook charr, *S. fontinalis* (Pisces, salmonidae). *Behav Gen* 13:213–222. <https://doi.org/10.1007/Bf01065670>
- Ferguson RG (1958) The preferred temperature of fish and their midsummer distribution in temperate lakes and streams. *J Fish Res Bd Can* 15:607–624. <https://doi.org/10.1139/f58-032>
- Filous A, Friedlander A, Wolfe B, Stamoulis K, Scherrer S, Wong A et al (2017) Movement patterns of reef predators in a small isolated marine protected area with implications for resource management. *Marine Biol* 164:1–16. <https://doi.org/10.1007/s00227-016-3043-3>
- Ford AT, Ågerstrand M, Brooks BW, Allen J, Bertram MG, Brodin T et al (2021) The role of behavioral ecotoxicology in environmental protection. *Environ Sci Technol* 55:5620–5628
- Foster JG, Algera DA, Brownscombe JW, Zolderdo AJ, Cooke SJ (2016) Consequences of different types of littoral zone light pollution on the parental care behavior of a freshwater teleost fish. *Wat Air Soil Poll* 227:1–9. <https://doi.org/10.1007/s11270-016-3106-6>
- Fraser DJ (2008) How well can captive breeding programs conserve biodiversity? A review of salmonids. *Evol Appl* 1:535–586. <https://doi.org/10.1111/j.1752-4571.2008.00036.x>
- Frazer TK, Jacoby CA, Edwards MA, Barry SC, Manfrino CM (2012) Coping with the Lionfish invasion: can targeted removals yield beneficial effects? *Rev Fish Sci* 20:185–191. <https://doi.org/10.1080/10641262.2012.700655>
- Fréon P, Gerlotto F, Misund O (1993) Consequences of fish behavior for stock assessment. *ICES J Mar Sci* 196:190–195
- Fréon P, Misund OA (1999) Dynamics of pelagic fish distribution and behavior: effects on fisheries and stock assessment. Blackwell Science, Oxford
- Goodenough J, McGuire B, Jakob E (2009) Perspectives on animal behavior. Wiley, Hoboken
- Gordon TAC, Harding HR, Clever FK, Davidson IK, Davison W, Montgomery DW et al (2018) Fishes in a changing

- world: learning from the past to promote sustainability of fish populations. *J Fish Biol* 92:804–827. <https://doi.org/10.1111/jfb.13546>
- Goss-Custard JD, Sutherland WJ (1997) Individual behaviour, populations and conservation. *Behav Ecol Evol Approach* 4:373–395
- Grant JWA, Noakes DLG (1986) A test of a size-selective predation model with juvenile brook charr, *Salvelinus fontinalis*. *J Fish Biol* 29:15–24. <https://doi.org/10.1111/j.1095-8649.1986.tb04995.x>
- Grant JWA, Noakes DLG (1987) Escape behavior and use of cover by young-of-the-year Brook Trout, *Salvelinus Fontinalis*. *Can J Fish Aquat Sci* 44:1390–1396. <https://doi.org/10.1139/F87-167>
- Grant JWA, Noakes DLG, Jonas KM (1989) Spatial distribution of defence and foraging in young-of-the-year Brook Charr, *Salvelinus fontinalis*. *J Anim Ecol* 58:773–784. <https://doi.org/10.2307/5123>
- Greenberg LA, Bergman E, Eklov AG (1997) Effects of predation and intraspecific interactions on habitat use and foraging by brown trout in artificial streams. *Ecol Freshw Fish* 6:16–26. <https://doi.org/10.1111/j.1600-0633.1997.tb00138.x>
- Griffin LP, Casselberry GA, Hart KM, Jordaan A, Becker SL, Novak AJ et al (2021) A novel framework to predict relative habitat selection in aquatic systems: Applying machine learning and resource selection functions to acoustic telemetry data from multiple shark species. *Front Mar Sci* 8:6311262. <https://doi.org/10.3389/fmars.2021.631262>
- Groot G, Margolis L (1991) Pacific salmon life histories. UBC Press, Vancouver
- Guerra AS, Kao AB, McCauley DJ, Berdahl AM (2020) Fisheries-induced selection against schooling behavior in marine fishes. *Proc Royal Soc B* 287(1935):20201752. <https://doi.org/10.1098/rspb.2020.1752>
- Gunn JM, Noakes DLG (1986) Avoidance of low pH and elevated Al concentrations by Brook Charr (*Salvelinus fontinalis*) alevins in laboratory tests. *Wat Air Soil Poll* 30:497–503. https://doi.org/10.1007/978-94-009-3385-9_48
- Gunn JM, Noakes DLG (1987) Latent effects of pulse exposure to aluminum and low pH on size, ionic composition, and feeding efficiency of Lake Trout (*Salvelinus namaycush*) Alevins. *Can J Fish Aquat Sci* 44:1418–1424. <https://doi.org/10.1139/F87-170>
- Guzzo MM, Blanchfield PJ, Rennie MD (2017) Behavioral responses to annual temperature variation alter the dominant energy pathway, growth, and condition of a cold-water predator. *PNAS* 114:9912–9917. <https://doi.org/10.1073/pnas.1702584114>
- Hale R, Blumstein DT, Mac Nally R, Swearer SE (2020) Harnessing knowledge of animal behavior to improve habitat restoration outcomes. *Ecosphere* 11:e03104. <https://doi.org/10.1002/ecs2.3104>
- Harris C, Brenden TO, Vandergoot CS, Faust MD, Herbst SJ, Krueger CC (2021) Tributary use and large-scale movements of grass carp in Lake Erie. *J Great Lakes Res* 47:48–58. <https://doi.org/10.1016/j.jglr.2019.12.006>
- Hatanpää A, Huuskonen H, Kekäläinen J, Kortet R, Hyvärinen P, Vitellietti ML, Piironen J (2020) Early winter foraging success, swimming performance, and morphology of juvenile landlocked Atlantic salmon reared under semi-wild and hatchery conditions. *Can J Fish Aquat Sci* 77:770–778. <https://doi.org/10.1139/cjfas-2019-0079>
- Hawkins LA, Magurran AE, Armstrong JD (2008) Ontogenetic learning of predator recognition in hatchery-reared Atlantic salmon, *Salmo salar*. *Anim Behav* 75:1663–1671. <https://doi.org/10.1016/j.anbehav.2007.10.019>
- Helfman G, Collette BB, Facey DE, Bowen BW (2009) The diversity of fishes: biology, evolution, and ecology. Wiley, Hoboken
- Helfman GS (1999) Behavior and fish conservation: introduction, motivation, and overview. *Environ Biol Fish* 55:7–12
- Herbert-Read JE, Kremer L, Bruintjes R, Radford AN, Ioannou CC (2017) Anthropogenic noise pollution from pile-driving disrupts the structure and dynamics of fish shoals. *Proc Royal Soc B* 284:20171627. <https://doi.org/10.1098/rspb.2017.1627>
- Hilborn R, Amoroso RO, Anderson CM, Baum JK, Branch TA, Costello C et al (2020) Effective fisheries management instrumental in improving fish stock status. *PNAS* 117:2218–2224
- Hobbs RJ, Norton DA (1996) Towards a conceptual framework for restoration ecology. *Rest Ecol* 4:93–110. <https://doi.org/10.1111/j.1526-100X.1996.tb00112.x>
- Hohenlohe PA, Funk WC, Rajora OP (2020) Population genomics for wildlife conservation and management. *Mol Ecol* 30:62–82. <https://doi.org/10.1111/mec.15720>
- Holmlund CM, Hammer M (1999) Ecosystem services generated by fish populations. *Ecol Econ* 29:253–268. [https://doi.org/10.1016/S0921-8009\(99\)00015-4](https://doi.org/10.1016/S0921-8009(99)00015-4)
- Holway DA, Suarez AV (1999) Animal behavior: an essential component of invasion biology. *Trends Ecol Evo* 14:328–330
- Horodysky AZ, Cooke SJ, Brill RW (2015) Physiology in the service of fisheries science: why thinking mechanistically matters. *Rev Fish Biol Fish* 25(3):425–447
- Horwitz DF (2008) Managing pets with behavior problems: realistic expectations. *Vet Clin North Am Small Anim Pract* 38:1005–1021. <https://doi.org/10.1016/j.cvsm.2008.04.006>
- Houck LD, Drickhamer LC (1996) Foundations of animal behavior: classic papers with commentaries. University of Chicago Press, Chicago
- Hrodey PJ, Lewandoski SA, Sullivan WP, Barber JM, Mann KA, Paudel B, Symbai MJ (2021) Evolution of the sea lamprey control barrier program: the importance of lowermost barriers. *J Great Lakes Res* 47:S285–S296. <https://doi.org/10.1016/j.jglr.2021.10.006>
- Hudina S, Hock K, žganec K, (2014) The role of aggression in range expansion and biological invasions. *Curr Zool* 60:401–409. <https://doi.org/10.1093/czoolo/60.3.401>
- Huntingford FA (2004) Implications of domestication and rearing conditions for the behavior of cultivated fishes. *J Fish Biol* 65:122–142. <https://doi.org/10.1111/j.0022-1112.2004.00562.x>
- Hussey NE, Kessel ST, Aarestrup K, Cooke SJ, Cowley PD et al (2015) Aquatic animal telemetry: a

- panoramic window into the underwater world. *Science* 348:1255642. <https://doi.org/10.1126/science.1255642>
- Hutchinson GE (1958) Concluding remarks on the Cold Spring Harbor Symposium on quantitative biology. *Ecology* 22:415–427
- Hyrenbach KD, Forney KA, Dayton PK (2000) Marine protected areas and ocean basin management. *Aquat Conserv Mar Freshwat Ecosyst* 10:437–458
- Hyvärinen P, Rodewald P (2013) Enriched rearing improves survival of hatchery-reared Atlantic salmon smolts during migration in the River Tornionjoki. *Can J Fish Aquat Sci* 70:386–1395. <https://doi.org/10.1139/cjfas-2013-0147>
- Islam D, Berkes F (2016) Indigenous peoples' fisheries and food security: a case from northern Canada. *Food Secur* 8:815–826
- Jackson CD, Brown GE (2011) Differences in antipredator behavior between wild and hatchery-reared juvenile Atlantic salmon (*Salmo salar*) under seminatural conditions. *Can J Fish Aquat Sci* 68:2157–2166. <https://doi.org/10.1139/f2011-129>
- Jacquin L, Petitjean Q, Côte J, Laffaille P, Jean S (2020) Effects of pollution on fish behavior, personality, and cognition: some research perspectives. *Front Ecol Evol* 8:86. <https://doi.org/10.3389/fevo.2020.00086>
- Jones JC, Reynolds JD (1997) Effects of pollution on reproductive behavior of fishes. *Rev Fish Biol Fish* 7:463–491. <https://doi.org/10.1023/A:1018456315671>
- Jørgensen C, Enberg K, Dunlop ES, Arlinghaus R, Boukal DS, Brander K et al (2007) Ecology-Managing evolving fish stocks. *Science* 318:5854. <https://doi.org/10.1126/science.1148089>
- Keenleyside MHA, Hoar WS (1954) Effects of temperature on the responses of young salmon to water currents. *Behavior* 7:77–87
- Kellison GT, Eggleston DB, Taylor JC, Burke JS, Osborne JA (2003) Pilot evaluation of summer flounder stock enhancement potential using experimental ecology. *Mar Ecol Prog Ser* 250:263–278
- Kershner MW, Schael DM, Knight RL, Stein RA, Marschall EA (1999) Modeling sources of variation for growth and predatory demand of Lake Erie walleye (*Stizostedion vitreum*), 1986–1995. *Can J Fish Aquat Sci* 56:527–538. <https://doi.org/10.1139/f98-193>
- Killen SS, Marras S, Metcalfe NB, McKenzie DJ, Domenici P (2013) Environmental stressors alter relationships between physiology and behaviour. *Trends Ecol Evol* 28(11):651–658
- Klimley AP, Putman NF, Keller BA, Noakes DLG (2021) A call to assess the impacts of electromagnetic fields from subsea cables on the movement ecology of marine migrants. *Cons Sci Prac* 3(8):e436. <https://doi.org/10.1111/csp2.436>
- Kolar CS, Lodge DM (2001) Progress in invasion biology: predicting invaders. *Trends Ecol Evol* 16:199–204. [https://doi.org/10.1016/S0169-5347\(01\)02101-2](https://doi.org/10.1016/S0169-5347(01)02101-2)
- Koster WM, Stuart I, Tonkin Z, Dawson D, Fanson B (2021) Environmental influences on migration patterns and pathways of a threatened potamodromous fish in a regulated lowland river network. *Ecohydrology* 14:e2260. <https://doi.org/10.1002/eco.2260>
- Kuparinen A, Merila J (2007) Detecting and managing fisheries induced evolution. *Trends Ecol Evol* 22:652–659. <https://doi.org/10.1016/j.tree.2007.08.011>
- Laffaille P (2011) Impact of stocked Atlantic salmon (*Salmo salar* L.) on habitat use by the wild population. *Ecol Freshw Fish* 20:67–73
- Lea JSE, Humphries NE, von Brandis RG, Clarke CR, Sims DW (2016) Acoustic telemetry and network analysis reveal the space use of multiple reef predators and enhance marine protected area design. *Proc Royal Soc B* 283:20160717. <https://doi.org/10.1098/rspb.2016.0717>
- Lemopoulos A, Uusi-Heikkilä S, Hyvärinen P, Alioravainen N, Prokkola JM, Elvidge CK, Vasemägi A, Vainikka A (2019) Association mapping based on a common-garden migration experiment reveals candidate genes for migration tendency in brown trout. *G3* 9:2997–2896. <https://doi.org/10.1534/g3.119.400369>
- Lennox R, Blouin-Demers G, Rous AM, Cooke SJ (2016) Tracking invasive animals with electronic tags to assess risks and develop management strategies. *Biol Invasions* 18:1219–1233. <https://doi.org/10.1007/s10530-016-1071-z>
- Lennox RJ, Engler-Palma C, Kowarski K, Filous A, Whitlock R, Cooke SJ, Auger-Méthé M (2019) Optimizing marine spatial plans with animal tracking data. *Can J Fish Aquat Sci* 76:497–509. <https://doi.org/10.1139/cjfas-2017-0495>
- Linton ED, Jónsson B, Noakes DLG (2007) Effects of water temperature on the swimming and climbing behavior of glass eels, *Anguilla* spp. *Environ Biol Fishes* 78:189–192. <https://doi.org/10.1007/s10641-005-1367-9>
- Locke B (1995) An investigation of relationships between otolith age and growth and foraging behaviour in recently emerged brook charr *Salvelinus fontinalis*. MSc University of Guelph.
- Luczkovich JJ, Mann DA, Rountree RA (2008) Passive acoustics as a tool in fisheries science. *Trans Am Fish Soc* 137:533–541
- Lynch AJ, Cooke SJ, Deines AM, Bower SD, Bunnell DB, Cowx IG et al (2016) The social, economic, and environmental importance of inland fish and fisheries. *Enviro Rev* 24:115–121. <https://doi.org/10.1139/er-2015-0064>
- Magnuson JJ, Crowder LB, Medvick PA (1979) Temperature as an ecological resource. *Integr Comp Biol* 19:331–343
- Malik DS, Sharma AK, Sharma AK, Thakur R, Sharma M (2020) A review on impact of water pollution on freshwater fish species and their aquatic environment. *Adv Environ Pollut Manag Wastewater Impacts Treat Technol* 1:10–28
- Manny BA, Roseman EF, Kennedy G, Boase JC, Craig JM, Bennion DH, Read J, Vaccaro L, Chiotti J, Drouin R, Ellison R (2015) A scientific basis for restoring fish spawning habitat in the St. Clair and Detroit Rivers of the Laurentian Great Lakes: Restoring fish spawning habitat. *Rest Ecol* 23:149–156
- Marsden JE, Binder TR, Johnson J, He J, Dingledine N, Adams J, Johnson NS, Buchinger TJ, Krueger CC (2016) Five-year evaluation of habitat remediation in Thunder Bay, Lake Huron: comparison of constructed reef characteristics that attract spawning lake trout. *Fish Res* 183:275–286. <https://doi.org/10.1016/j.fishres.2016.06.012>

- Marsden JE, Binder TR, Riley SC, Farha SA, Krueger CC (2021) Habitat. In: Muir AM, Krueger CC, Hansen MJ, Riley SC (ed) The Lake Charr *Salvelinus namaycush*: biology, ecology, distribution, and management. Springer International Publishing, New York, pp 167–202 https://doi.org/10.1007/978-3-030-62259-6_6
- Martin G, Espinoza M, Heupel M, Simpfendorfer CA (2020) Estimating marine protected area network benefits for reef sharks. *J Appl Ecol* 57:1969–1980. <https://doi.org/10.1111/1365-2664.13706>
- Martin GR, Crawford R (2015) Reducing bycatch in gillnets: a sensory ecology perspective. *Glob Ecol Conserv* 3:8–50
- Martins EG, Hinch SG, Patterson DA, Hague MJ, Cooke SJ, Miller KM, Lapointe MF, English KK, Farrell AP (2011) Effects of river temperature and climate warming on stock-specific survival of adult migrating Fraser River sockeye salmon (*Oncorhynchus nerka*). *Glob Chang Biol* 17:99–114. <https://doi.org/10.1111/j.1365-2486.2010.02241.x>
- McCarthy SG, Incardona JP, Scholz NL (2008) Coastal storms, toxic runoff, and the sustainable conservation of fish and fisheries. *Am Fish Soc Symp* 64:7–27
- McLaughlin RL, Ferguson MM, Noakes DLG (1995) Concentrations of nucleic acids and protein as indices of nutritional status for recently emerged brook *Salvelinus fontinalis*. *Can J Fish Aquat Sci* 52:848–854
- McLaughlin RL, Ferguson MM, Noakes DLG (1999) Adaptive peaks and alternative foraging tactics: evidence of short-term divergent selection for sitting-and-waiting and actively searching. *Behav Ecol Sociobiol* 45:386–395
- McLaughlin RL, Noakes DLG (1998) Going against the flow: an examination of the propulsive movements made by young brook trout in streams. *Can J Fish Aquat Sci* 55:853–860. <https://doi.org/10.1139/F97-308>
- McLaughlin RL, Porto L, Noakes DLG, Baylis JR, Carl LM, Dodd HR, Goldstein JD, Hayes DB, Randall RG (2006) Effects of low-head barriers on stream fishes: taxonomic affiliations and morphological correlates of sensitive species. *Can J Fish Aquat Sci* 63:766–779. <https://doi.org/10.1139/F05-256>
- McNamara JM, Houston AI (1986) The common currency for behavioral decisions. *Am Nat* 127(3):358–378
- McNicol RE, Noakes DLG (1981) Territories and territorial defense in juvenile brook charr, *Salvelinus fontinalis* (Pisces: Salmonidae). *Can J Zool* 59:22–28. <https://doi.org/10.1139/Z81-005>
- McNicol RE, Noakes DLG (1984) Environmental influences on territoriality of juvenile brook charr, *Salvelinus fontinalis*, in a stream environment. *Environ Biol Fishes* 10:29–42. <https://doi.org/10.1007/Bf00001660>
- Mench J (1998) Why it is important to understand animal behavior. *ILAR J* 39:20–26. <https://doi.org/10.1093/ilar.39.1.20>
- Miranda LE, Raborn SW (2013) Interactions between striped bass and other game fish in reservoirs. *Am Fish Soc Symp* 80:501–519
- Monk CT, Bekkevold D, Klefoth T, Pagel T, Palmer M, Arlinghaus R (2021) The battle between harvest and natural selection creates small and shy fish. *PNAS* 118:e2009451118. <https://doi.org/10.1073/pnas.2009451118>
- Moreno CB, Muñoz-Delgado J (2007) An account on the history of ethology. *Suma Psicol* 14:213–224
- Morissette O, Paradis Y, Pouliot R, Lecomte F (2018) Spatio-temporal changes in littoral fish community structure along the St. Lawrence River (Québec, Canada) following round goby (*Neogobius melanostomus*) invasion. *Aquat Invasions* 13:501–512. <https://doi.org/10.3391/ai.2018.13.4.08>
- Muir AM (2022) A CHARRmed life: a synthesis of scientific contributions by David Lloyd George Noakes (1942–2020). *Environ Biol Fish*. <https://doi.org/10.1007/s10641-022-01242-8>
- Munakata A, Ogihara E, Schreck CB, Noakes DLG (2017) Effects of short term acclimation in cool and warm water and influent water temperatures on temperature selection behavior in juvenile steelhead trout, *Oncorhynchus mykiss*. *Aquaculture* 467:219–224
- Myles-Gonzalez E, Burness G, Yavno S, Rooke A, Fox MG (2015) To boldly go where no goby has gone before: boldness, dispersal tendency, and metabolism at the invasion front. *Behav Ecol* 26:1083–1090. <https://doi.org/10.1093/beheco/arv050>
- Naisbett-Jones LC, Putman NF, Scanlan MM, Noakes DLG, Lohmann KJ (2020) Magnetoreception in fishes: the effect of magnetic pulses on orientation of juvenile Pacific salmon. *J Exp Biol* 223:p.jeb222091
- Naish KA, Taylor JE III, Levin PS, Quinn TP, Winton JR, Huppert D, Hilborn R (2007) An evaluation of the effects of conservation and fishery enhancement hatcheries on wild populations of salmon. *Adv Mar Biol* 53:61–194. [https://doi.org/10.1016/s0065-2881\(07\)53002-6](https://doi.org/10.1016/s0065-2881(07)53002-6)
- Noakes DL, Beamish FWH, Rossiter A (1999) Conservation implications of behaviour and growth of the lake sturgeon, *Acipenser fulvescens*, in northern Ontario. *Environ Biol Fish* 55(1):135–144
- Noakes DLG, Curry RA (1995) Lessons to be learned from attempts to restore *Salvelinus* species other than *S. namaycush*: a review of reproductive behavior. *J Great Lakes Res* 21:54–64. [https://doi.org/10.1016/S0380-1330\(95\)71083-8](https://doi.org/10.1016/S0380-1330(95)71083-8)
- Noakes DLG, Leatherland JF (1977) Social dominance and interrenal cell activity in rainbow trout, *Salmo gairdneri* (Pisces, Salmonidae). *Environ Biol Fish* 2:131–136. <https://doi.org/10.1007/Bf00005368>
- Nyberg P (1984) Effects of liming on fisheries. *Phil Trans R Soc Lon B* 305:549–560. <https://doi.org/10.1098/rstb.1984.0076>
- O’Keefe CE, Cadrin SX, Stokesbury KD (2014) Evaluating effectiveness of time/area closures, quotas/caps, and fleet communications to reduce fisheries bycatch. *ICES J Mar Sci* 71:1286–1297
- O’Hara K (1986) Fish behavior and the management of freshwater fisheries. In: Pitcher T (ed) *The Behavior of Teleost Fishes*. Springer, Boston, pp 496–521
- Ochwada F, Loneragan NR, Gray CA, Suthers IM, Taylor MD (2009) Complexity affects habitat preference and predation mortality in postlarval *Penaeus plebejus*: implications for stock enhancement. *Mar Ecol Prog Ser* 380:161–171. <https://doi.org/10.3354/meps07936>
- Olsen EM, Heupel MR, Simpfendorfer CA, Moland E (2012) Harvest selection on Atlantic cod behavioral traits: implications for spatial management. *Ecol Evol* 2:1549–1562. <https://doi.org/10.1002/ece3.244>

- Ovando D, Hilborn R, Monnahan C, Rudd M, Sharma R, Thorson JT, Rousseau Y, Ye Y (2021) Improving estimates of the state of global fisheries depends on better data. *Fish Fisheries* 22:1377–1391. <https://doi.org/10.1111/faf.12593>
- Owens IP (2006) Where is behavioral ecology going? *Trends Ecol Evol* 21:356–361. <https://doi.org/10.1016/j.tree.2006.03.014>
- Parsons GR, Foster DG, Osmond M (2012) Applying fish behavior to reduce trawl bycatch: evaluation of the nested cylinder bycatch reduction device. *Mar Technol Soc J* 46:26–33
- Peat TB, Gutowsky LFG, Doka SE, Midwood JD, Lapointe NWR, Hlevca B, Wells MG, Portiss R, Cooke SJ (2016) Comparative thermal biology and depth distribution of largemouth bass (*Micropterus salmoides*) and northern pike (*Esox lucius*) in an urban harbour of the Laurentian Great Lakes. *Can J Zool* 94:767–776. <https://doi.org/10.1139/cjz-2016-0053>
- Pedersen LF, Koed A, Malte H (2008) Swimming performance of wild and F1-hatchery-reared Atlantic salmon (*Salmo salar*) and brown trout (*Salmo trutta*) smolts. *Ecol Freshw Fish* 17:425–431. <https://doi.org/10.1111/j.1600-0633.2008.00293.x>
- Pelicice FM, Pompeu PS, Agostinho AA (2015) Large reservoirs as ecological barriers to downstream movements of Neotropical migratory fish. *Fish Fisheries* 16:697–715. <https://doi.org/10.1111/faf.12089>
- Pitcher T (1992) Behavior of teleost fishes. Springer, Boston
- Porto LM, McLaughlin RL, Noakes DLG (1999) Low-head barrier dams restrict the movements of fishes in two Lake Ontario streams. *N Am J Fisheries Manag* 19:1028–1036. [https://doi.org/10.1577/1548-8675\(1999\)019%3c1028:Lhbdrt%3e2.0.Co;2](https://doi.org/10.1577/1548-8675(1999)019%3c1028:Lhbdrt%3e2.0.Co;2)
- Portt CB, Balon EK, Noakes DLG (1986) Biomass and production of fishes in natural and channelized streams. *Can J Fish Aquat Sci* 43:1926–1934. <https://doi.org/10.1139/F86-238>
- Putman NF, Lohmann KJ, Putman EM, Quinn TP, Klimley AP, Noakes DLG (2013) Evidence for geomagnetic imprinting as a homing mechanism in Pacific salmon. *Current Biol* 23:312–316. <https://doi.org/10.1016/J.Cub.2012.12.041>
- Putman NF, Meinke AM, Noakes DLG (2014a) Rearing in a distorted magnetic field disrupts the “map sense” of juvenile steelhead trout. *Biol Lett* 10:20140169. <https://doi.org/10.1098/Rsbl.2014.0169>
- Putman NF, Scanlan MM, Billman EJ, O’Neil JP, Couture RB, Quinn TP, Lohmann KJ, Noakes DLG (2014b) An inherited magnetic map guides ocean navigation in juvenile Pacific salmon. *Current Biol* 24:446–450. <https://doi.org/10.1016/J.Cub.2014.01.017>
- Raby GD, Vandergoot CS, Hayden TA, Faust MD, Kraus RT, Dettmers JM, Cooke SJ, Zhao Y, Fisk AT, Krueger CC (2018) Does behavioural thermoregulation underlie seasonal movements in Lake Erie walleye? *Can J Fish Aquat Sci* 75:488–496. <https://doi.org/10.1139/cjfas-2017-0145>
- Redpath TD, Cooke SJ, Suski CD, Arlinghaus R, Couture P, Wahl DH, Philipp DP (2010) The metabolic and biochemical basis of vulnerability to recreational angling after three generations of angling-induced selection in a teleost fish. *Can J Fisheries Aquat Sci* 67:1983–1992. <https://doi.org/10.1139/F10-120>
- Reid AJ, Carlson AK, Creed IF, Eliason EJ, Gell PA, Pieter TJ, Kidd KA et al (2019) Emerging threats and persistent conservation challenges for freshwater biodiversity. *Biol Rev* 94:849–873. <https://doi.org/10.1111/brv.12480>
- Ricklefs RE, Wikelski M (2002) The physiology/life-history nexus. *Trends Ecol Evol* 17(10):462–468
- Robinson RA, Crick HQ, Learmonth JA, Maclean IM, Thomas CD, Bairlein F et al (2009) Travelling through a warming world: climate change and migratory species. *Endanger Species Res* 7:87–99
- Ruland F, Jeschke JM (2020) How biological invasions affect animal behavior: a global, cross-taxonomic analysis. *J Anim Ecol* 89:2531–2541. <https://doi.org/10.1111/1365-2656.13306>
- Saaristo M, Brodin T, Balshine S, Bertram MG, Brooks BW et al (2018) Direct and indirect effects of chemical contaminants on the behavior, ecology and evolution of wildlife. *Proc Royal Soc B* 285:20181297. <https://doi.org/10.1098/rspb.2018.1297>
- Sahrhage D, Lundbeck J (2012) A history of fishing. Springer Science and Business Media, Boston
- Sbragaglia V, Klamsler PP, Romanczuk P, Arlinghaus R (2022) Evolutionary impact of size-selective harvesting on shoaling behavior: individual-level mechanisms and possible consequences for natural and fishing mortality. *Am Nat* 199(4):000–000
- Scanlan MM, Putman NF, Pollock AM, Noakes DLG (2018) Magnetic map in nonanadromous Atlantic salmon. *PNAS* 115:10995–10999. <https://doi.org/10.1073/Pnas.1807705115>
- Schemmel EM (2009) Managing adult hatchery summer steelhead for a recreational fishery with reduced hatchery and wild interactions. Master’s thesis, Oregon State University
- Scherer E (1992) Behavioral responses as indicators of environmental alterations: approaches, results, developments. *J Appl Ichthyol* 8:122–131. <https://doi.org/10.1111/J.1439-0426.1992.TB00674.X>
- Schindler DE, Armstrong JB, Reed TE (2015) The portfolio concept in ecology and evolution. *Front Ecol Environ* 13:257–263. <https://doi.org/10.1890/140275>
- Schindler DE, Hilborn R, Chasco B, Boatright CP, Quinn TP, Rogers LA, Webster MS (2010) Population diversity and the portfolio effect in an exploited species. *Nature* 465:609–612. <https://doi.org/10.1038/nature09060>
- Scott RJ, Judge KA, Ramster K, Noakes DLG, Beamish FWH (2005a) Interactions between naturalised exotic salmonids and reintroduced Atlantic salmon in a Lake Ontario tributary. *Ecol Freshw Fish* 14:402–405. <https://doi.org/10.1111/J.1600-0633.2005.00115.X>
- Scott RJ, Kosick R, Clement M, Noakes DLG, Beamish FWH (2005b) Nest site selection and spawning by captive bred Atlantic Salmon, *Salmo salar*, in a natural stream. *Environ Biol Fishes* 74:309–321. <https://doi.org/10.1007/S10641-005-1330-9>
- Scott RJ, Noakes DL, Beamish FWH, Carl LM (2003) Chinook salmon impede Atlantic salmon conservation in Lake Ontario. *Ecol Freshw Fish* 12:66–73. <https://doi.org/10.1034/j.1600-0633.2003.00002.x>

- Scott RJ, Poos MS, Noakes DLG, Beamish FWH (2005c) Effects of exotic salmonids on juvenile Atlantic salmon behavior. *Ecol Freshw Fish* 14:283–288. <https://doi.org/10.1111/J.1600-0633.2005.00099.X>
- Self KE, Schreck CB, Cogliati KM, Billman EJ, Noakes DLG (2018a) Egg size and growth in steelhead *Oncorhynchus mykiss*. *J Fish Biol* 93(465–468):199
- Self KE, Schreck CB, Cogliati KM, Billman EJ, Noakes DLG (2018b) The effect of rearing structures on behaviour and movement of juvenile steelhead *Oncorhynchus mykiss*. *J Fish Biol* 93:449–454
- Shumway CA (1999) A neglected science: applying behavior to aquatic conservation. *Environ Biol Fishes* 55:183–201
- Siefkes MJ, Steeves TB, Sullivan WP, Twohey MB, Li W (2013) Sea lamprey control: past, present, and future. In: Taylor WW, Lynch AJ, Leonard NJ (eds) *Great Lakes Fisheries Policy and Management*. Michigan State University Press, East Lansing, pp 651–704
- Sih A, Bolnick DI, Luttbeg B, Orrock JL, Peacor SD et al (2010) Predator–prey naïveté, antipredator behavior, and the ecology of predator invasions. *Oikos* 119:610–621. <https://doi.org/10.1111/j.1600-0706.2009.18039.x>
- Sims DW, Wearmouth VJ, Genner MJ, Southward AJ, Hawkins SJ (2004) Low-temperature-driven early spawning migration of a temperate marine fish. *J Anim Ecol* 73:333–341. <https://doi.org/10.1111/j.0021-8790.2004.00810.x>
- Sims DW, Wearmouth VJ, Southall EJ, Hill JM, Moore P, Rawlinson K, Hutchinson N, Budd GC, Righton D, Metcalfe JD, Nash JP, Morritt D (2006) Hunt warm, rest cool: bioenergetic strategy underlying diel vertical migration of a benthic shark. *J Anim Ecol* 75:176–190. <https://doi.org/10.1111/j.1365-2656.2005.01033.x>
- Skúlason S, Snorrason SS, Ota D, Noakes DLG (1993) Genetically based differences in foraging behavior among sympatric morphs of arctic charr (Pisces: Salmonidae). *Anim Behav* 45:1179–2119. <https://doi.org/10.1006/Anbe.1993.1140>
- Smith BR, Blumstein DT (2008) Fitness consequences of personality: a meta-analysis. *Behav Ecol* 19(2):448–455
- Snucins EJ, Gunn JM (1995) Coping with a warm environment: behavioral thermoregulation by lake trout. *Trans Am Fish Soc* 124:118–123
- Sol D, Weis JS (2019) Highlights and insights from "Biological Invasions and Animal Behavior". *Aquat Invasions* 14:551–565. <https://doi.org/10.3391/ai.2019.14.3.12>
- Sorensen PW, Fine JM, Dvornikovs V, Jeffrey CS, Shao F, Wang J, Vrieze LA, Anderson KR, Hoye TR (2005) Mixture of new sulfated steroids functions as a migratory pheromone in the sea lamprey. *Nat Chem Biol* 1:324–328. <https://doi.org/10.1038/nchembio739>
- Speers-Roesch B, Norin T (2016) Ecological significance of thermal tolerance and performance in fishes: new insights from integrating field and laboratory approaches. *Function Ecol* 30:842–884
- Steinhart GB, Stein RA, Marschall EA (2004) High growth rate of young-of-the-year smallmouth bass in Lake Erie: a result of the round goby invasion? *J Great Lakes Res* 30:381–389. [https://doi.org/10.1016/S0380-1330\(04\)70355-X](https://doi.org/10.1016/S0380-1330(04)70355-X)
- Steneck RS, Pauly D (2019) Fishing through the Anthropocene. *Current Biol* 29:R987–R992. <https://doi.org/10.1016/j.cub.2019.07.081>
- Stewart HA, Cogliati KM, Billman EJK, Unrein JR, Noakes DLG, Schreck CB (2017) Effects of transportation timing on osmoregulation and survival in yearling hatchery Chinook salmon (*Oncorhynchus tshawytscha*). *J Appl Aquac* 29:277–290
- Stewart HA, Noakes DLG, Cogliati KM, Peterson JT, Iversen MH, Schreck CB (2016) Salinity effects on plasma ion levels, cortisol, and osmolality in Chinook salmon following lethal sampling. *Comp Biochem Physiol* 192:38–43
- Sumpter DJT, Broomhead DS (2001) Relating individual behaviour to population dynamics. *Proc Royal Soc London B* 268(1470):925–932
- Suski CD, Cooke SJ (2007) Conservation of aquatic resources through the use of freshwater protected areas: opportunities and challenges. *Biodivers Conserv* 16:2015–2029. <https://doi.org/10.1007/s10531-006-9060-7>
- Sutherland WJ (1996) *From individual behaviour to population ecology* (Vol. 11). Oxford University Press on Demand.
- Sutherland WJ (1998) The importance of behavioral studies in conservation biology. *Anim Behav* 56:801–809. <https://doi.org/10.1006/anbe.1998.0896>
- Thalinger B, Wolf E, Traugott M, Wanzenböck J (2019) Monitoring spawning migrations of potamodromous fish species via eDNA. *Sci Rep* 9:1–11. <https://doi.org/10.1038/s41598-019-51398-0>
- Thompson NF, Leblanc CA, Romer JD, Schreck CB, Blouin MS, Noakes DLG (2015) Sex-biased survivorship and differences in migration of wild steelhead (*Oncorhynchus mykiss*) smolts from two coastal Oregon rivers. *Ecol Freshw Fish* 98:1–10
- Tickner D, Opperman JJ, Abell R, Acreman M, Arthington AH, Bunn SE, Cooke SJ, Dalton J, Darwall W, Edwards G, Harrison I et al (2020) Bending the curve of global freshwater biodiversity loss: an emergency recovery plan. *Bioscience* 70:330–342. <https://doi.org/10.1093/biosci/biaa002>
- Tinbergen N (1963) On aims and methods of Ethology. *Ethology* 20:410–433. <https://doi.org/10.1111/j.1439-0310.1963.tb01161.x>
- Tuomainen U, Candolin U (2011) Behavioral responses to human-induced environmental change. *Biol Rev* 86:640–657. <https://doi.org/10.1111/j.1469-185X.2010.00164.x>
- Ueda H (2011) Physiological mechanism of homing migration in Pacific salmon from behavioral to molecular biological approaches. *Gen Comp Endocrinol* 170:222–232. <https://doi.org/10.1016/j.ygcen.2010.02.003>
- UNEA (2019) *New UN Decade on Ecosystem Restoration offers unparalleled opportunity for job creation, food security and addressing climate change*. United Nations Environment Agency. <https://www.unenvironment.org/news-and-stories/press-release/new-un-decade-ecosystem-restoration-offers-unparalleled-opportunity>. Accessed 15 November 2021
- Uusi-Heikkilä S, Wolter C, Klefoth T, Arlinghaus R (2008) A behavioral perspective on fishing-induced evolution. *Trends Ecol Evo* 23:419–421. <https://doi.org/10.1016/j.tree.2008.04.006>
- Vainikka A, Huusko R, Hyvärinen P, Korhonen PK, Laaksonen T, Koskela J, Vielma J, Hirvonen H, Salminen M (2012) Food restriction prior to release reduces precocious

- maturity and improves migration tendency of Atlantic salmon (*Salmo salar*) smolts. *Can J Fish Aquat Sci* 69:1981–1993. <https://doi.org/10.1139/f2012-119>
- Vainikka A, Hyvärinen P, Tiainen J, Lemopoulos A, Alioravainen N, Prokkola JM, Elvidge CK, Arlinghaus R (2021) Fishing-induced versus natural selection in different brown trout (*Salmo trutta*) strains. *Can J Fish Aquat Sci* 78:1586–1596. <https://doi.org/10.1139/cjfas-2020-0313>
- Vainikka A, Kallio-Nyberg I, Heino M, Koljonen M-L (2010) Divergent trends in life-history traits between Atlantic salmon *Salmo salar* of wild and hatchery origin in the Baltic Sea. *J Fish Biol* 76:622–640. <https://doi.org/10.1111/j.1095-8649.2009.02520.x>
- Vehanen T, Huusko A, Hokki R (2009) Competition between hatchery-raised and wild brown trout *Salmo trutta* in enclosures — do hatchery releases have negative effects on wild populations? *Ecol Freshw Fish* 18:261–268. <https://doi.org/10.1111/j.1600-0633.2008.00343.x>
- Villegas-Ríos D, Jacoby DM, Mourier J (2022) Social networks and the conservation of fish. *Commun Biol* 5(1):1–8
- Walters CJ, Holling CS (1990) Large-scale management experiments and learning by doing. *Ecology* 71:2060–2068. <https://doi.org/10.2307/1938620>
- Wardle CS (1986) Fish behavior and fishing gear. In: Pitcher T (ed) *The behavior of teleost fishes*. Springer, Boston, pp 463–495
- Warner RE, Peterson KK, Borgman L (1966) Behavioral pathology in fish: a quantitative study of sublethal pesticide toxication. *J Appl Ecol* 3:223–247. <https://doi.org/10.2307/2401462>
- Weis JS, Sol D (2016) *Biological invasions and animal behavior*. Cambridge University Press, Cambridge
- Whitmarsh SK, Fairweather PG, Huvneers C (2017) What is Big BRUVver up to? Methods and uses of baited underwater video. *Rev Fish Biol Fish* 27:53–73
- Wilcove DS, Rothstein D, Dubow J, Phillips A, Losos E (1998) Quantifying threats to imperiled species in the United States. *Bioscience* 48:607–615
- Wilson CC, Lavender M, Black J (2007) Genetic assessment of walleye (*Sander vitreus*) restoration efforts and options in Nipigon Bay and Black Bay, Lake Superior. *J Great Lakes Res* 33:133–144. [https://doi.org/10.3394/0380-1330\(2007\)33\[133:GAOWSV\]2.0.CO;2](https://doi.org/10.3394/0380-1330(2007)33[133:GAOWSV]2.0.CO;2)
- Wong B, Candolin U (2015) Behavioral responses to changing environments. *Behav Ecol* 26:665–673. <https://doi.org/10.1093/beheco/aru183>
- Woo-Durand C, Matte J-M, Cuddihy G, McGourdji CL, Venter O, Grant JWA (2020) Increasing importance of climate change and other threats to at-risk species in Canada. *Environ Rev* 28:449–456
- Yamamoto S, Nakamura H, Koga K (2008) Interaction between hatchery and wild juvenile white-spotted charr *Salvelinus leucomaenis* in a stream enclosure experiment. *J Fish Biol* 73:861–869
- Zielinski DP, McLaughlin RL, Pratt TC, Goodwin RA, Muir AM (2020) Single-stream recycling inspires selective fish passage solutions for the connectivity conundrum in aquatic ecosystems. *Bioscience* 70:871–886

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