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Review

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The value of electronic tagging and tracking studies for understanding fish–hypoxia interactions

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Abstract

***Objective*: Hypoxia (i.e., low dissolved oxygen availability) is a natural phenomenon but can also be induced by human activities (e.g., nutrient enrichment from runoff). Given that dissolved oxygen is essential for aquatic life, periods of hypoxia tend to have negative consequences (e.g., sublethal disturbances, mortality) for most fishes. Extensive laboratory research has documented hypoxia thresholds and physiological and behavioral outcomes for a variety of freshwater and marine fishes and there is also an extensive body of fieldwork assessing population-level responses (e.g., survival, distribution). Yet, studying how individual fish respond to hypoxia in the wild has proved challenging; electronic tagging and tracking tools (e.g., biotelemetry, biologging) have made it easier to study individual responses to hypoxia and complement other tools like hydroacoustics that tend to focus on population-level responses.**

***Methods*: We review what has been learned from contemporary studies that employ electronic tagging and tracking tools to understand how fish respond to hypoxia in the wild. Topics explored include identifying and validating hypoxia thresholds, habitat compression, connectivity, mortality, physiological and bioenergetic consequences, and extreme weather conditions. We also consider what we have learned about evaluating various management plans for hypoxia and reflect on how electronic tags have also been used in aquaculture systems and in hybrid studies that combine laboratory and field research. We highlight fishes in Lake Erie as a research narrative to demonstrate how electronic tagging and tracking have markedly improved our understanding of a longstanding hypoxia issue.**

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***Results*: Our synthesis revealed that electronic tagging and tracking have provided critical information on how fish respond to hypoxia in the field, revealing complex trade-offs and compensatory mechanisms as well as cryptic hypoxia-induced mortality. Beyond just illuminating space use and mortality, tags equipped with various sensors are revealing how fish deal with hypoxia in real time in terms of physiology, bioenergetics, and behavior.**

***Conclusions*: As electronic tagging and tracking methods experience further innovation and are increasingly applied to understand the effects of hypoxia on fish, we expect more unanticipated findings about the effects of hypoxia on fish in all aquatic ecosystems, which will strengthen our ability to manage and mitigate hypoxia. Combining tools and approaches (e.g., lab and field) is perhaps the best way to generate comprehensive understanding.**

Keywords: biologging, electronic tagging, hypoxia, management, telemetry

Lay summary

While the impact of hypoxia on fish has a long history of study in both the lab and field, the improvement of electronic tagging has gradually increased our understanding of hypoxia's impact on fish in the wild. Here we review and synthesize literature on the effect of hypoxia on wild fish, sharing insights gained from recent studies that have capitalized on electronic tag technology (i.e., biologgers, telemetry) and demonstrating its effectiveness with a case study on fishes from Lake Erie.

Introduction

Hypoxia is defined as conditions in aquatic systems (natural or human created) whereby dissolved oxygen (DO) levels are low or depleted (Farrell & Richards, 2009). This term is inherently subjective in that what is hypoxic in one system or for one organism may not be in a different system or for a different organism (Diaz & Breitburg, 2009; Farrell & Richards, 2009). Hypoxia occurs in marine waters, freshwaters, and estuarine waters and is a natural, albeit often episodic, and complex phenomenon that can occur as a result of physical processes, weather events, biological activities (e.g., microbial decomposition), or chemical reactions. Human activities can trigger hypoxic conditions that directly or indirectly influence natural phenomena (e.g., via climate change or nutrient enrichment), leading to more extreme or frequent hypoxic conditions (Jenny et al., 2016; Meire et al., 2013; Rabalais et al., 2010). Turning off water flows, whether in a fish tank in an aquaculture or research facility, or restricting flows in rivers (e.g., due to holding back water for hydropower generation) can also create hypoxic conditions that can typically be rapidly reversed simply by restoring water flow (Boyd & Tucker, 2014; Mallin et al., 2006). Hypoxia has been widely documented in systems that span the globe and range from under-ice conditions in polar regions to tropical floodplains with wide-ranging negative consequences for aquatic life (including fish), as well as humans and society more broadly (Diaz & Rosenberg, 2011). Some systems are particularly prone to hypoxia and have been the subject of extensive and high-profile research and mitigation efforts (e.g., the hypoxic zone at the mouth of the Mississippi River, which has been referred to as "the dead zone"; Rabalais & Turner, 2019).

Fish are common features in aquatic systems and deliver a wide range of ecosystem services that benefit nature and people (Holmlund & Hammer, 1999). It is not surprising then that hypoxia has the potential to dramatically impact fish populations and assemblages. For that reason, there are many syntheses on hypoxia and its impacts on fish. The vast majority of that work has been done in the laboratory and is quite reductionist or mechanistic, with a focus on various physiological (Richards, 2009; T. Wang et al., 2009; Wu, 2009) and sometimes behavioral end points (Chapman & Mckenzie, 2009; Kramer, 1987). Such work has provided a foundational understanding of hypoxia on individual fish. However, there is also a notable body of population-level work done in the wild using methods such as hydroacoustics, mark–recapture, and other assessments of vital rates. Emanating from that work are syntheses focused on a specific habitat or region (e.g., the Amazon, coral reefs, the intertidal zone). Of the broader, high-level reviews, most are 15+ years old (but see Roman et al., 2019; Z. Wang et al., 2023), but more importantly, none have considered the effects of hypoxia on individual fish based on research in the field, where fishes must contend with a range of ecological and environmental challenges and realities. We submit here that electronic tagging and tracking tools (see Hussey et al., 2015) are yielding novel data on how fishes in the wild deal with hypoxia, with incredible growth of the evidence base in that space over the past decade (Figure 1).

The objective of this paper was not to synthesize contemporary information on the effects of hypoxia on fishes as others have done, that well drawing upon large numbers of laboratory and field studies (see Roman et al., 2019; Z. Wang et al., 2023). Here we focus our review on field-collected data, where individual fish responses to hypoxia are studied using electronic tagging and tracking tools (i.e., biotelemetry and biologging). We acknowledge that there are other tools, like hydroacoustics (Ludsin et al., 2009; Meng et al., 2025), mark–recapture (Lappalainen et al., 2016), presence–absence studies (Killgore & Hoover, 2001), passive acoustics (Luczkovich et al., 2024), otolith microchemistry (Altenritter et al., 2018), whole-lake manipulations (Jeppesen et al., 1990), and so on, that can be used to study fishes in the wild at the population level, but that is outside the scope of our review. We include studies where fish–hypoxia relationships (e.g., presence–absence, space use, movement) are studied in the field and fish are entirely free-swimming (e.g., not held in cages or

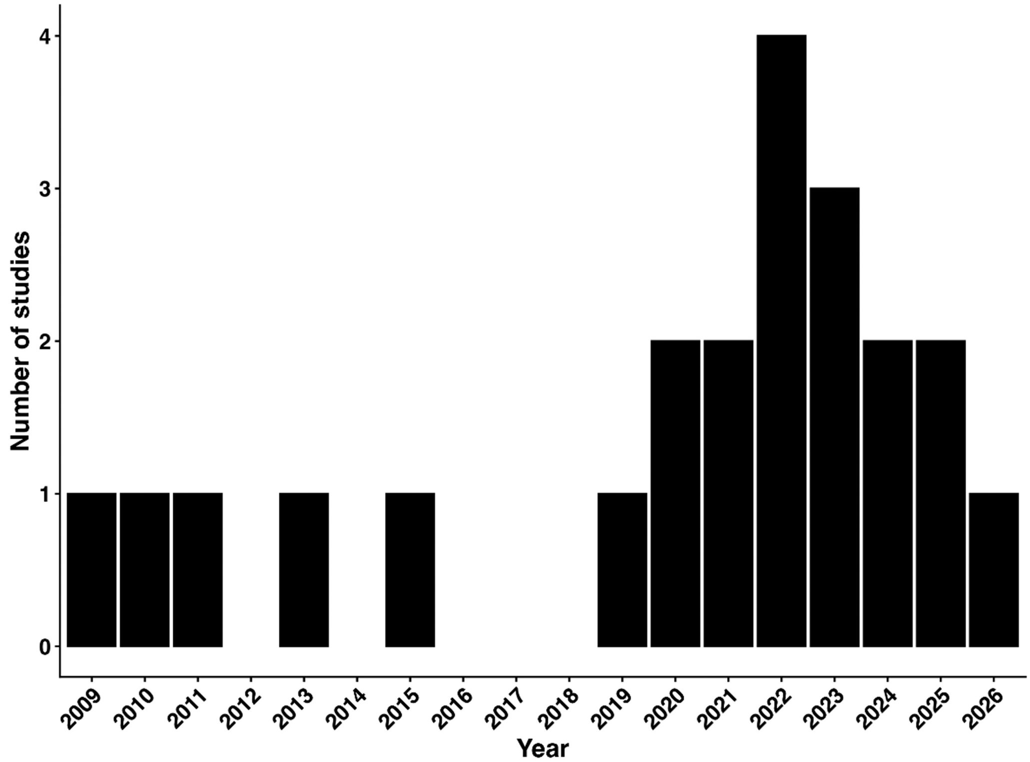

Figure 1 Visualization of temporal trends in studies located in Web of Science search conducted on June 3, 2026, using the Boolean search string [AB or TI = hypoxi* and fish* AND (telemetry OR biologg*)]. The papers located were screened at title and abstract to ensure that they were indeed electronic tagging and tracking studies of fishes related to hypoxia. That structured search did not locate all the references we ended up finding to support our review but provides a repeatable approach to assess trends through time. Notably, there are more studies on these topics published in the past 10 years than in history (the first that our structured search located was in 2009), which is remarkable given that various tracking tools have existed for over 50 years.

mesocosms) and exclude studies where fish are captured from field environments and brought into the laboratory for experimentation or observation (aside from a small section on using electronic tagging in captivity). In no way is our goal to imply that these electronic tools are better than others or should replace them—rather, it is a candid assessment of the opportunities they provide to complement other methods and approaches to achieve a more complete understanding of fish–hypoxia interactions. Our focus on electronic tagging and tracking tools is based on their ability to study the behavior and environmental relations of free-ranging individual fish across space and time—from the perspective of a fish. That individual-level approach is useful for understanding mechanisms but is most relevant when connected with population-level assessments that typically involve other methods (notwithstanding advances in assessing population-level impact with tracking tools; Pine et al., 2003). This is timely and unique in that most work in this space specific to hypoxia using electronic tagging and tracking tools has occurred over the past decade. The synthesis spans aquatic systems (e.g., freshwater, marine, estuarine) and natural phenomena, as well as experiments where hypoxic conditions are intentionally created in a field system to study free-swimming fish (e.g., in the context of hypoxia as a barrier to fish movement). We review the evidence base around several key themes (summarized graphically in Figure 2), present a case study that demonstrates the value of including electronic tagging and tracking tools to understand large-scale hypoxia phenomena in Lake Erie, briefly assess emerging technological innovations, and consider future opportunities to deploy electronic tagging and tracking tools to both understand hypoxia and identify solutions that benefit fish and fisheries.

Thematic issues

Identifying and validating hypoxia thresholds

The identification and validation of hypoxia thresholds (i.e., what is tolerable for a fish to live in) in fish require two key components: (1) quantification of environmental oxygen conditions and (2) measurement of the fish's physiological response. Because simultaneously capturing both of these data streams in natural settings is logistically challenging, most efforts to define hypoxia thresholds have been conducted in laboratory environments (e.g., Rogers et al., 2016). In the lab, DO levels can be precisely controlled and specialized equipment, such as respirometers, are used to measure physiological responses to hypoxia (e.g., Stecyk & Farrell, 2002). Lab studies typically rely on physiological metrics, such as the critical oxygen tension (P_{crit}) or oxygen uptake (MO_2), which reflects the oxygen level below which aerobic metabolic scope becomes constrained (Claireaux & Chabot, 2016; Fry, 1947). There have been increasing efforts to understand hypoxia thresholds in field settings despite logistical challenges with implementation. For example, there are studies that have used

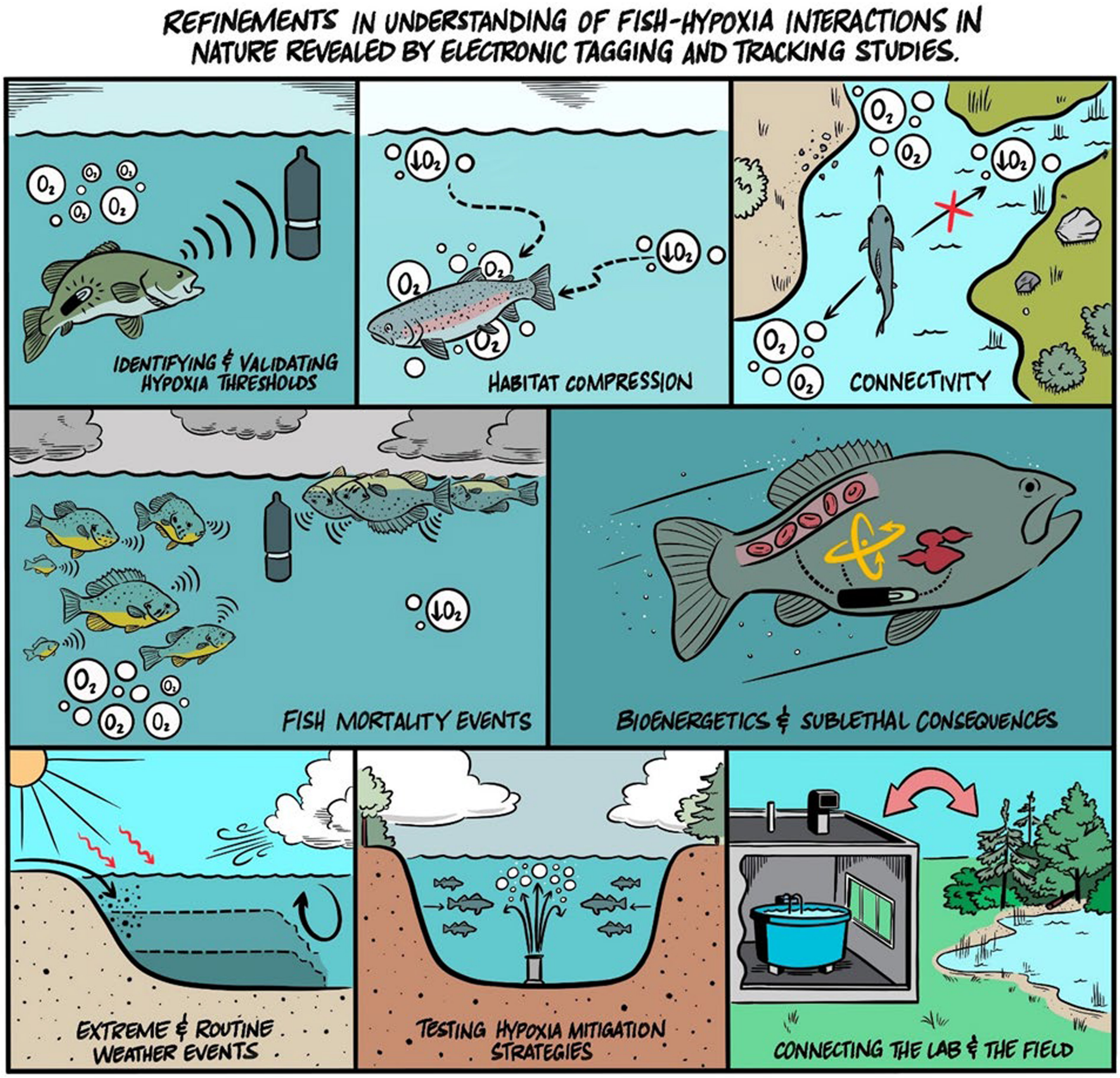

Figure 2 Visualization of key ways in which electronic tagging and tracking tools have improved our understanding of fish hypoxia—particularly in the field.

various netting (e.g., gill netting, trawling) and electrofishing methods to identify the presence/absence/density of fishes relative to environmental conditions, including gradients of DO (Breitburg, 2002; Chamberlin et al., 2020; Craig & Crowder, 2005; Eby & Crowder, 2002; Pihl et al., 1991). Building on these efforts, electronic tagging and tracking technologies now offer an alternative approach to identifying hypoxia thresholds by monitoring fish behavior and habitat use in situ, under natural oxygen regimes (see Williams et al., 2021).

The advancement of electronic tagging technology has made it increasingly feasible to assess hypoxia thresholds in the wild. Traditional biotelemetry tools—such as acoustic, satellite, or radio transmitters—can provide valuable insights into fish responses to hypoxia by tracking behavioral changes, including shifts in movement patterns (both horizontal and vertical) in relation to DO gradients. For instance, DO levels below 3 mg/L have been shown to result in habitat compression, as evidenced by reduced movement distances in Walleye *Sander vitreus* (Brooks et al., 2025). Building on these foundational tools, more recent innovations in electronic tagging now enable direct measurements of the two key components required to evaluate hypoxia thresholds: (1) in situ oxygen concentrations, using transmitters equipped with DO sensors (Coffey & Holland, 2015; Logan et al., 2022; J. C. Svendsen et al., 2006), and (2) physiological responses, through the deployment of biologgers (Cooke et al., 2016), such as monitors for heart rate (Brijs et al., 2019; Twardek et al., 2021), ventilation (Calduch-Giner et al., 2022), and arterial blood saturation (i.e., photoplethysmograms; E. Svendsen et al., 2021). Although most of these sensors and biologgers have been used in lab or mesocosm settings (e.g., aquaculture; E. Svendsen et al., 2023), there remains much opportunity to link environmental exposure with real-time biological responses, providing a more nuanced understanding of how fish interact with hypoxic conditions in natural, dynamic, and biologically relevant settings. It is worth noting that oxygen sensors require direct contact with water, constraining their use to externally mounted tags and thus limiting their application to larger species that can accommodate the additional drag and mass.

Habitat compression

Habitat compression is the reduction or loss of suitable habitats or areas that can be caused by a variety of factors, such as temperature, noise, or human-driven habitat degradation (e.g., Jones et al., 2018; López-Londoño et al., 2021; Ware et al., 2015). In marine and freshwater systems, the increasing temporal and spatial prevalence of hypoxia can result in loss of benthic or surface habitat, resulting in compression of available space (Campbell & Rice, 2014; Jenny et al., 2016; Keeling et al., 2010). In addition to many field studies focused on population-level responses (e.g., Eby et al., 2005), electronic tagging has shown how individual fish experience hypoxia-driven habitat compression and how that may alter their behavior and habitat use (e.g., Brooks et al., 2025). For example, acoustic tracking of Striped Bass *Morone saxatilis* in the Chesapeake Bay suggested that the tagged fish experienced seasonal habitat compression in the period between June and September (Itakura et al., 2021; Kraus, Secor, & Wingate, 2015), while radio tracking of Arctic Grayling *Thymallus arcticus* in the Upper Red Rock Lake, Montana, showed that grayling exploited the deeper and more oxygenated water layer rather than the lower oxygen surface layer during ice coverage (Davis et al., 2019). When animals cease to use previously available space within their niche, habitat compression can lead to direct loss of habitat and the resources found within the given habitat by fish exhibiting avoidance behavior and remaining outside of hypoxic areas (Abascal et al., 2011; Mitamura et al., 2009, 2020; Nyboer & Chapman, 2013; Watsham, 2016).

Avoidance behavior can lead to crowding and competition when fish move to normoxic (i.e., within normal DO levels for a given species) conditions (Stramma et al., 2012). Hypoxia-driven habitat compression can also alter predator–prey dynamics and increase interactions between fish and humans (Benito et al., 2015; Hedges & Abrahams, 2015; Stramma et al., 2012; Thompson et al., 2010). For example, Prince and Goodyear (2006) used pop-up satellite archival tags with depth (pressure) sensors on Blue Marlin *Makaira nigricans*, Black Marlin *Istiompax indica*, and Atlantic Sailfish *Istiophorus platypterus* and showed that the cold, hypoxic layer restricted the tagged fish to a shallower and more surface-oriented habitat in the eastern tropical Pacific Ocean, which renders them more vulnerable to surface fishing gears. With the advancement of electronic tagging tools, tracking studies can be an important aid to understanding the ecological impacts of hypoxia-driven habitat compression and driving actions such as restoration.

An important aspect of understanding the effects of hypoxia is to investigate whether fish experience vertical habitat compression, for which electronic tracking tools instrumented with pressure (depth) sensors are frequently being implemented (e.g., C. M. Roberts et al., 2017). Using SPOT (Smart Position and Temperature) tags combined with an inertial measurement unit equipped with an oxygen sensor, Logan et al. (2023) found evidence for vertical habitat compression of Blue Marlin and Atlantic Sailfish, where they only spent a small proportion of their time below the oxycline (i.e., boundary layer between normoxia and hypoxia). Rasmuson et al. (2021) tracked Deacon Rockfish *Sebastes diaconus* using acoustic transmitters equipped with depth sensors and found that the depth range was restricted during an 11-d-long hypoxia event compared with under normoxic conditions.

Although habitat compression as a result of hypoxia can force fish to move and limit their habitats vertically, horizontally, or temporally (e.g., Carlisle et al., 2017; Carver, 2023; Halvorsen, 2013; Prince et al., 2010), fish tolerate low oxygen levels differently, where some fish have a greater tolerance to hypoxia than others. Acoustically tagged Golden Perch *Macquaria ambigua* in the Condamine River, Australia, remained in the hypoxic area and seemingly did not experience habitat compression due to hypoxia (Crook et al., 2024), while S. Baker (2019) found that the 50% core habitat use area was first reduced under anoxic conditions rather than hypoxic conditions in acoustically tagged Red Drum *Sciaenops ocellatus*. Tagging of female Salmon Sharks *Lamna ditropis* with pop-up satellite archival tags revealed that they could remain in areas with reduced DO concentrations, although the sharks avoided areas with low oxygen concentrations when the water temperature was cold (Coffey et al., 2017). Because fish respond differently to hypoxia (e.g., Jorgensen et al., 2009; Rodrigues et al., 2022), electronic tagging tools are a useful instrument to study whether fish experience habitat compression due to hypoxia in the wild, which is valuable for management and implementation of mitigation efforts to ensure sufficient availability of suitable habitats.

Connectivity

Habitat connectivity refers to the extent to which separate habitat areas are linked, affecting the movement, distribution, genetic diversity, and overall health of populations (Beger et al., 2022; Ward, 1989). Permanent or temporary habitat loss and fragmentation leading to a loss of connectivity can have severe consequences for affected populations and species. Hypoxic habitat patches can, for example, disturb connectivity through preventing access to vital areas for feeding or reproduction. Migratory fish like salmonids often inhabit complex systems using distinct habitats for reproduction and feeding, which often leads to a complex population substructuring and local adaptation (Hendry & Stearns, 2003). Connectivity and access to spawning habitats specifically is therefore crucial to maintain overall population resilience and fitness. Such spawning migrations can also be temporally inhibited during hypoxic episodes as was shown in the Loire estuary for the anadromous fish Allis Shad *Alosa alosa* using acoustic telemetry (Tétard et al., 2016). The trans-estuarine migration of Allis Shad was inhibited during hypoxic episodes in the middle part of the estuary, and fish therefore stayed in the other, oxygen-richer parts. Migration runs could only occur hastily during neap tide, when the estuarine turbidity maxima decreased. Another study on Red Drum, also using acoustic telemetry, suggested that prolonged exposure to hypoxic conditions in combination with artificial structures can not only reduce movement of Red Drum and decrease habitat connectivity but also increase risk of mortality (S. M.

Baker et al., 2023). Relative to some of the other topics explored in this review, relatively few explored the impacts of hypoxia on connectivity.

Fish mortality events

It is well known that hypoxic (or anoxic, i.e., the absence of DO) events can cause mortality in fish as evident by mass fish kills observed in nature (e.g., Thronson & Quigg, 2008, reviewed in Hurst, 2007 and in Pollock et al., 2007) and in captivity (e.g., technical or human failure in aquaculture facilities; see Zhan et al., 2023). Although morbidity and mortality thresholds have been well defined in laboratory environments (e.g., Rogers et al., 2016; Small et al., 2014), nature is more complex and there may be mechanisms by which fish can avoid mortality (e.g., by changing behavior; Pollock et al., 2007). Similarly, the mortality of fish can be cryptic given that dead fish are not always evident to observers (e.g., O'Connor et al., 2010), and because hypoxia is often transient, it is possible that hypoxia-related mortality events are underrepresented as a driver of fish population abundance (La & Cooke, 2011). Hence, electronic tagging and tracking studies have created new opportunities to reveal the timing and severity of hypoxia-related mortality events in the field.

To date, there have been relatively few studies that have attempted to estimate or understand hypoxia-related mortality in wild fish (e.g., Rao et al., 2014). Davis et al. (2019) tagged Arctic Grayling with radio transmitters in a shallow, winter-prone lake to understand fish–hypoxia interactions. Mortality rates were exceedingly low despite hypoxic waters in some areas, emphasizing potential for behavioral responses to mitigate mortality. Rice et al. (2013) opined about the need for telemetry data to better understand summer mortality events for Striped Bass in reservoirs in the southern United States. Telemetry studies had been done in a number of reservoirs over a number of years (e.g., Thompson et al., 2010), but mass mortality events did not align with any of those study periods. Nonetheless, relying on what was known about behavior of Striped Bass from telemetry studies during nonlethal levels of hypoxia, the authors suggested that meta-limnetic "squeeze" (Rice et al., 2013) of fish may indeed be the specific mechanism by which summer mortality of Striped Bass occurs. O'Connor et al. (2010) tagged Largemouth Bass *Micropterus salmoides* (listed in *Common and Scientific Names of Fishes from the United States, Canada, and Mexico*, 8th edition [Page et al., 2023] as *M. nigricans*) in a small freshwater lake equipped with a whole-lake acoustic telemetry array as part of a general study on fish behavior (i.e., no intention of it being a hypoxia mortality study). An unanticipated winter cryptic mortality event happened in January (under ice), leading to near-complete mortality of all tagged fish (and presumably the near complete mortality of untagged conspecifics, which was confirmed by negligible capture success in subsequent sampling). What was remarkable was that despite knowing that there had been a mortality event (based on telemetry downloads) and our ability to use the high-resolution tracking system to identify where and when fish died, not a single dead fish was ever observed. Although it is unclear if dead fish (and their tags) ended up in the sediment or were removed by predators, this mass mortality event would have gone totally unnoticed, emphasizing how not all mortality events are visible to observers. In that sense, the researchers were able to watch fish "die" in near real time on their computer screens. That example is unique (full-lake, high-resolution array deployed at same time as a cryptic mortality event was observed) but emphasizes the opportunistic nature of being able to do post hoc analyses of the growing masses of telemetry data to understand hypoxia–fish mortality interaction.

Bioenergetics and sublethal consequences

Not only are hypoxic events linked directly to mortality (e.g., Breitburg, 2002), they also subject fish to various bioenergetic (i.e., how organisms obtain, transform, and use energy) and sublethal (e.g., stress response, reduced immune function, reproductive effects; reviewed in Pollock et al., 2007) consequences. In recent years, in-field approaches like electronic tagging and tracking tools have helped to better understand physiological, behavioral, and population dynamic changes in response to hypoxia. Electronic tagging and telemetry studies have reported on behavioral responses such as habitat selection, foraging, movement, and migration. Various telemetry studies have found that fish move towards preferable oxygen environments when encountering low DO levels (Braun et al., 2015; Brown et al., 2015; Kraus et al., 2023; Roloson et al., 2021). Acoustic telemetry data have shown that fish use depth and thermal stratification layers in the water column to seek DO-rich areas (Brooks et al., 2022, 2025) or increased movement towards oxygenated refugia to avoid hypoxic events (Craig et al., 2023; Roloson et al., 2021; Westrelin et al., 2022). Sometimes, due to various impeding factors (e.g., dams, bollards, eutrophication), fish are not able to leave hypoxic environments, which leads to slowed and overall reduced movement (S. M. Baker et al., 2023; Tétard et al., 2016). Sublethal effects on movement influence foraging activity as well as predator–prey interactions. This is supported by less food found in stomachs of fish inhabiting low DO levels in combination with acoustic telemetry (Brown et al., 2015). Though hypoxia drives movement towards DO-rich regions, various studies have depicted trade-offs between oxygen and other necessities, such as food availability versus predation avoidance. For example, fish have been seen to go towards hypoxic environments to feed, where there is a lower predation threat or higher prey availability (Hedges & Abrahams, 2015; Thompson et al., 2010). Contrastingly, predation from humans may also increase or decrease, as fish find refuge in normoxic conditions (Kraus, Cook, et al., 2024). Different hypoxia tolerances influence how certain species may utilize or tolerate hypoxic waters better than others (Benito et al., 2015; Davis et al., 2019; Gaulke et al., 2015). Understanding foraging and predation activities relies on species tolerances to abiotic limits and their impacts on behavior with relation to the environment (Hansen et al., 2013).

The study of fish movement and foraging through telemetry and biologging can be used in combination with bioenergetic models to predict effects on life history. Deciphering bioenergetics for wild fish is challenging, as direct metabolic rate (i.e., the transformation of energy) measurements are difficult to obtain (Cooke et al., 2016). A bioenergetics model coupled with acoustic telemetry was used by Kraus, Secor, &

Wingate (2015) to project growth rate in a changing summer habitat (low DO and high temperature) for wild fish. Another study used acoustic telemetry to combine a visual foraging model and a bioenergetic model to understand the effects of high temperature and low DO on foraging success in Cutthroat Trout *Oncorhynchus clarkii* (listed in *Common and Scientific Names of Fishes from the United States, Canada, and Mexico*, 8th edition [Page et al., 2023] as Coastal Cutthroat Trout; Hansen et al., 2013). No study has used accelerometers to measure energy metabolism of wild fish responding to hypoxia in real time (Brodie et al., 2016; Metcalfe et al., 2016), but it has been done in captive fish (Zupa et al., 2021). Additionally, other studies have used bioenergetic models to analyze long-term population level changes via estimating growth, reproduction, and mortality (K. A. Rose et al., 2018) and spatial modeling of fish afflicted with low DO levels (LaBone et al., 2019). Telemetry studies would help refine these models.

Beyond behavioral analyses, few studies use biologging and tracking tools to detect direct physiological responses (e.g., cortisol, lactate, glucose, gill respiration, heart rate) to hypoxia in free-swimming fish. One notable study used exogenous hormone implants to treat fish with cortisol, followed by winter movement tracking, where cortisol-treated fish died prior to the controls when afflicted with a mass hypoxia event (O'Connor et al., 2010). There are many physiological measures that can be detected by biologgers and tracking tools that are predictive of energy metabolism but have not been applied with respect to hypoxia in free-swimming fish. An example would be using heart rate loggers with bioenergetic models (Lefrançois et al., 1998; Lucas et al., 1993). Another study used a differential pressure sensor on the operculum to predict changes in metabolic demand (Dalla Valle et al., 2003). There is also potential for studies to consider reproduction with hypoxia as one such study did by using oviduct tags and acoustic telemetry to locate spawning events (Dubos et al., 2025). Overall, there is a need for more studies that consider fish responses to hypoxia on the physiological level and further development of bioenergetic models testing hypoxia responses of fish using biologgers and tracking tools. To this end, in the past decade, these tools have provided data related to energy usage by fish responding to hypoxia through changes in activity, movement, and foraging behavior.

Extreme and routine weather events

Weather plays a key role in hydrological regimes and therefore in the mixing of water and the ensuing oxygen dynamics, particularly in lakes and seas. In many systems, wind in particular may be the most important factor for oxygenation of the bottom waters that become hypoxic, as it forces water movements that are key to driving turnover (Ribaudo et al., 2021). Extreme winds and storms can cause the sudden and dramatic turnover of systems like lakes and ponds, causing anoxic bottom water that has not been circulated in some time to upwell towards the surface (e.g., Daněk et al., 2023), and tropical storms, which are well documented as becoming more frequent in recent years owing to climate change (Walsh et al., 2016), have a key role in the mixing of marine waters. Extreme weather can also result in pollution and eutrophication that depletes oxygen and defoliation of terrestrial vegetation that results in prolonged oxygen deficits (e.g., (Mallin & Corbett, 2006; Stevens et al., 2006). Drought or alternatively high levels of precipitation can also induce hypoxia. Despite the potential for electronic tagging and tracking tools to elucidate fish responses to such events, we only found two examples. The first involved the use of telemetry to characterize a fish kill event following a flood in the Murray River, Australia, that incorporated extensive organic matter into the water, increasing the biological oxygen demand and then depleting the DO in the water (King et al., 2012). We also found one study that provided a general description of fish evacuating nearshore areas during storms yet without specific measures of hypoxia (see Bailey & Secor, 2016). In general, there is much opportunity for research in this space using electronic tagging and tracking tools.

Testing hypoxia mitigation strategies

Hypoxia mitigation strategies are important to sustain fish populations that undergo frequent or prolonged hypoxic events (e.g., Conley et al., 2009). The three most common approaches to hypoxia mitigation are (1) nutrient abatement, (2) hypolimnetic oxygenation, and (3) water flow manipulation. Nutrient abatement is a long-term initiative and thus not overly amenable for study given the relative short-term nature of tracking studies. Hypolimnetic oxygenation involves injecting or facilitating oxygen release near the substrate or reducing oxygen demand below the hypolimnion (Beutel & Horne, 1999; Bierlein et al., 2017). Water flow manipulation can also improve DO levels in hypoxic water bodies, particularly in regulated rivers and reservoirs where changes in flow are an associated driver of hypoxia (Poff & Zimmerman, 2010). In marine waters, the injection of freshwater into deeper layers to alter water density to ease turnover in sill fjords has also been proposed as a mitigation strategy (Aksnes et al., 2023). This mitigation is being tested in Norway with simultaneous tracking studies being conducted in the city center of Bergen (Piczak et al., 2024). Studying how fish respond to hypoxia mitigation strategies has typically focused on fish survival and growth (e.g., (Müller & Stadelmann, 2004). Electronic tagging and tracking studies could be useful tools to understand further how fish respond to hypoxia mitigation strategies.

Hypolimnetic oxygenation is a method that has been well studied using methods like deepwater gill netting (Aku & Tonn, 1997). Using electronic tags or tracking studies to understand the "success" of hypolimnetic oxygenation has rarely been done; however, in the few cases that have used these technologies, oxygenation benefits fish. For example, over a 6-year period, Rainbow Trout *Oncorhynchus mykiss* and Brook Trout *Salvelinus fontinalis* tagged with acoustic and archival tags were found to use hypolimnetic habitat in North Twin Lake, Washington, proportionately more following oxygenation, and swimming speeds decreased after oxygenation, possibly indicating less movement in search for better quality habitat (Moore et al., 2014). This study highlights how, when using electronic tags, tracking the responses of fish to hypolimnetic oxygenation can be measured at fine scales and can offer individual-based data to better understand the effectiveness of the strategy.

Studies using electronic tags or tracking to assess the use of flow manipulation for reducing hypoxic conditions are lacking.

There are, however, a few examples. First, threatened Salish Sucker *Catostomus* sp. cf. *catostomus* and juvenile Coho Salmon *O. kisutch* from Pepin Creek (British Columbia) were tagged with passive integrated transponder tags and placed into an off-channel pond that was curtained off to create split channels where flow could be manipulated (Zinn et al., 2021). On one side of the channel, flow was restricted, creating a side of the pond that experienced hypoxia over a multiweek study. Within the channel, an oxygenated refuge was created by diverting flow from the unmanipulated side of the pond into an area outfitted with a passive integrated transponder antenna. The total number of daily detections in the oxygenated refuge was higher in the no-flow treatment than the flow treatment, and species differences in the refuge use was noted (the more hypoxia-tolerant Salish Sucker used the refuge more at night, when DO was at its lowest). In a different and more natural experiment, various Australian freshwater species (Golden Perch, Murray Cod *Maccullochella peelii*, and Silver Perch *Bidyanus bidyanus*) were tagged with acoustic transmitters and found to undergo large-scale movements during a large flood event that featured hypoxic conditions for several weeks (Thiem et al., 2020). Acoustic telemetry allowed for the estimation of mortality across the three species, which was high, ranging from 97% to 100%. The movement data collected from the study were less conclusive as to the direct response of hypoxia on fish behavior, as though fish consistently underwent large-scale movements, different species and individuals went in either direction and there was a lag between when the movements occurred and the onset of hypoxia. The findings of the Thiem et al. (2020) study do support the notion that management of flow to avoid flooding would reduce the impacts of hypoxic conditions on fish. Overall, both these studies and the ones described above support the usefulness of including electronic tagging and tracking studies to better understand hypoxia mitigation strategies.

Connecting the lab and the field

Laboratory studies have been instrumental in determining thresholds of tolerance for DO levels, determining the mechanisms underlying these thresholds, and understanding the intersection of behavioral and physiological responses. Those studies on how fish respond to DO levels under lab conditions are useful for developing testable hypotheses for field studies, but it is also possible to design comprehensive studies that include both lab and field components as has been done on several occasions. For example, after examining the behavioral and physiological response of Largemouth Bass to hypoxia in the lab, Hasler et al. (2009) tagged Largemouth Bass with acoustic tags to obtain high-resolution positioning data in a lake. The behavior of Largemouth Bass could then be linked to DO levels that were measured periodically. The study demonstrated that areas with DO levels below 2.0 mg/L were avoided by tagged fish, but areas with intermediate levels of DO were used rather extensively. The lab work demonstrated significant changes to behavior at levels below 2.0 mg/L, though without physiological changes, suggesting a critical threshold for Largemouth Bass (Hasler et al., 2009). A similar lab-and-field study was conducted on Arctic Grayling using radio telemetry and showed that adults have a high tolerance for acute hypoxia exposure, exhibit physiological and behavioral stress at DO levels below 4.0 mg/L, and select deeper more oxygenated waters in winter (Davis et al., 2019). Undertaking laboratory studies that offer considerable control and field telemetry studies that afford realism, we will be able to obtain a more complete understanding of fish responses to hypoxia.

Modeling exercises can also be used in combination with known aspects of fish responses to hypoxia from lab studies to understand the broader implications of low DO levels on individuals and populations, though relatively few examples of these exist. One such study performed a series of preference tests (DO, temperature, and salinity) on Marbled Sole *Pseudopleuronectes yokohamae* in the lab, tracked the movements of the fish in an enclosed bay in Japan, and then used that data to model fish preferences and mortality (Karim et al., 2003). The model was then used to demonstrate that the construction of new land through an ongoing land reclamation project would lower hypoxia-related mortality by simply eliminating a significant portion of the area that experiences the highest hypoxia. Physiology-based modeling approaches—such as aerobic scope models and dynamic energy budget models—can be used to characterize fish habitat suitability based on predicted fish responses to changes in DO concentrations or extreme hypoxic events (Teal et al., 2018). This requires knowledge about fish responses to changing DO levels, likely from the lab but ideally also from data that have been ground-truthed in the field. Cucco et al. (2012) used lab studies to determine the mathematical equations that describe the relationship between metabolic scope and environmental conditions in Striped Mullet (also known as Flathead Grey Mullet) *Mugil cephalus*. These equations were then applied to a hydrodynamic-ecological model to reproduce the spatiotemporal variation in metabolic scope of the fish in the Oristano Gulf (Italy). The results matched fisheries data and showed that this approach could accurately predict fish productivity. Modeling is a useful tool, and more focus is needed on bridging telemetry data outcomes with statistical modeling to project the outcomes of potential intervention scenarios.

Synthetic understanding via case study of Lake Erie hypoxia

Lake Erie has expansive seasonal hypolimnetic hypoxia covering up to 10,000 km^2 of one subbasin of the lake (i.e., the central basin dead zone; Ludsin et al., 2001). Continuous monitoring of the central basin dead zone has been ongoing since the 1980s, but only during recent decades has the highly complex spatial and temporal variability of bottom hypoxia become evident (Bocaniov & Scavia, 2016; Bouffard et al., 2012; Kraus, Knight, et al., 2015; Rowe et al., 2019). During this same period, a large, coordinated effort to investigate migration and movements of fish across the Great Lakes with passive acoustic telemetry was initiated (Krueger et al., 2018) and refined through the development of a systematic sampling design (Kraus et al., 2018). Due to its expansive coverage, the acoustic telemetry receiver network was identified as a platform to leverage better water quality monitoring by outfitting receivers with data loggers to ground-truth hypoxia forecast models (Rowe et al., 2019) and more generally improve understanding of the seasonal dynamics of the dead zone (Oldham & Kraus, 2022). Mutual benefits of data logger deployments have been realized for the hypoxia monitoring program, hypoxia modeling, and fish habitat investigations. This unique situation with fish movement data that can be spatially indexed to modeling predictions and to direct measurements from buoys and data loggers has provided an unprecedented opportunity to investigate the implications of hypoxia on spatial fishery management in Lake Erie.

Migratory fishes in Lake Erie are jointly managed by four U.S. states and the Canadian province of Ontario through a treaty agreement (Gaden et al., 2008) that involves annual coordination of harvest across jurisdictional boundaries and spatial management units. Additionally, through the Great Lakes Water Quality Agreement, a binational USA–Canada partnership has aimed to address recent increasing trends in severity and extent of hypoxia in Lake Erie with goals to reduce nutrient loads (International Joint Commission, 2012). For fishery managers, success (or failure) to achieve water quality goals may act through changes in spatial aspects of hypoxia on the distribution of highly valuable fishery resources, as well as efforts to rehabilitate native species. Applications of electronic tagging methods are currently providing new insights to answer critical questions about fish behavioral responses to hypoxia.

Lake Erie fisheries are prominently supported by two species of Percidae: Yellow Perch *Perca flavescens* and Walleye. These species exhibit varying degrees of tolerance to low DO (Arend et al., 2011), and recent studies indicated that they may shift from demersal to pelagic habitats to avoid hypoxia in the central Lake Erie basin (Gorman et al., 2019; J. J. Roberts et al., 2009). For Yellow Perch, tolerance to hypoxia appears to represent an adaptation to exploit macroinvertebrate prey that become more vulnerable to fish predation in the presence of hypoxia (Bodamer & Bridgeman, 2014; Pihl et al., 1992); these fish may foray into hypoxia from midwater habitat to forage (J. J. Roberts et al., 2012). Walleye are less tolerant of low DO conditions than Yellow Perch (Arend et al., 2011), but they are wider ranging in their movements across Lake Erie (Matley et al., 2020) and thus can presumably better avoid areas that are impacted by hypoxia. Depth telemetry studies have also provided evidence of more pelagic habitat use when fish are present in the central basin during summer (Gorman et al., 2019), highlighting the need for tagging studies (currently in progress) to correlate site-specific oxygen measurements with occupancy and depth information. While the percid fisheries in Lake Erie are foremost at the attention of the managers, a critical and equally interesting story involves coregonines, which are either the subject of rehabilitation (Cisco *Coregonus artedi*) or improved management (Lake Whitefish *C. clupeaformis*) to ensure sustainability certification of fisheries. Cisco have been extirpated from Lake Erie but once supported one of the largest freshwater fisheries in the world (Van Oosten, 1930). To understand the feasibility of restoring Cisco, acoustic telemetry has aided efforts to understand whether naïve hatchery fish would select oxythermal conditions that would provide a refuge during hypoxic periods (Kraus, Markham, et al., 2024; Schmitt et al., 2020).

Lake Whitefish in Lake Erie provide the most compelling example of what information can be provided to inform decision making in the context of spatial fishery management. Lake Whitefish are demersal and less tolerant of low DO than the other species already mentioned, and by combining modeling interpolations of bottom DO with passive acoustic telemetry, behavioral analysis has revealed that fish move from low to high oxygen more frequently when the initial conditions are more hypoxic (Kraus et al., 2023). The pairing of bottom DO with simultaneous tagged fish detections was later extended to an examination of movements between spatial management units, providing further evidence that fish avoid central basin habitats during periods when hypoxic conditions typically occur (Kraus, Cook, et al., 2024). The effect of hypoxia on the redistribution of Lake Whitefish has important implications for fishery managers because, during periods of hypoxia, fish tended to move to spatial units with lower fishing intensity. Thus, while hypoxia may increase catchability of other species that aggregate around the edges of hypoxia (Chamberlin et al., 2020; Kraus, Knight et al., 2015), Lake Whitefish behavior may provide a seasonal reprieve from fishery exploitation. The results raise many important applied questions, including how the Lake Whitefish stock would be affected if hypoxia reduction goals are achieved and whether fishing effort might shift among spatial management units. More importantly, the Lake Erie example illustrates the need to integrate electronic tagging with water quality and related habitat investigations to understand the possible responses of fish that aggregate around or avoid hypoxia and realize key new insights for conservation and sustainability.

Learning from aquaculture and laboratory research

Although the focus of this paper is on wild fish and hypoxia in nature, there are some learnings that could come from research in the aquaculture sector. Fish are cultured in freshwater and salt water in tanks, ponds, and pens with potential to experience hypoxia. Research on hypoxia in culture systems involving electronic tagging and tracking has largely focused on welfare assessment and to improve production. For example, Gesto et al. (2020) used acoustic telemetry to assess how Rainbow Trout in tanks responded to acute hypoxia and ammonia exposure. That study also involved a comparison of fish with different competitive abilities to determine if use of fish selected for certain characteristics was associated with more resilience to the hypoxia and ammonia stressors. The acoustic accelerometers revealed behavior differences in fish when challenged with stressors, revealing the potential of such tags to be useful for real time welfare assessment. A similar conclusion was reached by Kolarevic et al. (2016), who used similar tags for monitoring swimming activity of cultured Atlantic Salmon *Salmo salar* in recirculating systems. They noted reductions in swimming activity (based on accelerometer records) during hypoxia. More recently, Morgenroth et al. (2024) did laboratory calibration studies to further the development of acceleration and heart rate tagging deployments to assess both behavioral and physiological responses of Atlantic Salmon in sea-pens. Those (or similar) validation studies and application of tools are equally salient to wild fish. Lefevre et al. (2011) used depth- and oxygen-sensing acoustic transmitters to study Striped Catfish *Pangasianodon hypophthalmus* behavior in aquaculture ponds in the Mekong Delta, where hypoxia is common. The researchers found that much of the pond was inaccessible to the fish due to low oxygen (i.e., fish tended to select shallow waters), leading to the conclusion that there was need for more aeration to improve production potential. That approach (including the use of depth and DO sensors) in wild fish could help to explain fish vertical distributions in the presence of vertical oxygen gradients.

Beyond the aquaculture sector, learning may also come from laboratory research on fish and hypoxia using electronic tags. Indeed, one of the "classic" and pioneering studies on fish and hypoxia using electronic tags was done in a large "aquatron" research facility at Dalhousie University. Claireaux et al. (1995) exposed fish to experimental gradients of salinity and oxygen and used heart rate and depth-sensing transmitters to provide detailed information on fish distribution serving as a foundation for future field studies. However, we are now three decades later and the application of those tools—especially sensors—on fish in the wild remains rather nascent. Another more recent lab study that provides a strong foundation for moving from the lab to the field is Mignucci et al. (2021). Those researchers implanted Gilt-head Seabream *Sparus aurata* in tanks with biologgers equipped with acceleration and heart rate sensors. Fish were challenged with periods of low DO and high water temperature where it became apparent that behavioral responses (e.g., spontaneous activity during warming) would have been misleading in terms of physiological responses had the behavior not been quantified. Similar to Claireaux et al. (1995), they concluded that there was much benefit from combining behavioral and physiological indicators (sensor types), which is likely even more important when studying wild fish in natural systems.

Technological innovations

Given the importance of DO concentration as a factor affecting physiological and behavioral responses in fish (Laffoley & Baxter, 2019)—in many ways even determining where and when a fish can live—there is a strong desire in advancing tag technology to enable continuous in situ DO measurements. This desire is stronger than ever before considering global climate-driven ocean warming and deoxygenation, suggesting a loss of approximately 2% in DO concentrations since 1960 (Schmidtko et al., 2017). Although deoxygenation is widely recognized as one of the most critical changes in marine ecosystems, it is not unique to this realm: deoxygenation in freshwater ecosystems is in fact an overlooked threat (K. C. Rose et al., 2024).

The responses of fish to low DO tend to be poorly resolved because simultaneous data on their movements and instantaneous DO are rarely obtained. As such, scientists have been on a decades-long quest to develop a tag with a DO sensor that could fill this knowledge gap. The first such tag was developed in the 1980s using a Clark-type electrode on an acoustic tag, and it had a battery life of 10 d (Priede et al., 1988). The tag was externally mounted on a sea-run Brown Trout *Salmo trutta*, as continuous water flow over the tip of the tag was required for accurate readings. While the tag was successful at reading and transmitting DO values, a "chase boat" was required to follow the tagged fish to record the transmitted data. As with all polarographic sensors, drift is problematic and recalibration is necessary. Though several attempts have been made to develop (or improve) such tags since (e.g., Coffey & Holland, 2015; J. C. Svendsen et al., 2006), the issues related to external tag mounting, the need for continuous flow over the sensor, and sensor drift continue to persist. J. C. Svendsen et al. (2006) developed an acoustic DO transmitter consisting of a sensing unit connected to a transmitter unit that showed high accuracy over a range of DO from 0% to 191% saturation in the lab. But as with all externally mounted tags, the authors warned that biofouling, especially in the marine environment, could be highly problematic. Biofouling by algae and biofilm is a critical limiting factor for long-term sensor accuracy in aquatic systems. Coffey and Holland (2015) developed a DO pop-up satellite archival tag, which provided fast, accurate, and stable measurements. The tag was deployed on Bluntnose Sixgill Sharks *Hexanchus griseus* and also captured the oceanography of the region successfully, though the tag needed to be recovered for DO data to be obtained. Both J. C. Svendsen et al. (2006) and Coffey and Holland (2015) relied on a galvanic cell oxygen sensor as opposed to the early attempts that relied on Clark-type electrodes. Other DO sensors have been added to conductivity-temperature-depth satellite relay data loggers and mounted on animals, primarily mammals (like elephant seals *Mirounga* sp.) but also some large sharks, to collect oceanographic data (Bailleul et al., 2015). Again here, drift appears to be problematic. A recently developed DO measuring (DOME) archival tag uses an optical oxygen sensor with additional sensors and triaxial accelerometer for fine-scale movements and activity (da Costa et al., 2024). Deployment on four Blue Sharks *Prionace glauca* showed no drift over a time period of 4.2 to 15.8 h (and up to 9-d in the lab). For longer deployments, drift will likely continue to be an issue. This tag type appears promising (though only for short deployments), though similar to the DO pop-up satellite archival tag, it requires retrieval for data to be obtained, perhaps limiting the temporal and spatial scale of its use. Further technological advancements are still highly desired, not only to address the issue of sensor drift but also to enable the miniaturization of sensor technology and transmission of that data without the need for tag recovery, thereby enabling simultaneous DO and movement data from smaller species.

Conclusions

We have argued that there is much value added by including field studies of hypoxia using electronic tagging and tracking methods (Figure 2). Yet, there are inherent limitations with any method, including with the suite of electronic tagging and tracking tools (Table 1). Being aware of the limitations is as important as being aware of their strengths. This review and our focus on electronic tagging and tracking are not meant to undermine the hundreds of controlled laboratory studies or other field studies that have been conducted using other methods but rather to increase ecological realism. From the pioneering studies by Claireaux et al. (1995) on Atlantic Cod

Table 1 Summary of the benefits and limitations of using electronic tagging and tracking methods to study hypoxia in fish.

Benefits	Limitations
• Can be used in both lab and field environments • Potential to bridge behavior and physiology using sensors • Potential to measure environmental conditions (e.g., dissolved oxygen) from animal-borne sensors • Creates realism by being able to study fish in the field, including trade-offs • Can be paired with laboratory studies to obtain greater understanding of system function • Can be used opportunistically (e.g., tagged fish are being studied in a lake to understand habitat use and there is an unanticipated hypoxia event) • Can be used to test hypotheses generated in the lab in field settings • Can generate observations in the field leading to hypotheses that can be tested in the lab	• Potential for negative consequences for tagged individuals associated with tagging (e.g., surgery, burden of a tag in terms of mass or drag), limiting inferences that can be made about untagged conspecifics • Limitations on the size/life stage of fish that can be tagged, especially with tags that include sensors • Tag life (battery) and data storage limitations particularly on small tags leading to "short" data sets (becoming less of an issue with new technology) • Difficult to control for other factors when using electronic tagging and tracking methods in the field • Challenges with recapturing fish (or finding jettisoned tags) to download archival loggers • Can be expensive leading to small sample sizes, which impedes ability to understand interindividual variation in responses • Difficult to scale to population level although there are a growing number of statistical methods for doing so

Gadus morhua equipped with heart rate and depth transmitters in a large aquatron to the widespread deployment of tagged fish in the field to study how fish interact with dynamic hypoxic conditions in nature (e.g., Davis et al., 2019; Kraus, Cook, et al., 2024; Rice et al., 2013), electronic tagging and tracking tools have allowed researchers to move beyond laboratory environmental exposures (e.g., in a sensory deprivation chamber) to include ecological and environmental realism. Doing so has revealed complex trade-offs, as fish make decisions about where to forage (J. J. Roberts et al., 2012), mitigate risk of predation (Hedges & Abrahams, 2015; Thompson et al., 2010), and seek environmental conditions that support life (Brooks et al., 2022, 2025; Craig et al., 2023; Roloson et al., 2021)—that is not easily doable in a lab environment. And just like fundamental lab studies can lead to testable hypotheses for field studies, observations and learnings from field tagging studies can also yield hypotheses that could be tested and further explored in controlled laboratory settings. In no way are we suggesting that electronic tagging and tracking is better than lab studies or other field methods (e.g., hydroacoustics), nor are we suggesting that other approaches or types of studies should be replaced. In fact, there are a number of limitations with the use of electronic tagging and tracking tools to study hypoxia that must be acknowledged (Table 1). There may be instances where electronic tagging tools are not necessary or cannot be used due to lack of technical expertise, tracking infrastructure, or financial resources. The real strength comes in combining lab and field studies (and different methods for doing field studies), either in the same research project/program or by drawing on literature from the other realm as needed. Electronic tagging and tracking studies are increasing demonstrating their value in complementing other approaches.

Today we have the tools to study free-swimming fish and document behavioral and physiological responses, as well as mortality events, in situ. From under ice (O'Connor et al., 2010) to episodic hypoxic events in Lake Erie (see case study) and the Chesapeake Bay (Itakura et al., 2021; Shunk et al., 2024), and from aquaculture facilities (Gesto et al., 2020; Kolarevic et al., 2016) to those researchers at the frontier of bridging lab and field studies (E. Svendsen et al., 2023; Williams et al., 2021), electronic tagging and tracking tools have opened the eyes and minds of researchers to what is possible in terms of understanding the influence of hypoxia on fish. Notably, these tools are well suited to complementing the near real-time environmental monitoring so that fish distribution and hypoxic conditions can be overlaid to understand the dynamics of those interactions. Beyond documenting the typical negative consequences of hypoxia, the electronic tagging and tracking toolbox has opened doors for testing hypoxia mitigation strategies and alternative management strategies in response to hypoxia. We anticipate that in as little as a decade from now, the evidence base around fish–hypoxia interactions will be substantially larger such that we will be able to develop more ecologically and environmentally realistic conceptual models. The opportunities are plentiful, particularly with the advent of novel sensors and fine-scale positioning systems that allow researchers to understand the physiological and behavioral states of free-swimming fish. In many ways, our understanding of hypoxia–fish interactions based on laboratory threshold studies is being rewritten as we explore hypoxia from the perspective of fish. Moving forward, the real strength will come from combining methods and approaches given electronic tagging and tracking methods complementary to those methods. Combining methods that span individuals to populations and communities will allow us to tackle outstanding questions such as those that deal with synergistic effects of multiple stressors (e.g., hypoxia + elevated temperatures) and the mechanistic basis for interspecific interactions in waters impacted by hypoxia.

Data availability

No data sets were used or generated for this manuscript.

Ethics statement

This manuscript was written in accordance with the ethical guidelines for all author countries and institutions involved. No ethical approval was required, as no animal experimentation or handling was involved.

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Conflicts of interest

Caleb T. Hasler holds the position of associate editor for *Transactions of the American Fisheries Society* and has not peer reviewed or made any editorial decisions for this paper.

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