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1 **Electronic tagging and tracking aquatic animals to understand a world increasingly**
 2 **shaped by a changing climate and extreme weather events**

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73 **Abstract**

74
75 Despite great promise for understanding the impacts and extent of climate change and
76 extreme weather events on aquatic animals, their species, and ecological communities, it is
77 surprising that electronic tagging and tracking tools, like biotelemetry and biologging, have
78 not been extensively used to understand climate change or develop and evaluate potential
79 interventions that may help adapt to its impacts. In this review, we provide an overview of
80 methodologies and study designs that leverage available electronic tracking tools to
81 investigate aspects of climate change and extreme weather events on aquatic ecosystems. Key
82 interventions to protect aquatic life from the impacts of climate change, including habitat
83 restoration, protected areas, conservation translocations, mitigations against interactive effects
84 of climate change, and simulation of future scenarios can all be greatly facilitated by using
85 electronic tagging and tracking. We anticipate that adopting animal tracking to identify
86 phenotypes, species, or ecosystems that are vulnerable or resilient to climate change will help
87 in applying management interventions such as fisheries management, habitat restoration,
88 invasive species control, or enhancement measures that prevent extinction and strengthen
89 resilience of communities against the most damaging effects of climate change. Given the
90 scalability and increasing accessibility of animal tracking tools for researchers, tracking of
91 individual organisms will hopefully also facilitate research into effective solutions and
92 interventions against the most extreme and acute impacts on species, populations, and
93 ecosystems.

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96 **Keywords:** global warming, electronic tagging, acoustic telemetry, PSAT, applied ecology

1. Introduction

Anthropogenic-driven climate change will likely continue to intensify, at least in the near-term, regardless of international agreements to cut harmful emissions. Indeed, the climate system has a time lag such that the effects of emissions cuts now will not be able to completely mitigate the future amount of these gases in the atmosphere (Samset et al. 2020). Evolutionary adaptation of animals to future climate scenarios is therefore needed as ecosystems continue to change (Nagelkerken et al. 2023). The consensus is that climate change will generally lead to a net loss of biodiversity, which yields biotic homogenization in most areas (Malhi et al. 2020). Extreme habitats where specialists have evolved will likely accept more generalist species, driving a loss of endemism and further homogenization (Gordó-Vilaseca et al. 2023). Physiological tolerance to stressors, phenotypic plasticity and capacity to adapt, both physiologically and behaviourally, in response to climate stress will determine the winners and losers of climate change (Somero 2011; Pecl et al. 2017; Webster et al. 2017; Andreasson et al. 2022). Identifying the likely losers, and managing for their resilience is one of few options available to mitigate or forestall the impacts of climate change (Schuurmann et al. 2022). Tackling the climate crisis is an enormous challenge but the focus must be on adaptation to the new realities imposed by the changes. In actionable terms, this means identifying the phenotypes, species, or ecosystems that are most vulnerable to climate change, and using tools and actions such as fisheries management, habitat restoration, invasive species control, or enhancement measures to forestall extinctions and fortify ecological communities against the most damaging impacts.

Essential to managing under the constraints of a changing climate in inland and marine waters are data that accurately describe the responses of biological units to change. In water, behavioural changes play a key role because the initial response of individuals to human-induced environmental change is often behavioural (Toumainen and Candolin 2011). In many ways, behaviour is the first line of defense for most aquatic organisms. Such responses can then initiate a predictable sequence of observable changes (e.g. alteration of individual fitness and population dynamics) that manifest as changes in population abundance (Cerini et al. 2023). The role of aquatic animal electronic tagging and tracking tools (including both biotelemetry and biologging; herein E3Ts) in informing how wild animal populations react to these global changes occurring in lakes, rivers, and seas is therefore important, allowing researchers to identify, and understand and preview the resilience of species and ecosystems to climate change. Investigating how aquatic tagging and tracking can make an actionable and enduring contribution to climate research requires a suitable framework of climate change impacts with which to consider the study designs that could be implemented. Pörtner and Peck (2010) provided a simple framework to scale climate change impacts from individuals to communities, which was created for causal inference about the impacts of climate change on fish. In their framework, they suggest three scales at which climate affects fish: the individual (physiology and behaviour), its population, and their ecosystem. Other researchers have drawn similar frameworks based on these fundamental levels of organization (also Nagelkerken et al. 2023), including the hierarchical response framework proposed by Smith et al. (2009), where individual, within-ecosystem, and between-ecosystems effects of climate are considered. Here, we consider the role of aquatic E3Ts within existing climate change impact frameworks, focusing on aquatic animals that are at particularly high risk due to climate change and extreme weather events (Pinsky et al. 2022; Figure 1).

2. Applying animal tracking to studying climate change

146 2.1 Impacts of climate change on the performance of individuals

147
148 *Background for linking the framework to electronic tagging and tracking:* Physiological rates
149 controlled by the environment (aka the Fry Paradigm; Fry 1959) dictate progress towards life
150 history checkpoints. Laboratory experiments have demonstrated the importance of
151 temperature as a mediator of individual life histories; in fact, temperature is often referred to
152 as the ‘master factor’ controlling biological rates (Fry 1971; Hochchka and Somero 2002;
153 Sunday et al. 2012; Nakayama et al. 2016). However, field data from tracking can offer a
154 much more comprehensive view of individual ecologies (Metcalf et al. 2012, 2016; Šmejkal
155 et al. 2021). Major effects of climate change include extremification of water temperature
156 (including cold shock; Szekeres et al. 2016) and pH, and hypoxia in many areas, which
157 determine vital rates (including rates of physiological functioning and rates of movement),
158 and constrain activities to hospitable water conditions. All of these processes may in turn
159 drive competition for space and access to resources, as well as vulnerability to capture by
160 people and predators. For example, Vedor et al. (2021) demonstrated that climate-induced
161 hypoxia will promote habitat compression for blue sharks (*Prionace glauca*) and enhanced
162 vulnerability to surface-oriented fisheries. Better individual data from tagging may provide
163 insights into the maturation of fish as they initiate spawning migrations inferred from
164 movement patterns (Griffin et al. 2022) and lifespans of species based on tag detections that
165 can be linked to environmental experiences. E3Ts can also be used to explain how
166 exploitation removes high-performing metabolic phenotypes from populations (Duncan et al.
167 2019). Animal tracking can also help identify mortality events and specific responses of
168 animals to extreme scenarios that operate at a population scale (floods, heat waves, warm
169 winters, swells, etc.; Clark et al. 2020; Jarić et al. 2022; Sarkar and Borah, 2018; Šmejkal et
170 al. 2023; Williams et al., 2017; Lempidakis et al. 2022) as well as the impacts of more gradual
171 changes (e.g. increased accumulated thermal units) on life histories. Such questions can be
172 directly answered by logging the environmental temperatures experienced by fish throughout
173 their lifespans. Using individual tagging data, analysts can query: where are the animals, how
174 do they use micro- and macro-habitats, how does their behaviour change during extreme
175 weather (e.g. heat waves, drought, natural disasters), how heritable are the phenotypes that
176 persist through climatic bottlenecks, and how does behaviour affect competition, predation,
177 reproduction, and senescence? Beyond behaviour, E3Ts can also help to assess the
178 physiological constraints and demands that environmental conditions pose, including for
179 example, measures of metabolism (Metcalf et al. 2016).

180 *Examples:* Several studies have combined track and sensor data to investigate climate
181 vulnerabilities of individual animals. Depth-temperature records have been used to identify
182 environmental windows where loggerhead turtles (*Caretta caretta*) thrive (Patel et al. 2021),
183 and to compare chinook salmon (*Oncorhynchus tshawytscha*) and lake trout (*Salvelinus*
184 *namaycush*) habitat partitioning in a lake (Raby et al. 2020). Combining habitat, temperature
185 and tracking data, Freitas et al. (2016) showed that given favourable sea surface temperatures,
186 Atlantic cod (*Gadus morhua*) individuals selected shallow, food-rich vegetated habitats;
187 however, with warmer surface waters such as those predicted under future climate scenarios,
188 individuals remained at deeper waters in less productive habitats. Matching the thermal niche
189 of species to the future available thermal habitat using climate models can provide projections
190 for species’ ranges under climate change using species distribution modeling (e.g. Legrand et
191 al. 2021; Patel et al. 2021). Movement tracks can be used to link abiotic features to
192 energetically sensitive behaviours, for example, revealing the importance of moderate ice
193 cover to the foraging behaviour of bowhead whales (*Balaena mysticetus*) in Nunavut, Canada
194 (Pomerleau et al. 2011). Similarly, Hamilton et al. (2017) found that sea ice decline
195 effectively reduced the degree of spatial overlap between polar bears (*Ursus maritimus*) and

196 their prey, ringed seals (*Pusa hispida*). Payne et al. (2018) used accelerometer loggers to
197 reveal that tiger sharks (*Galeocerdo cuvier*) had peak activity and, consequently, were more
198 vulnerable to fisheries bycatch at 22 °C. Kneebone et al. (2018) observed juvenile sand tiger
199 sharks (*Carcharias taurus*) in a bay (Massachusetts, USA) with acoustic transmitters outfitted
200 with accelerometer sensors and implemented Gaussian Markov random fields to model areas
201 with high activity and energy expenditure. Direct calibration of acceleration metrics to oxygen
202 consumption can provide estimates of oxygen consumption and energy landscapes, revealing
203 how habitat and climate interact to shape the metabolic demands and life course (aka pace of
204 life) of individuals. Such methods must be extended beyond temperature for aquatic species to
205 see how other water parameters affect energetics, to fully appreciate how climate change
206 affects aquatic animals across a range of climate-related impacts, including water volume loss
207 (i.e. drought), flow regimes, cyclones/hurricanes, pH extremification, or hypoxia. E3Ts can
208 also be used to study winter ecology, under the assumption that cold-water adapted fish show
209 elevated fitness in harsh winters and lose performance as winters warm (McMeans et al.
210 2020).

211 *Designing studies:* With careful planning and the availability of environmental data at
212 relevant spatial and temporal scales, it is possible to assess relationships between individual
213 animal movement and environmental change. Simulations can facilitate projections describing
214 how niches (estimated from computer models) correspond to expected changes in
215 distributions (e.g., Patel et al. 2021). However, direct manipulations including habitat
216 alterations, such as studies with experimentally warmed outflows (e.g. from power plants),
217 and experimental displacement can be useful to test resilience and climate vulnerability across
218 species or phenotypes within species. There is a need to seek tools that will help make more
219 thorough assessments of the individual's status and fitness (e.g., survival) when exposed to
220 climate stressors, such as heart rate loggers and transmitters that measure indicators of
221 physiology (i.e., stress) that may be independent of other metabolic demands (e.g.,
222 movement). Studying the impacts of climate change on individuals requires some control over
223 the habitat or the animals, which can be achieved using ponds or lakes to better understand
224 climate change impacts at this scale (Lennox et al. 2021). If combined with physiological
225 metrics of thermal performance and tolerance, E3Ts could provide us with a powerful tool to
226 predict climate impacts on individuals and species. Physiological measures of performance
227 and tolerance have predominantly been undertaken in the lab, creating opportunities to expand
228 the testing of temperature-mediated performance hypotheses in the field (Rezende et al.
229 2014). In this regard, E3Ts could be pivotal in elucidating whether these metrics are, in fact,
230 relevant in the wild.

231 2.2 Species responses to climate change

232 *Background for linking the framework to electronic tagging and tracking:* Detecting
233 responses to climate change at the species level depends on distributional models that treat
234 individual replication, the inherent unit at which E3Ts is conducted, as a means to understand
235 a representative sample of a species. Using tracking data and models that account for
236 individual variation (i.e. mixed effects), it can be possible to assess the species-scale
237 responses of animals to climate change. It is logical that inferences made at the individual
238 level can be extrapolated to the species scale, but specific approaches and aims will guide
239 researchers to use E3T data at the species scale. Indeed, the changing habitats and the impact
240 climate change will have on physiological processes will influence mass movements of
241 animals, transferring matter and nutrients in bulk across boundaries (Nathan et al. 2008).
242 Warmer water temperatures will force poleward or vertical changes in distribution as animals
243 seek thermal refuge (Perry et al. 2005). Changes in river hydromorphology or ocean currents
244
245

246 will alter species assemblages (Vannote et al. 1980) or species distributions (e.g. Gardner et
247 al. 2015). Diel vertical behaviour might also be influenced, as the northward distribution will
248 lead to shifts in seasonal variability in light availability, both impacting foraging for food and
249 predation risks, an impact on one of the planet's major biological pumps (Ljugstrøm et al.
250 2021). Beyond species-specific effects, climate change can cause spatiotemporal alterations to
251 the interactions between species or populations, which ultimately affect the structure of
252 ecosystems and their functioning (van Zuiden et al. 2016; Tunney et al. 2014).

253 *Examples:* To be relevant at the species scale, E3T experiments should aim to identify broad-
254 scale movement and behavioural shifts representative of the species, including spatial or
255 temporal shifts, meaning data series that are broad in geographic scale or long in term are
256 most robust. Models using E3Ts can be used to generate distribution or niche models that are
257 built on representatives of a population and focus less so on intraspecific variation. This can
258 be accomplished by using individual data to generate models or predictions, such as in
259 Aspillaga et al. (2017) where a general northward shift of common dentex (*Dentex dentex*)
260 was projected based on mechanistic niche data established from tracking. Spatial shifts at the
261 species level have been revealed from tracking data in a lake, where Řiha et al. (2022)
262 identified a collective shift in the depth use of wels catfish (*Silurus glanis*) in response to
263 bottom hypoxia. As the climate continues to change, the centroid of animal distributions may
264 shift over time, which can be tracked from E3T data using archived data in a time series.
265 Moreover, migration routes could also shift; however, Horton et al. (2020) found that 15 years
266 of satellite tracking data did not reveal any significant changes in the migration routes of
267 humpback whales (*Megaptera novaeangliae*) despite changes in the oceanography and
268 magnetic fields during that period. This contrasts with 15 years of bluefin tuna (*Thunnus*
269 *thynnus*) tracking data from the Pacific, where tunas were observed to adapt their distributions
270 according to marine temperatures, including an extreme anomaly during a heatwave (Carroll
271 et al. 2022). In terms of timing of key life history events, Douglas et al. (2011) observed
272 phenological shifts in striped bass (*Morone saxatilis*) in the Miramichi River, while Hauser et
273 al. (2017) used time series data from satellite telemetry of beluga whales (*Delphinapterus*
274 *leucas*) to identify changing migration timing in the Arctic.

275 *Designing studies:* Understanding how species are responding (and will respond) to climate
276 change using E3Ts likely needs a reliance on temporal comparisons with long-term time
277 series for tracking changes at a relevant scale. Time series can identify gradual or stepped
278 changes in the phenology of key events, or may simply provide insights from aberrant events
279 such as heat waves or extreme weather that cannot be planned for (e.g. Heupel et al. 2002;
280 Carroll et al. 2021). Projects with several years of data sampling are likely to include some
281 periods of abnormally warm temperature or extreme weather, and data sampled during such
282 events are valuable to explain or even predict potential shifts in behaviour (e.g., refuge
283 seeking, foraging areas) that a population/species will face in the future (Westrelin et al. 2022,
284 2023). Experiments at the population scale using tracking may include randomized control
285 treatment trials in which control fish are systematically released and compared to a treatment
286 group that is reared under projected future environmental scenarios such as warming. Such
287 designs are possible using E3Ts to track the fate of a suitable fraction of a population to draw
288 inferences at scale using experimental rearing or challenge tests combined with fate tracking.
289 Interventions that could be considered include acute exposure or chronic immersion in warm
290 temperatures or acidified water, simulating the rearing conditions likely to be encountered by
291 fish experiencing climate change. Long-term tracking of these fish and comparison with a
292 control group will be instructive to understand the magnitude of the challenges faced by these
293 animals and proactively adopt management actions. For most studies aiming to generate
294 results at the population scale, customisation of battery lifetime to be long enough to detect

295 animals later in life, or addition of sensors to the tags for tracking days or total activity, can
296 greatly improve current data collection.

297 One important methodological possibility at the population scale is to track offspring
298 and assign them to different parents, thereby tracking how exposure to different environments
299 affects reproduction and fitness. In Caspian terns (*Hydroprogne caspia*), cultural transmission
300 of migration routes was inferred from tracking birds with their own offspring and with fosters
301 (Byholm et al. 2022). Genotyping tagged individuals could then allow us to also follow the
302 temperature preferences across intraspecific genetic lines, and study evolutionary adaptations
303 to climate change over time. Although designs using electronic tagging to better understand
304 population responses to climate change are promising, caution is warranted when attempting
305 to scale observations of individuals to establish trends about species or populations.

307 2.3 Global influence of climate change on ecosystems and communities

308
309 *Background for linking the framework to electronic tagging and tracking:* Climate change has
310 the potential to induce ecosystem-level changes, such altering the ecology, density, and
311 phenotypic structure of keystone species, creating mismatches between the migration
312 phenology of keystone species and their prey (Renner and Zohner, 2018), changing the
313 outcome of interspecific competition (Helland et al., 2011; Carmona-Catot et al., 2013),
314 increasing ecosystem vulnerability to invasive species (Ilarri et al., 2022; Souza et al., 2022),
315 shifting temporal and spatial niches of thermal specialists (Santiago et al., 2016), affecting
316 parasite-host interactions (Löhmus and Björklund, 2015; Cable et al., 2017), increasing the
317 frequency and intensity of ecosystem perturbations, and ultimately causing interconnected
318 cascading effects that can disrupt ecosystem functioning (Durant et al., 2007; Thackeray et al.,
319 2010). Climate change impacts can be further exacerbated through synergistic interactions
320 with other stressors such as eutrophication, pollution, water regulation, and biological
321 invasions (Woodward et al. 2010). Climate change can also create novel heterogeneity
322 through asymmetrically altering environmental conditions in space, which can alter mobile
323 generalist consumer species behaviour and broadly reorganize food webs (Bartley et al.
324 2019). However, to fully track impacts, detailed ecosystem information has to be collected,
325 starting with abiotic variables, food resources, and various organismal responses, representing
326 a subset of taxa and trophic levels in the ecosystem (recognizing that not all species are
327 suitable for tagging). Detailed animal tracking, in combination with other monitoring tools,
328 can provide valuable insights into the extent of resulting changes in reproductive phenology,
329 the level of their synchronization across different animal taxa, and how they affect the timing
330 of food supply (Reglero et al., 2018; Renner and Zohner, 2018; Beltran et al. 2019, 2022). For
331 larger organisms, E3Ts can effectively track responses to climate change that affect migration
332 timing, nesting behavior, or small-scale habitat shifts due to migration.

333 *Examples:* Despite a broad agreement that ecosystem approaches are needed to understand
334 and manage environmental resources, incorporating animal tracking into whole-ecosystem
335 research is still quite rare, and only a few ecosystem studies have used E3Ts. Yet, the
336 movements and distributions of animals are crucial, as evidenced by the little auk (*Alle alle*),
337 which deposits guano in lakes that yield such eutrophic conditions that invertebrates and fish
338 are excluded; climate-induced range shifts would therefore induce landscape-scale changes in
339 freshwater ecosystems (González-Bergonzoni et al. 2017). However, the highlighted
340 examples demonstrate the enormous potential of tracking data to reveal ecosystem
341 consequences of climate change-induced alterations of animal behaviour. Guzzo et al. (2017)
342 combined long-term acoustic telemetry with diet analysis to show that warming reduced lake
343 trout use of the nearshore areas, and thus reduced exploitation of limnetic food resources. This
344 resulted in a reduction in the growth and condition factor of lake trout and significant changes

345 in carbon flux throughout the lake ecosystem. Caldwell et al. (2020) examined the effects of
346 earlier ice breakup on water temperatures and habitat production, as well as the consequences
347 for habitat use, behaviour, and fitness of brook trout (*Salvelinus fontinalis*). The study showed
348 that earlier ice breakup created resource-rich littoral-benthic habitat compared to pelagic
349 habitat. Nevertheless, movement data revealed that brook trout did not exploit the littoral
350 habitat due to warm temperature avoidance, which reduced their fitness. Thus, changes in ice
351 break-up drive multi-directional results for resource production within lake habitats and have
352 important consequences for predators.

353 The effects of climate change on the coupling between terrestrial and aquatic
354 ecosystems were studied by Hamilton et al. (2016) and Deacy et al. (2017). Hamilton et al.
355 (2016) used satellite telemetry to show that polar bears (*Ursus maritimus*) spent more time on
356 land during periods of reduced sea ice, spatially isolated from their preferred prey, ringed
357 seals (*Pusa hispida*). While on land, polar bears spent more time near ground-nesting bird
358 colonies and predated more on nesting seabirds. Deacy et al. (2017) used GPS telemetry in
359 Kodiak brown bears (*Ursus arctos*) to examine the response of bear behaviour to global
360 warming-induced changes in the availability of two important food resources, red elderberry
361 (*Sambucus racemosa*) and sockeye salmon (*Oncorhynchus nerka*). Climate warming
362 advanced the elderberry blooming to align with the spawning of sockeye, causing bears to
363 prioritize elderberry, and weakening the link between salmon and its contributions to the
364 surrounding land by fertilizing the earth and enhancing local biodiversity.

365 *Designing studies:* The ecosystem approach can be challenging because it requires
366 consideration of other trophic levels and how changes in focal animal behavior translate to
367 population, species, or community scales. Behavioral changes can alter ecological interactions
368 (e.g., predator-prey dynamics, competition, social behaviors), and these consequences can be
369 tracked using a suite of complementary tools that link tracking data to metrics collected at
370 different levels of the ecosystem. For example, approaches may require examining population
371 and life history parameters of key species, system productivity, and the strength or direction
372 of ecological interactions prior to, or during, movement tracking. In this way, the impacts of
373 climate change can be comprehensively studied using animal tracking. Effects of climate
374 change on ecosystems and communities could be studied through experiments involving
375 islands or small pond ecosystems using telemetry where manipulations can be undertaken,
376 including experimental warming. Space or time replication (e.g., across lakes) and reciprocal
377 transplant studies can be used to study evolutionary adaptation to climate change at an
378 ecosystem scale. For example, ponds could be warmed at different temperatures, exposed to
379 different water levels or fluctuations, different nutrient loads, as well as different levels of pH
380 and dissolved oxygen. Alternative designs could involve tracking in replicated tracts, such as
381 whole lakes, along a latitudinal gradient that would treat climatic variation as a component of
382 the behavioural variation (Lennox et al. 2022). Experiments could additionally address
383 changes to physiological and behavioural phenotypic frequencies related to changing
384 environments, including activity, phenology, and interspecific interactions (e.g., predation
385 rates). Of special relevance would be multi-species experiments that integrate fish behaviour
386 with physiology (Cooke et al. 2008; Komoroske and Birnie-Gauvin 2022), to infer responses
387 at the level of communities, as well as effects on ecosystem metabolism. Where possible,
388 there should be an increasing emphasis on building models with multiple species to better
389 understand how different species respond when confronted by changes not in isolation, but in
390 the presence of competitors or predators. Experiments using predation tags—tools that
391 continue to be developed for identifying the fate of animals and a key ecological interaction—
392 should become a tool that helps reveal some of the most important aspects of ecological
393 dynamics symptomatic of climate change in both experimental and observational studies
394 (Lennox et al. 2023).

3. Testing climate resilience and management

3.1 Habitat restoration

Physicochemical habitat is linked to climate and therefore measures aimed at improving habitat suitability or availability can play a key role in buffering climate change effects for individuals (Timpone-Padgham et al. 2017). For aquatic species reliant on physical habitats, the most important mitigation effort is to conserve or restore essential habitats that minimize impacts of climate change. Some of the most concrete examples are canopy shelters in rivers (Fullerton et al. 2022; Kirk et al. 2022), artificial reef construction in the sea (Getz and Kline 2019), or artificial nests for seabirds (Burke et al. 2022). Indeed, animals may find refuge in the landscape that helps them cope with climate change, but how this process operates in nature may be challenging to understand for aquatic species. In an effective illustration of this, Freitas et al. (2021) tracked several species of a fish community in a Norwegian fjord to find that their depth distribution responded to environmental temperatures, showing that they were allocating their time to spatial areas in the landscape that provided thermal refuge. Tracking animals and their temporal and spatial use of habitat in various climate scenarios is therefore an important avenue of research to inform restoration efforts that can be engineered in a way to minimise climate effects. Indeed, our knowledge of what constitutes an effective refuge for aquatic species may be biased or incomplete without empirical data from the field. Opportunistic data may be key to generating new knowledge where experiments are not feasible. For example, tracking animals can help identify areas of high use during weather anomalies that provide refuge, or strategic use of areas that help maintain homeostasis and that are key to protect, restore or even expand to face climate change (e.g. Henesy et al. 2022). Amat-Trigo et al. (2022) suggested that behavioural thermoregulation may provide an innate mechanism of resilience to fish encountering a changing climate. Effective behavioural thermoregulation, however, depends on the availability of suitable habitat, which may require spatial planning measures in rivers, lakes, and coasts. Using this knowledge, action can be taken to generate heterogeneity that buffers warming and protects important inflows and seeps and upwellings.

3.2 Protected areas to facilitate persistence of vulnerable species

Protected areas (PAs) are often used as a management intervention to protect species against disturbance (Agardy 1994; Edgar et al. 2014). Although marine PAs are widely known, freshwater PAs are equally valuable and actionable (Saunders et al. 2002). PAs are globally used to buffer exposure of animals to stressors, but their role in mitigating climate change effects should be further explored (Hannah et al. 2008; Soares-Filho et al. 2010; Roberts et al. 2017). Adapting PAs to buffer vulnerable species from climate change may be a viable option to mitigate the effects of temperature warming. Most advice suggests that marine PAs need to be larger and better connected (McLeod et al. 2009) to effectively benefit species experiencing climate change. However, there is an opportunity for gathering additional evidence using tracking tools. Animal tracking is vital to understand how the functionality of PAs will change as animals migrate and change their movements according to climate, especially in open aquatic systems, where range shifting can alter the protection afforded by area-based measures. In a climate change scenario, where the conditions in the ecosystems are in constant change, the effectiveness of PAs might be challenged, as temperature fluctuations can alter the suitability of certain habitats for constituent species (Hooker et al., 2011; Sahri et al. 2022; Freitas et al., 2016). E3T studies can be designed to monitor how species respond to

445 warming conditions with and without protections from potential synergistic stressors, which
446 in turn can inform conservation efforts and potentially lead to reconsideration and reallocation
447 of PAs and even the option for dynamic PAs based on seasonally changing needs of animals
448 (Sequeira et al. 2019).

450 3.3 Translocations or assisted migration

451
452 Climate change is challenging species to respond to rapidly changing conditions in their local
453 environments. Species may not have the capacity to adapt at a sufficient pace to these changes
454 (i.e. evolutionary adaptational lag) or may lack the dispersal capacity to colonise suitable
455 habitats (Schloss et al., 2012; Fréjaville et al., 2020). To overcome these limitations, “assisted
456 migration” (see Twardek et al. 2023 for definition) of animals to more suitable areas has been
457 proposed as a means of facilitating the resilience of a population impacted by climate change
458 by providing suitable habitats faster than they could reach them by natural range expansion
459 (Hällfors et al., 2014). Typically, these movements occur into areas where those individuals
460 would be predicted to move, provided they had sufficient time and connectivity between the
461 habitats, as they might be expected to in a slower climate change scenario (Hällfors et al.,
462 2014). Assisted migration is gaining increased attention as a potential conservation tactic
463 (Twardek et al. 2023; Benomar et al., 2022), though much uncertainty and controversy
464 remains regarding the potential ecological risks and benefits (Ricciardi and Simberloff 2009;
465 Aitken and Whitlock 2013; Bucharova 2017). Thus far, successful cases of assisted migration
466 for conservation have been very limited, with most movements pertaining to trees and other
467 vascular plants in the context of forestry (Pedlar et al. 2012). Aquatic animals have rarely
468 been the subjects of assisted migration studies (Twardek et al. 2023), though there is
469 recognition of the values these movements may have in supporting fisheries (Green et al.
470 2010), and it seems likely that these movements will be increasingly considered to abate the
471 impacts of climate change on highly valued species, possibly at the cost of less economically
472 valued counterparts. Careful study and monitoring will be critical to this endeavour given that
473 it would not be desirable to have assisted migration become a broad-scale invasion (Mueller
474 and Hellmann 2008). Electronic tagging and tracking will be uniquely positioned to inform
475 how introduced species are using their newfound environments, expanding their ranges, and
476 interacting with the broader aquatic ecosystem. As a unique example of this, western swamp
477 turtles (*Pseudemys umbrina*), Australia’s rarest herpetile, were outfitted with
478 radiotelemetry transmitters and temperature loggers and were introduced into a wetland
479 located 300 km south of the species’ native range (Bouma et al. 2020). Over a six month
480 period, researchers gained insights into habitat use, movement, growth rates, mortality rates,
481 and microclimate conditions, providing important knowledge for future assisted migration
482 efforts for the species. Although fish have not been the focus of many assisted migration
483 studies, humans have inadvertently conducted assisted migration of fish at a large scale
484 through the stocking of fish throughout freshwater systems around the world (Halverson
485 2010). Whereas most of these movements would not constitute assisted migration, there is
486 great potential to study these movements in the context of assisted migration (see Banting et
487 al. 2021). As E3Ts continue to revolutionize how we understand aquatic animal movements
488 and species interactions (e.g. predation tags), it will undoubtedly be at the forefront of efforts
489 to study and monitor assisted migration.

491 3.4 Mitigation of interactive effects

492
493 Although the intensity of future climate change can be mitigated, aquatic temperatures will
494 continue to warm, with limited potential for direct intervention for abatement. Climate change

495 may, however, be an exacerbating factor for other stressors such as invasive species or
496 pollution (Bertram et al. 2022), that is operating interactively with warming; in many cases,
497 the other factors may be easier to address than the climate impacts (Brook et al. 2008).
498 Litchman and Thomas (2023) reviewed the role of several exacerbating factors that affect
499 species' metabolism and can interactively affect the vulnerability to warming. In such cases,
500 identification and removal of the interactive stressor will be an efficient remedy for the
501 species or population. For such interactive effects, it may be possible to mitigate the impact of
502 climate change on species by removing or addressing the interacting stressor, for example
503 invasive species removal or pollution remediation could enhance climate resilience of species
504 exposed to warming. In general, appreciation that climate vulnerability can be interactive is
505 still developing and we submit that animal tracking can help to reveal where interactions exist
506 and what actionable solutions can intervene to buffer the impacts of climate change. Such
507 approaches will necessarily rely on multi-disciplinary methods, and likely experimentation, to
508 identify and test how interactive effects operate.

509 510 3.5 Simulation of future scenarios

511
512 At a larger spatial scale, some studies suggest using global change projections together with
513 predictive species distribution models (Santos et al. 2020). To predict species distributions
514 using models, a first step is to understand the tolerance of individuals and populations to
515 different environmental conditions, including for instance how individual performance (e.g.
516 survival, reproduction) is affected by warming temperatures. Remote observation of thermal
517 experiences by animals can be more important than theoretical or laboratory challenge tests
518 for understanding the temperature selections made by aquatic animals, in large part because of
519 plasticity that they may exhibit to cope with such changes (e.g. Levy et al. 2019). The
520 relevance of thermal tolerance metrics derived from laboratory experiments have been
521 debated (Rezende et al. 2014). The collation of animal tracking data into large databases
522 allows for such synthetic modelling exercises and should be an important product of such
523 open access products (Iverson et al. 2019). This is already being put into practice to prepare
524 for climate change with a stronger understanding of likely animal responses (e.g. Hückstädt et
525 al. 2020; Reisinger et al. 2022a,b; Chambault et al 2022).

526 527 **4. Future directions**

528
529 Aquatic E3Ts are part of a rapidly advancing field in movement ecology, with
530 continually expanding use in ecological research and management (Hellström et al. 2022;
531 Nathan et al. 2022). Examples of these technological advances include continuous
532 improvements in battery technology that enable the miniaturisation of transmitters, permitting
533 researchers to track smaller species (Hazen et al. 2012) and younger age-classes of aquatic
534 organisms (Li et al. 2020). Emerging technologies such as self-powered tags that can harness
535 the biomechanical energy of the host animal may allow for the study of individual fish over
536 their entire life-span in the wild, across ontogenetic shifts, maturation, and eventual death
537 (Liss et al. 2022). Parallel advances in on-board processing capabilities coupled with artificial
538 intelligence programming make the next generation of transmitters able to remotely analyse
539 large amounts of high-resolution sensor data to identify complex behaviours and
540 physiological states, which can be quantified, summarised, and transmitted. Such on-board
541 data-processing would bypass the current bottleneck posed by the narrow bandwidth in
542 underwater communication, and further integrate big data science with animal tracking
543 (Figure 2; Nathan et al. 2022; e.g. Adachi et al. 2023). In addition, new communication
544 protocols and transmission techniques are being developed to reduce false detections and

545 signal collisions, making it possible to track large numbers of fish simultaneously with very
546 high spatial and temporal resolution (Lennox et al. 2023). Technological advances, in
547 combination with real-time transmission of detection data, creates the potential for automated
548 tracking systems that function at resolutions comparable to terrestrial GPS (Yang et al. 2022).
549 Such real-time tracking can be applied in experimental contexts to facilitate manipulation
550 treatments, as well as improving adaptive management by allowing for data-driven decision
551 making with minimal delay when data are made available and accessible to end-users
552 efficiently. It would also allow the expanded capacity to detect routinely-tagged animal
553 behavioral responses to unpredicted climate-change related events, such as extreme weather
554 regional/localized events.

555 Innovative use of acoustic tags capable of both transmitting and receiving signals,
556 particularly in combination with GPS technology, will generate exciting opportunities to
557 study social interactions and predation dynamics between tagged animals across scales and
558 contexts not previously possible (Krause et al. 2013; Lidgard et al. 2014; Nathan et al. 2022).
559 Autonomous underwater and surface vehicles can be used for mobile tracking of tagged fish
560 outside receiver arrays (Nash et al. 2021). There have also been solutions introduced to
561 facilitate remote off-loading of data from deployed receivers, such as using autonomous
562 vehicles and daisy-chained receiver links (Dagorn et al. 2007), which promise to drastically
563 cut maintenance costs of remote receiver networks and increase the update frequency of
564 detection data. At the same time, expanding networks of receiver infrastructure globally,
565 organised via data-sharing hubs such as the Ocean Tracking Network (Iverson et al. 2019),
566 are increasing the areas of the world's oceans where aquatic species can be tracked and
567 studied. Extremely high-power transmitters that can be detected thousands of kilometres away
568 may in the future reduce the need for dense receiver networks when tracking large-bodied fish
569 across oceans (Bronger and Sheean 2019). All of these developments will enable long-lived
570 and highly migratory species such as whales, seabirds, pelagic sharks, billfishes, and tunas,
571 that cross vast expanses of water, and potentially experience very different climate-impacted
572 habitats over their life-span, to be tracked with increased detail, including into areas of the
573 deep-sea to track their use of oxythermal habitat at a global scale. Overall, the continued
574 advancement of E3T tools has the potential to revolutionise research on the impacts of climate
575 change on aquatic wildlife and prepare for implementing solutions and interventions where
576 possible. By harnessing the full capabilities of these technologies, researchers can gain a
577 better understanding of how climate change is affecting these species and develop strategies
578 to protect and conserve them.

580 5. Limitations

581
582 Whereas tracking the movements of aquatic animals can provide valuable insight into
583 their spawning aggregations, migration routes, and barriers to movement, aquatic E3Ts have
584 mostly been applied to adult organisms, due to the limitation of the tag size with decreasing
585 body size until quite recently. Many aquatic species have a planktonic stage, during which
586 they disperse and inhabit different habitats before reaching adulthood. By mainly having
587 tracked adult aquatic animals, we have missed crucial information about the connectivity
588 between metapopulations and shifts mediated by climate change in dispersion and nursery
589 areas. In order to fully understand the movements and behaviours of aquatic species, we must
590 also track the movement of these earlier, smaller stages.

591 The importance of tracking all life stages can be extended to further scales, including
592 investigations of different personalities within a life stage. Indeed, larger variations in
593 behaviour among individuals could be expected with warming temperatures as a function of
594 differences in personality, but it has been found that seabirds encountering stressful conditions

595 may become more homogenous in their behaviour (Gillies et al. 2023), as do fish exposed to
596 certain pollutants (Tan et al. 2020; Polverino et al. 2021). To capture the whole spectrum of
597 behaviours and gather an unbiased representation of responses of the population to
598 environmental changes, it is then of utmost importance to track a representative sample of all
599 personalities and thermal preferences within the considered population (Villegas-Rios et al.
600 2018 ; Cooper et al. 2018), strengthening the importance of obtaining affordable tracking
601 technologies adapted to large samples. For acoustic telemetry, this may mean adopting more
602 CDMA (code division multiple access) or BPSK (binary phase shift key) systems to allow for
603 more animals to be tagged simultaneously within an area, without false detections (e.g.
604 Aspillaga et al. 2017)

606 6. Conclusions

607
608 Here, we have presented a case for how animal trackers can design studies to reveal
609 how aquatic organisms respond to climate-related changes in their environment while
610 providing a useful tool to inform management and human adaptation strategies. Climate
611 change will result in more dynamic environmental conditions that span warming waters, cold
612 shock events, changing ocean currents, varied runoff conditions, and extreme weather events
613 (e.g., storms, hurricanes, blizzards), which will undoubtedly impact aquatic animals in diverse
614 ways, many of which are unpredictable without empirical data. E3T data are able to provide
615 unprecedented information on animal-environment interactions, and these baseline data are
616 already being used to understand contemporary climate change impacts, and to predict how
617 future climate change may impact aquatic animals.

618 Simply documenting changes in the distribution, timing, and survival of aquatic
619 animals in the face of climate change will not fully realise the potential of E3T data to support
620 climate change adaptation efforts. Moreover, waiting for decades to do so will mean that we
621 will continue to invest in management strategies that may be ineffective. Reliance on
622 observational data as the climate gradually changes will nevertheless be valuable, and there
623 should be investment in long-term data series for tracking key species in climate-sensitive
624 areas. Indeed, despite the high-throughput nature of E3T data and the capacity to provide
625 immensely valuable and highly detailed data from remote observations of animals that are
626 otherwise very hard to observe, there seems to be a lack of long-term time series using
627 tracking of electronic tags that could be used to identify inter-annual or decadal responses to
628 climate, as well as the magnitude of changes to behaviour in anomalous years. Fortunately,
629 time series can be assembled *post hoc* from international databases, albeit with limitations of
630 study design interoperability to overcome. Notwithstanding, time series alone will provide
631 limited power unless there is a great adoption of manipulative experiments that reduce
632 uncertainty and accelerate our understanding of climate change impacts on aquatic species,
633 populations, and ecosystems.

634 There is a dire need to future-proof today's management initiatives so that they
635 provide resilience to aquatic systems and resource users in the face of a more dynamic future.
636 Consequently, it is necessary to develop science-based climate change human adaptation
637 strategies from tracking data that will provide decision makers with a new management
638 toolbox to ensure that aquatic animals are managed in a sustainable manner. We are confident
639 that biotelemetry and biologging tools for tracking aquatic animals can be used to generate
640 novel information to support such efforts and do so at scales relevant to environmental
641 decision makers.

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644

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660 661 **Competing Interests**

662
663 The authors have no interests in competition

664 665 **Data Availability**

666
667 There are no data in this manuscript.

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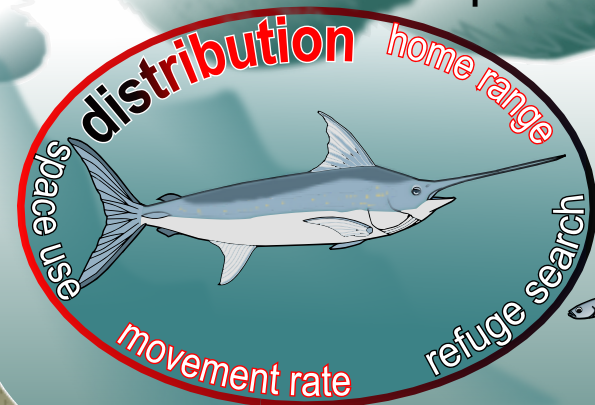
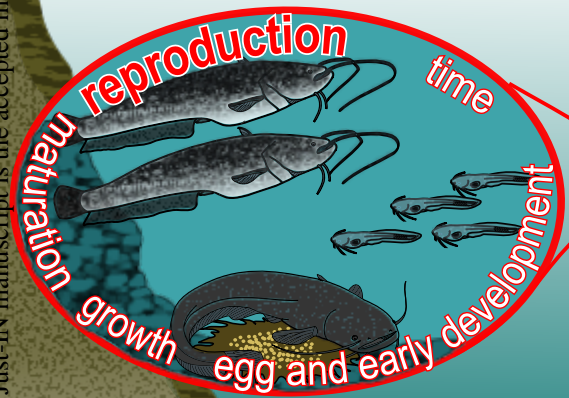
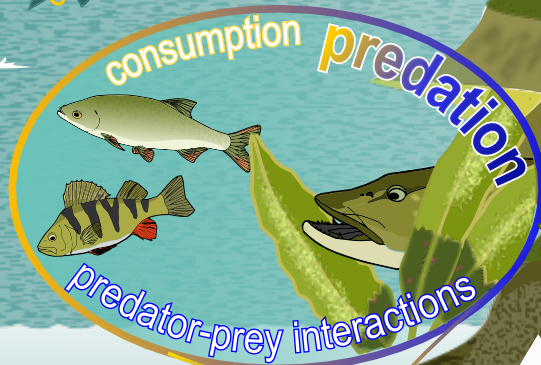
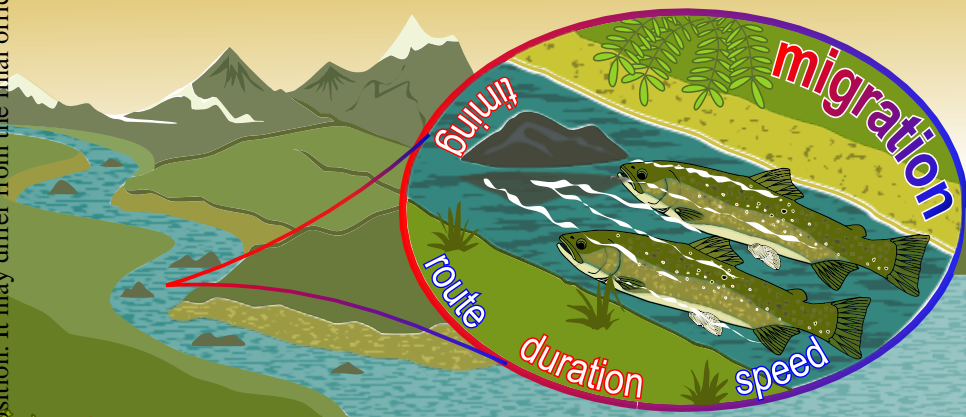
Figure Captions

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Figure 1. Illustration of the complexity of aquatic ecosystems down to the individual level. The features likely to be affected by climate change and into which telemetry can give insight are highlighted in ellipses. Each ellipse presents a feature (larger font) and the variables that can be estimated by acoustic telemetry (smaller font). The features listed on the figure are coloured according to the level they are concerned with (ecosystem in black, community in orange, population in blue, and individual in red). The pyramid displays the hierarchical order of the levels with arrows to show the interactions among them. Artwork by Zuzana Sajdlová.

Figure 2. Currently available sensors for acoustic tags and their study objectives. The types of tags are indicated in the inner circles with uppercase text and colour coded. The features that can be studied in the context of climate change using one or more of these tags are detailed in the smaller outer circles with lowercase text.

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