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Reasons to Be Skeptical about Sentience and Pain in Fishes and Aquatic Invertebrates

Benjamin K. Diggles^a, Robert Arlinghaus^b, Howard I. Browman^c, Steven J. Cooke^d, Robin L. Cooper^e, Ian G. Cowx^f, Charles D. Derby^g, Stuart W. Derbyshire^h, Paul JB Hartⁱ, Brian Jones^j, Alexander O. Kasumyan^k, Brian Key^l , Julian G. Pepperell^m, D Christopher Rogersⁿ, James D. Rose^o, Alex Schwab^p, Anne B. Skiftesvik^c, Don Stevens^q, Jeffrey D. Shields^r and Craig Watson^s

^aDigsFish Services, Banksia Beach QLD, Australia; ^bDepartment of Fish Biology, Fisheries and Aquaculture, Leibniz Institute of Freshwater Ecology and Inland Fisheries & Humboldt, Universität zu Berlin, Berlin, Germany; ^cInstitute of Marine Research, Austevoll Research Station, Norway; ^dDepartment of Biology, Carleton University, Ottawa, ON, Canada; ^eDepartment of Biology, University of Kentucky, Lexington, KY, USA; ^fHull International Fisheries Institute, University of Hull, UK; ^gNeuroscience Institute and Department of Biology, Georgia State University, Atlanta, Georgia, USA; ^hDepartment of Psychology, National University of Singapore, Singapore; ⁱDepartment of Psychology and Vision Science, University of Leicester, Leicester, UK; ^jSchool of Veterinary Science, Murdoch University, Perth, WA, Australia; ^kDepartment of Ichthyology, Faculty of Biology, Lomonosov Moscow State University, Moscow, Russia; ^lSchool of Biomedical Sciences, University of Queensland, Australia; ^mPepperell Research and Consulting, Noosaville, QLD, Australia; ⁿKansas Biological Survey, and the Biodiversity Institute, The University of Kansas, Lawrence, KS, USA; ^oEmeritus (Retired) Department of Zoology and Physiology, University of Wyoming Laramie, WY, USA; ^pBritannia Heights, Nelson, New Zealand; ^qBiomed Sci, Atlantic Veterinary College, University of PEI, Charlottetown, Canada; ^rThe College of William & Mary, Virginia Institute of Marine Science, Gloucester Point, Virginia, USA; ^sEmeritus (Retired) Tropical Aquaculture Laboratory, University of Florida, Gainesville, USA

ABSTRACT

The welfare of fishes and aquatic invertebrates is important, and several jurisdictions have included these taxa under welfare regulation in recent years. Regulation of welfare requires use of scientifically validated welfare criteria. This is why applying Mertonian skepticism toward claims for sentience and pain in fishes and aquatic invertebrates is scientifically sound and prudent, particularly when those claims are used to justify legislation regulating the welfare of these taxa. Enacting welfare legislation for these taxa without strong scientific evidence is a societal and political choice that risks creating scientific and interpretational problems as well as major policy challenges, including the potential to generate significant unintended consequences. In contrast, a more rigorous science-based approach to the welfare of aquatic organisms that is based on verified, validated and measurable endpoints is more likely to result in “win-win” scenarios that minimize the risk of unintended negative impacts for all stakeholders, including fish and aquatic invertebrates. The authors identify as supporters of animal welfare, and emphasize that this issue is not about choosing between welfare and no welfare for fish and aquatic invertebrates, but rather to ensure that important decisions about their welfare are based on scientifically robust evidence. These ten reasons are delivered in the spirit of organized skepticism to orient legislators, decision makers and the scientific community, and alert them to the need to maintain a high scientific evidential bar for any operational welfare indicators used for aquatic animals, particularly those mandated by legislation. Moving forward, maintaining the highest scientific standards is vitally important, in order to protect not only aquatic animal welfare, but also global food security and the welfare of humans.



KEYWORDS


Animal ethics; fisheries; aquaculture; sentience; suffering; welfare; verification; policy

Introduction

Some countries, including the United Kingdom (UK), have recently passed legislation recognizing fish and selected aquatic invertebrates (decapod crustaceans and cephalopods) as “sentient beings” requiring protection under animal welfare regulations (Birch et al. 2021;

Crump et al. 2022; Moylan 2022). Given their important ecological and food production roles (Golden et al. 2021; FAO 2022; Tigchelaar et al. 2022), more interest in fish and aquatic invertebrate welfare is welcome. Nevertheless, extending welfare legislation to more and more animal groups, often following intense lobbying by activist non-government organizations (NGOs) is problematic,

CONTACT Brian Key  brian.key@uq.edu.au  School of Biomedical Sciences, University of Queensland, Australia.

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as the evidence used to support this move includes advocacy-based reviews (not meta-analyses) which provide contentious interpretations of a limited body of scientific evidence that has significant technical and interpretational flaws (reviewed in Rose et al. 2014; Key 2015; Browman et al. 2019; Diggles 2019; Mason and Lavery 2022; Hart 2023). In fact, the reviews of Birch et al. (2021) and Crump et al. (2022) are being interpreted so broadly and so uncritically in certain policy-making circles that legislators risk following a path ending with all animals including insects and even plankton, eventually being included in welfare legislation (Gibbons et al. 2022; Crump et al. 2022, 2023). The ramifications of these developments on food production, and on how humans interact with animals, would be profound and far reaching (Browman et al. 2019).

Historically, most animal welfare legislation worldwide was based on a suffering-centered framework focussed on the needs of individual terrestrial vertebrates in food production or laboratory settings, specifically those that are sentient and, therefore, may suffer during experimentation, husbandry, and slaughter (Arlinghaus et al. 2009; Browman et al. 2019). Bringing aquatic species under the same suffering-centered legislation frameworks might seem logical at first, but it risks a rush to legislate that may sideline many well-established physiological,

pathological, nutritional, and health-related performance indicators that are currently used to operationally define welfare for these animal groups (i.e., criteria used by the functional, pragmatic approach to aquatic animal welfare, see Arlinghaus et al. 2009; Browman et al. 2019). Given the uncertainty surrounding the quality and interpretation of the available science (see Michel 2019; Mason and Lavery 2022 for detailed accounts), applying suffering-centered criteria to the welfare of fishes and aquatic invertebrates under existing legislative frameworks presents major policy challenges and has the potential to generate significant unintended consequences for both animal and human welfare (Browman et al. 2019). The risk of unintended consequences to food security is already being recognized in some countries, leading to societal reluctance and political unwillingness to enact the revised legislation (e.g., <https://www.bbc.co.uk/news/science-environment-65691321>; <https://www.politico.eu/article/uk-conservatives-abandon-plan-protect-animal-welfare/>)

Presented here are ten scientifically sound and prudent reasons to maintain skepticism (in the Mertonian sense) when the topics of sentience and pain in fish and aquatic invertebrates are used to justify inclusion of these organisms in legislation governing their use in the wild, food production or research (Table 1).

Table 1. Ten reasons to be skeptical about fishes and invertebrates being sentient and feeling pain.

| Reason | General principle | Examples | Consequences and outcomes |
|---|---|--|--|
| 1. Changing definitions | Deviation from accepted definitions of pain. Development of "sentience criteria" based on "confidence levels". | Replacing ethological terms with loaded human psychology terms. Promoting " <i>the idea of pain</i> " without considering alternative explanations for observed behavior. Philosophical/political risk analysis approach to defining sentience. | "Shifts the goalposts" to pain definitions which no longer discriminate between nociception and pain. Lowers "evidential bar" to include behaviors that do not even require nociception. Encourages anthropomorphism which invites false equivalence between the experience of animals and that of human pain. |
| 2. Ignoring or dismissing conflicting or contradictory evidence | Selectively ignoring data or studies that are inconsistent with the pain hypothesis. | Accepting evidence that is context specific as being broadly representative of all taxa without consideration of the full range of available evidence. Ignoring existence of "no effect" studies. Ignoring the very low % of C type nociceptors in teleosts (absent in elasmobranchs), circa 5 times less than humans with some forms of congenital insensitivity to pain. Ignoring letters and reviews highlighting significant fundamental flaws in research methodology/ interpretation. Role of "Guest Editors" ensuring publication of biased reviews used during activist campaigns. | Bias and overinterpretation of context specific data with few/no alternative explanations presented or considered. Asymmetrically ignoring studies that report contradictory outcomes. Use of overly emotive language. Invoking a double standard by accept pain as "animals response to stimuli that would be painful for humans" while ignoring behaviors alien to humans like autotomy, autophagy, auto-mutilation and limb regrowth. Erosion of normal scientific standards of peer review and publication ethics. Paucity of rigorous, unbiased and transparent systematic reviews of the relevant literature that include critical appraisal of the evidence base. |
| 3. Lack of replicable empirical evidence | Results "consistent with pain and/or sentience" are not replicable or independently verifiable by multiple research groups. | Grooming and rubbing of prawn antennae exposed to vinegar, bases and anesthetics not repeatable. Rocking and rubbing behavior in rainbow trout not repeatable. Claims of emotional fever in zebrafish as supporting consciousness in fishes not repeatable and shown to be false. | Mischaracterization of possible grooming and/or chemosensory behavior in crustaceans as evidence of "pain". Mischaracterization of possible experimental artifacts (e.g., recovery from anesthesia in fishes) as evidence of "pain". Overinterpretation of behavioral studies that cannot be replicated by independent research groups. Potential for new feelings-based operational welfare indicators in fish and crustaceans to be inconsistent, unreliable and/or unverifiable outside the laboratory. |

(Continued)

Table 1. Continued.

| Reason | General principle | Examples | Consequences and outcomes |
|---|--|---|--|
| 4. <i>Ad hominem</i> attacks on skeptics | Attempts to discredit skeptical scientists who highlight flaws in evidence base. | Attacks in pseudo journals or the popular media. Labeling skeptical scientists as “deniers”, “creationists” or “racists”. Promoting the “bandwagon effect”, to claim a manufactured “consensus” in biased, unrepresentative unreviewed forums or online. | Attempting to silence scientific debate upon the need for reliable empirical evidence for decision making. Erroneous claims of “scientific consensus”. Asymmetrical, <i>ad hominem</i> public attacks on those seeking replicable evidence. “Cancel culture” reminiscent of animal rights activism generating “lose-lose” scenarios instead of a balanced “win-win” approach to solving welfare issues in fish and invertebrates. |
| 5. Testing of unfalsifiable hypotheses | Testing hypotheses that are unfalsifiable negates the fundamental self-corrective aspect of the scientific method. | Utilizing pain definitions that encompass any “non-normal” behavior or any behavior deemed “consistent with the idea of pain”. Claims that pain will be expressed differently not only between species but even between individual animals of same species. Ignoring important differences between stress, nociception and pain. | Switching burden of proof. Promoting pain definitions which encompass any behavioral changes (whether from a specific noxious stimulus or not). Using unfalsifiable criteria to underpin legislation means any abnormal behavior could be interpreted as “painful”, resulting in infringement and prosecution (with no foreseeable way to prove ones innocence). Using unfalsifiable criteria to determine whether organisms are sentient will mean all organisms could meet criteria for sentience. |
| 6. Arbitrary application of criteria | Selective application of sentience criteria. | Application of sentience criteria to decapod crustaceans but not copepods. Application of sentience criteria to cephalopod molluscs but not bivalves or gastropods. Apparent unwillingness to apply the same sentience criteria to protozoans, and microorganisms. | Highly permissive criteria mean that all animals (and possibly even plants) meet threshold for alleged sentience at some level. Arbitrary application of criteria will be required to maintain relevance and meaning of welfare concept. These outcomes bring the validity of the criteria themselves into serious question. If criteria are accepted, further arbitrary decision making will be required to exempt certain activities to preserve the human population's food supply. |
| 7. Dilution/devaluation of the welfare concept | Welfare protection being extended from terrestrial vertebrates and fishes into crustaceans, insects and other invertebrates, even plants. | If all organisms are considered “sentient” based on alleged pain perception, this severely devaluates the feelings based welfare concept itself, because everything (and therefore nothing) is special all at the same time. Inability to classify “non-suffering” issues which threaten biodiversity (e.g., endocrine disruption) as a welfare concern. | A need for widespread noncompliance with welfare legislation to avoid “lose-lose” scenarios for animal and human welfare, and to ensure global food security. Workable animal welfare frameworks need to be able to align with ecological reality in the natural world. Need to reframe pragmatic animal welfare principles within an integrated “One Health” approach that encompasses welfare as a “win-win” linked with ecological sustainability and global food security. |
| 8. High risk of unintended consequences | Dangers of application of unvalidated welfare criteria to new animal groups under suffering-centered animal welfare legislation frameworks. | Ignoring proven functional welfare indicators in favor of “new” unvalidated feelings based operational welfare indicators. Threatening fines/prosecution of people housing live crabs because crabs had claws tied to body. Demanding bans on eyestalk ablation in broodstock penaeid shrimp. Banning electric pulse trawling due in part because of damage to some larger fish. | “Lose-lose” scenarios, including retrograde welfare outcomes for both animals and humans. Banning ablation conflicts with 3R's by requiring use of 10-20 times more broodstock shrimp to achieve same levels of larval production. Endangering larval supply of entire aquaculture industries would threaten regional/global food security. Prosecution of innocent people. Stifling of innovation which could reduce environmental impacts and improve sustainability. |
| 9. Dangers of the precautionary approach | Invoking the precautionary approach to act before validated operational welfare criteria have been established. | Misleading claims of equivalence between aquatic species and terrestrial bird and mammalian farm animals. Need for the suffering-centered welfare approach to consider individual sentient animals. Application of suffering-centered welfare frameworks to predator/prey situations results in inability to feed predatory aquatic taxa. | Potential bans on live feeding of larval aquatic animals would impact welfare of fed animals and could shut down entire aquaculture industries overnight, threatening regional/global food security. Unnecessary bans on farming new taxa (e.g., cephalopods) increase risk of overexploitation of wild populations. Stifling of innovation which could reduce environmental impacts and improve sustainability. |
| 10. The need for organized skepticism and critical thinking | Scientists must understand the limitations of the scientific method and must speak up when the scientific method is being misapplied or ignored. | Misapplication of the scientific method in the context of fish and invertebrate sentience, pain and welfare. Internet misinformation, “alternative facts” and AI written research which fabricates its own references. Blurring/inflation of the science boundary. | Pseudoscience, if left unchallenged, promotes Lysenkoism-like activity which harms society. High risk of “lose-lose” scenarios involving retrograde welfare outcomes and unintended consequences. Need for organized skepticism and critical thinking to ensure limitations of the scientific method are not exceeded and avoid a rapid downward spiral in scientific rigor. Robust science is needed to generate reliable empirical data for evidence-based decision making on important topics that affect food security and livelihoods. |

To be absolutely clear, the authors identify as supporters of animal welfare: this article is not about choosing between no welfare, and welfare for the animal groups involved. Including more animal taxa under welfare legislation is a societal choice that can be undertaken without firm scientific evidence using the precautionary approach. To do so while avoiding significant unforeseen consequences to food security and human welfare, however, requires reliable, scientifically proven operational welfare indicators that uphold the fundamental principles and standards required of the scientific method (Table 2). These ten reasons are presented not as an exhaustive review of the relevant literature, but as a guide to scientists and policy makers to raise awareness of the limitations of the available science about sentience and pain in aquatic animals (Sutherland et al. 2013), and to encourage application of higher scientific standards of evidence to any new operational welfare indicators for aquatic taxa which may be prescribed in welfare legislation. Each of the ten reasons is anchored in case studies or relevant literature and based on real-world examples.

The discussions presented here are underpinned by the philosophy that science advances by conjectures and refutations (Popper 1963). If it is hypothesized that fish, crabs or octopuses are sentient, then predictions must be derived from that hypothesis and tested by experimentation. Only when the various predictions have passed the appropriate tests can it be said that the null hypothesis has been disproven, although complete certainty may never be achieved. The nature of consciousness as experienced by humans is such that testing predictions in animals which are evolutionarily far removed from humans is particularly challenging (Hart 2023). As will be explored in what follows, there is still a long way to go before a satisfactory consensus can be reached regarding sentience of fishes and aquatic invertebrates.

Ten reasons to be skeptical

i. Changing definitions

As will become apparent, it is important to establish a common baseline for several definitions. The meaning of “pain” in English has been relatively consistent

Table 2. Summary of replicability, accuracy and reliability for a range of operational welfare indicators for aquatic organisms (excludes molecular, environmental and nutritional parameters).

| Taxa | Welfare indicator category | Welfare indicator type | Parameters measured | Replicable | Verified accurate | Reliability as operational welfare indicator |
|---------|----------------------------|---------------------------------------|-------------------------|------------|-------------------|--|
| Finfish | Disease status | External lesions/deformities | Injury/infection | ✓ | ✓ | High |
| | | Internal/microscopic lesions | Injury/infection | ✓ | ✓ | High |
| | | Parasitic infection | Infection | ± | ± | Low/Moderate (depends on parasite) |
| | | Diagnostic pathogen testing | Infection | ✓ | ✓ | Low-High (depends on pathogen) |
| | Performance | Toxicology testing | Contamination | ✓ | ✓ | Moderate |
| | | Condition factor | Nutritional status | ✓ | ✓ | High |
| | | Food conversion rate | Nutritional efficiency | ✓ | ✓ | High |
| | | Specific growth rate | Weight/size | ✓ | ✓ | High |
| | Physiology | Survival rate | Survival | ✓ | ✓ | High |
| | | Blood glucose | Activity | ✓ | ✓ | High |
| | | Blood lactate/pH | Activity | ✓ | ✓ | High |
| | | Cortisol (blood/excreted) | Stress | ✓ | ✓ | High |
| | | Haematocrit/ cell counts | Immune status | ✓ | ✓ | High |
| | | Heart rate | Many factors | ± | ± | Moderate |
| | | Immunoglobulins, antibodies, peptides | Immune status | ✓ | ✓ | High |
| | Behavior | Acoustic activity | Alertness | ± | ± | Moderate |
| | | Electric activity | Alertness | ± | ± | Moderate |
| | | Feeding | Appetite | ✓ | ✓ | High |
| | | General activity | Many factors | ± | ± | Moderate |
| | | Moribund/lethargic | Death | ✓ | ✓ | High |
| | | Opercular beat /gill ventilation rate | Many factors | ± | ± | Moderate |
| | | Pain | Unknown | x | x | ? |
| | | Reproduction | Fecundity/fertilisation | ✓ | ✓ | High |
| | | Righting/tail grab reflex | Alertness, exhaustion | ✓ | ✓ | High |
| | | Rubbing | Many factors | ± | ± | Low |
| | | Rocking | Unknown | x | x | ? |
| | | Swimming activity | Many factors | ± | ± | Moderate |
| | | Vestibulo-ocular reflex | Alertness, exhaustion | ✓ | ✓ | High |

(Continued)

Table 2. Continued.

| Taxa | Welfare indicator category | Welfare indicator type | Parameters measured | Replicable | Verified accurate | Reliability as operational welfare indicator |
|-------------|----------------------------|--|---|------------|-------------------|---|
| Crustaceans | Disease status | External lesions/deformities | Shell disease/injury | x | ± | Low/Moderate (may indicate predator activity) |
| | | Internal/microscopic lesions | Injury/infection | ± | ± | Low/Moderate (depends on pathogen) |
| | | Parasitic infection | Infection | ± | ± | Low/Moderate (depends on parasite) |
| | Performance | Diagnostic pathogen testing | Infection | ✓ | ± | Low to High (depends on pathogen) |
| | | Toxicology testing | Contamination | ✓ | ✓ | Moderate |
| | | Autotomy | Injury/Stress | ± | ± | Low/Moderate (context dependent) |
| | | Food conversion rate | Nutritional efficiency | ✓ | ± | Moderate (diet dependent) |
| | | Moulting | Growth | ✓ | ✓ | High |
| | | Specific growth rate | Weight/size | ± | ✓ | Moderate (variable in captivity) |
| | | Survival rate | Survival | ✓ | ✓ | High |
| | Physiology | Crustacean hyperglycemic hormone (CHH) | Hormonal status | ± | ± | Moderate (varies throughout molt cycle) |
| | | Differential hemocyte count | Infection, immune status | ± | ± | Low/Moderate (highly variable) |
| | | Haemolymph colour/clotting | Infection | ± | ± | Low/Moderate (context dependent) |
| | | Haemolymph glucose | Activity, molt status | ± | ± | Low/Moderate (context dependent) |
| | | Haemolymph lactate | Activity, molt status | ✓ | ± | Moderate (context dependent) |
| | | Haemolymph protein | Molt status | ✓ | ✓ | Moderate (varies throughout molt cycle) |
| | | Heart rate | Many factors | ± | ± | Moderate (context dependent) |
| | | Heat shock protein | Many factors | ± | ± | Low/Moderate (context dependent) |
| | Behavior | Autotomy | Many factors | ± | ± | Low (context dependent) |
| | | Feeding | Appetite | ± | ✓ | Low/Moderate (varies throughout molt cycle) |
| | | General activity | Many factors | ± | ± | Moderate |
| | | Grooming | Many factors | x | x | Low |
| | | Moribund/lethargic | Death | ✓ | ✓ | High |
| | | Pain | Unknown | x | x | ? |
| | | Reproduction | Fecundity/fertilisation | ✓ | ✓ | High |
| | | Righting reflex | Vitality | ✓ | ✓ | High |
| | | Tail flipping | Many factors | ± | ± | Low (context dependent) |
| | | Ventilation rate | Many factors | ± | ± | Low (context dependent) |
| Molluscs | Disease status | External lesions | Injury/infection | ± | ± | Low/Moderate (may indicate predator activity or senescence) |
| | | Internal/microscopic lesions | Infection | ± | ± | Low/Moderate (depends on pathogen) |
| | | Parasitic infection | Infection | ± | ± | Low/Moderate (depends on parasite) |
| | Performance | Diagnostic pathogen testing | Infection | ± | ± | Low to High (depends on pathogen) |
| | | Toxicology testing | Contamination | ✓ | ✓ | Moderate |
| | | Food conversion rate | Nutritional efficiency | ± | ± | Low/Moderate (diet dependent, difficult to ascertain in filter feeders) |
| | | Specific growth rate | Weight/size | ± | ± | Moderate (depends on species) |
| | Physiology | Survival rate | Survival | ✓ | ✓ | High |
| | | Differential hemocyte count | Infection, immune status | ± | ± | Low/Moderate (highly variable) |
| | | Heart rate | Many factors | ± | ± | Low (highly variable) |
| | | Haemocyanin | Activity, air exposure | ± | ? | Low (context dependent) |
| | | Haemolymph colour/osmolality | Infection, stress? | ± | ? | Low (context dependent) |
| | | Haemolymph glucose | Activity | ± | ? | Low (context dependent) |
| | | Haemolymph lactate | Activity ? | ± | ? | Low (context dependent) |
| | | Haemolymph pH | Activity, air exposure | ± | ± | Low (context dependent) |
| | | Lysozyme | Activity ? | ± | ? | Low (context dependent) |
| | Behavior | Autophagy/Automutilation | Damaging/eating oneself (in cephalopods) | ± | ? | Low (context dependent) |
| | | Colour | Colour change (not applicable to bivalves) | ± | ? | Low (context dependent and highly variable) |
| | | Grooming | Many factors | ± | ± | Low (context dependent) |
| | | Inking | Expulsion of ink (not applicable to bivalves) | ± | ± | Low (context dependent) |
| | | Pain | Unknown | x | x | ? |
| | | Reproduction | Fecundity/fertilisation | ✓ | ✓ | High |
| | | Ventilation rate | Many factors | ± | ± | Low (context dependent) |
| | | Righting reflex | Vitality (cephalopods, gastropods) | ✓ | ✓ | High |

✓ = yes, x=no, ± = variable or context specific, ? = unknown/unreliable.

throughout history, referring to physical suffering or discomfort caused by illness or injury. A formal definition of the word “pain” was established to describe the human emotional experience that is often, but not always, associated with trauma or injury (<https://www.iasp-pain.org/resources/terminology/>). The most recent definition endorsed by the International Association for the Study of Pain (IASP) in 2020 describes pain as “*An unpleasant sensory and emotional experience associated with, or resembling that associated with, actual or potential tissue damage*”. This wording was revised from the previous definition because it could have excluded those unable to verbally articulate their pain such as infants, elderly people, and non-human animals (Raja et al. 2020; IASP 2020). Pain is, therefore, the ability of an individual to experience an emotional response to tissue damage or trauma that is detected *via* a process called nociception. Here nociception is defined as the non-conscious processing of noxious stimuli by the peripheral and central nervous system (Tracey 2017).

Pain and nociception are different phenomena (Rose et al. 2014; Tracey 2017). Pain is but one (of many) potential responses to nociception, and merely observing an animal’s detection of and response to a stimulus cannot automatically be interpreted as pain. For this reason, the IASP specifically notes that “*Pain cannot be inferred solely from activity in sensory neurons*” (IASP 2020). Nevertheless, some researchers working in the field of fish and invertebrate pain and welfare have developed their own criteria for defining and assessing animal pain based on a range of neurological, behavioral and motivational criteria that they believe is consistent with “*the idea of pain*” (Sneddon et al. 2014; Walters 2018a; Elwood 2021; Sneddon and Roques 2023). These unconventional definitions “shift the goalposts” considerably, as many of the criteria (e.g., avoidance behavior) cannot discriminate between nociception and pain, with some behaviors (e.g., those arising from exposure to chemicals in water) not even requiring nociception. These inconsistencies undermine confidence that interpretation of animal behavioral reactions “consistent with pain” is analogous to how the word pain is defined, used, and understood by humans in accordance with the IASP definition. This has been particularly problematic in the fish and crustacean welfare literature in which any behavior in response to noxious stimuli is usually interpreted as “consistent with pain” (e.g., Elwood 2021; Sneddon and Roques 2023), with few, if any, of the several other alternative explanations being considered (see Rose et al. 2014; Key 2015; Diggles 2019; Browman et al. 2019 for detailed accounts).

The gold standard for pain is verbal reporting. For humans unable to communicate (such as infants, or patients with dementia), pain is assessed by examining motor responses and brain activity in response to noxious stimuli known to produce pain in healthy adult subjects. Similar comparative approaches are often adopted when attempting to infer pain in non-human animals. Use of the word “pain”, however, becomes progressively less defensible as taxa further and further away in evolutionary and morphological terms from humans are considered, because it becomes progressively less plausible that there is an equivalent psychological experience across those taxa. Philosophically speaking, humans struggle to “read the minds” of evolutionarily distant animals (Mameli and Bortolotti 2006), as it is very easy to overinterpret their reactions from a human perspective (Hart 2023). This is particularly so for invertebrates because the neuroanatomy and physiology of insects, crustaceans and molluscs are vastly different to those of mammals (Eisemann et al. 1984; Zullo and Hochner 2011; Walters 2018b; Key et al. 2021), but the same issues also apply to the > 33,000 species of fish which have evolved a vast array of highly specialized sensory systems (Nelson et al. 2016). The closest common ancestor between the invertebrates and early chordates is thought to have lived more than 550 million years ago (Walters 2018b), and while fish do possess a central brain for processing information, in the various aforementioned invertebrate groups many behaviors occur *via* peripheral processing in multiple neural centers without requiring involvement of a central brain (e.g., Ayali 2009; Derby and Thiel 2014; Smarandache-Wellmann 2016; Kuuspalu et al. 2022; Chang and Hale 2023). For these reasons, it is reasonable to ask how analogous (if at all) their experiences to noxious stimuli are to the human experience, and thus how relevant phylogenetically retrospective use of the word pain becomes in these groups (Derbyshire 2016; Walters 2018a, 2018b, 2022; Diggles 2019; Hart 2023). Furthermore, an evolutionary prerequisite for pain in these taxa is not necessarily required, as nociception (or other sensory pathways through which an organism can impart nocifensive reactions or learn avoidance responses to noxious or life-threatening stimuli), is sufficient to guarantee fitness and be selected upon. Importantly, since current legislation regulating the welfare of animals is based on pain (or related concepts such as suffering) and not nociception, caution must be applied when the word pain, or the phrase “consistent with pain”, is transposed with nociception without unequivocal justification (see Browman et al. 2019).

The discipline of ethology has developed an extensive set of terms intended to avoid anthropomorphism and observer bias when describing animal behavior (e.g., Bolgan et al. 2015). For example, when it is uncertain that a particular animal group is sentient or can feel pain and psychologically suffer, the term nociception is used (Mason and Lavery 2022). Using the word pain in association with behaviors for which nociception may not necessarily be required (such as avoidance behavior), in species where sentience is impossible to unequivocally prove, is therefore not scientifically appropriate. This is because transposing “pain” for nociception is a “red herring” (Mason and Lavery 2022), in that it presupposes sentience. It is particularly inappropriate to make such a transposition when interpreting experiments that are used to assess whether a particular animal group is sentient. For these reasons, all due skepticism should be applied to research on the welfare of fishes and invertebrates that uses terms that unnecessarily stray from ethological neutrality and replaces them with loaded words or terms used in human psychology. All of this is an extravagant form of anthropomorphism (Rose et al. 2014) that invites false equivalence between the experiences (if any) of those animals and that of human pain (Derbyshire 2016; Hart 2023).

Sentience is the “what it is like” experience of sensory stimuli (e.g., feeling pain and pleasure) (Nagel 1974). Fish and aquatic invertebrates such as molluscs, decapod crustaceans, as well as their arthropod relatives the insects, have a variety of sensory organs that allow them to respond to various stimuli (food odors, predator cues, pheromones etc.) in their environment and to learn from them to maintain fitness (survival and reproduction) under natural selection. Nevertheless, their responses to potentially life threatening stimuli do not necessarily demonstrate awareness or prove pain, consciousness or sentience. For example, the reaction of certain fish species to olfactory detection of chemical alarm cues is usually manifested as flight and hiding behavior, accompanied by physiological stress (Rehnberg and Schreck 1987; Rehnberg et al. 1987; Wisenden 2015). Despite all these behaviors, there is no reason to believe that fish reacting to chemical alarm cues experience pain or suffering. Even so, some political scientists and philosophers have recently introduced “eight sentience criteria” to assess the presence of pain and sentience based on “confidence levels” which supposedly consider both the amount of evidence for a claim, and the reliability and quality of the scientific work behind the evidence (e.g., Birch et al. 2021; Crump et al. 2022, 2023). There are many problems with this approach, including difficulties

associated with deciding whether, for example, a rubbing behavior (e.g., Sneddon 2003; Dickerson 2006) is self-protective when that behavior might be reflexive, like the stridulation by spiny lobsters after harmless capture (Bouwma and Herrnkind 2009). Loose interpretation of behaviors, combined with the high number of criteria used, essentially means that there is a very high chance that no organism will fail to meet their threshold for “some evidence of sentience” simply through their ability to sense the surrounding environment (Walters 2022). This type of sentience framework is tautological and, as such, violates the scientific method, because it cannot be refuted. These examples demonstrate that in the socio-political world of decision making about which animal groups should be protected under animal welfare regulations, “*The devil is in the definitions*”.

ii. Ignoring or dismissing conflicting or contradictory evidence

One characteristic of the literature claiming to support the existence of sentience and pain in fishes and invertebrates has been a certain tendency to ignore studies that either do not support this conclusion, or which fail to replicate certain experimental outcomes (Hart 2023). For example, Birch et al. (2021) concluded that cephalopods and decapod crustaceans are sentient, feel pain, and suffer. Yet in the case of crustaceans those authors did not mention the evidence-based reviews of Browman et al. (2019) and Diggles (2019) that concluded the opposing view, and, more importantly, ignored the many scientific problems and unresolved issues identified therein that greatly weaken the evidence used to support their conclusions. Rather, two newly published reviews that concluded crustaceans are sentient and feel pain (Conte et al. 2021; Passantino et al. 2021) were quickly embraced by activist NGOs during the “Crustacean Compassion” campaign and were cited by Birch et al. (2021), despite the fact that they also selectively ignored studies that do not support their conclusions, and overinterpreted and misrepresented other literature (including using strawman arguments). Purportedly authoritative and comprehensive reviews that “cherry-pick” literature to support their narrative fall well short of the scientific rigor that is needed to underpin policy decisions that have widespread implications. It is equally important to consider where such papers were published, because some journals have different editorial criteria, processes, and publication standards (Beall 2017; Grudniewicz et al. 2019; Crosetto 2021; Oviedo-Garcia 2021).

Similarly, a recent review paper on anesthesia in decapod crustaceans (Valente 2022) also excluded or misrepresented some of the literature, and used biased and emotive language, including an abstract which began with the statement “*Decapod crustaceans are sentient beings, not only responding to noxious stimuli but also being capable of feeling pain, discomfort, and distress*”. To avoid a downward spiral in scientific objectivity, rigorous and transparent systematic meta-analyses should be employed using structured methods that are routine in biomedicine and the biological sciences (Mulrow 1994; Dobrow et al. 2004; Aromataris and Pearson 2014; Clements et al. 2022). These methods have not yet been widely applied in the fish and invertebrate welfare literature (see Dawkins 2006; Cooke 2016).

Similar problems of excluding contradictory evidence also occur in the fish welfare literature. The widespread anecdote that hooking fish during angling is painful and hook removal requires analgesics stems from a relatively small body of scientific work (Sneddon 2003; Sneddon et al. 2003; Mettam et al. 2011). This anecdote is contradicted, however, by the studies of Eckroth et al. (2014), Pullen et al. (2017) and Hlina et al. (2021) which found no significant differences between control and treatment groups of Atlantic cod (*Gadus morhua*), northern pike (*Esox lucius*) or bluegill sunfish (*Lepomis macrochirus*) (respectively) exposed to fishing hooks and/or chemicals injected into the mouth. Hlina et al. (2021) found that bluegill that were hooked and then unhooked under controlled laboratory conditions did not significantly differ in their behavior compared with control fish that were not hooked at all. Only those bluegill that were hooked and retained the hook differed in behavior from controls, exhibiting increased use of a shelter. Similarly, hooked Atlantic cod exhibited head shaking but otherwise no other measurable response (Eckroth et al. 2014), which was mirrored by the result of Pullen et al. (2017) who found that northern pike with retained lures did not show behavioral or physiological reactions that differed from controls. The studies of Eckroth et al. (2014), Pullen et al. (2017) and Hlina et al. (2021) all indicate that these fish are resilient and do not significantly alter their behavior in response to acute tissue damage associated with hooking injury to the mouth. This is a consistent result found by disparate research groups that is largely ignored in the suffering-centered fish welfare literature (e.g. Sneddon and Roques 2023 which does not cite Eckroth et al. (2014), despite the two papers sharing at least one co-author).

Perhaps these contradictory studies are being ignored in certain literature because they indicate the behavioral criteria being advocated for defining “pain” behavior in fishes (as well as crustaceans and other invertebrates) are context specific, and, therefore, likely to be inconsistent and unreliable, especially under real world conditions outside of the laboratory. For example, some individual carp (*Cyprinus carpio*), which experience stress from catching by hook and line can remember this event for some time. This occurs through a process of insight learning, however this ability varies with different strains of carp as well as other factors (Beukema 1970a), while the memory of the experience itself is only transitory (Czapla et al. 2023). Northern pike also have the ability to learn hook avoidance, but only if they are caught on an artificial lure; such a memory is not formed if they are caught using live bait (Beukema 1970b). Moreover, the same protective insight learning occurs in many other fish species after a single exposure to a combination of a previously indifferent stimulus with a chemical alarm cue, an odor signal that cannot cause pain (Wisenden 2015). In yet other fish species (including some salmonids), recognition of predator chemical cues is innate and this instinctive response requires no learning process, while other species (including fathead minnows *Pimephales promelas*) show varying degrees of innate bias (Wisenden 2015).

The relative indifference to trauma to the mouth of fishes during angling (at least compared to a normal human exposed to a similar situation) has been recognized for centuries (Cholmondeley-Pennell 1870) and appears remarkable at first glance, but may be explained by neurological evidence. Studies have shown that the trigeminal nerves of teleost fishes have a very low (4–5%) percentage of unmyelinated “C type” or “C fibre” nociceptors (Sneddon 2002) which are responsible for transmitting nociceptive information that may result in sustained and diffuse burning or dull pain in humans (Rose et al. 2014). Furthermore, in elasmobranchs it appears that C type fibers may be absent altogether (Snow et al. 1993; Smith and Lewin 2009), even though sharks show similar behaviors to teleost fish (e.g., fleeing reaction) when hooked by anglers. The latter is also a widely recognized observation known for centuries, which again calls into question referring to pain states from behavior alone.

In contrast to fishes, around 80% of the cutaneous nerve fiber population in normal mammalian nerves are C type fibers. In some types of congenital insensitivity to pain in humans, however, C type fibers are reduced to around 20% of the axon population, with

the remainder being the A-delta type (Roseberg et al. 1994; Guo et al. 2004). Rose et al. (2014) discussed the functional significance of this extremely small percentage of C fibers in teleosts, which is around five times less than in humans with complete insensitivity to pain and up to 20 times less than a normal human. They concluded that “*It appears most logical to assume that in teleosts, at least those species that have been studied, A-delta afferents serve to signal potentially injurious events rapidly, thereby triggering escape and avoidance responses, but that the paucity of C fibers that mediate slow, agonizing, second pain and pathological pain states (in organisms capable of consciousness) is not a functional domain of nociception in fishes*” (Rose et al. 2014). The conclusions of Rose et al. (2014) remain valid, and provide context to the available evidence from Eckroth et al. (2014), Pullen et al. (2017) and Hlina et al. (2021) as well as that of the saline injected fishes from Sneddon (2003), Sneddon et al. (2003) and Mettam et al. (2011), all of which also exhibited no “pain behaviors”.

Rose et al. (2014) noted that “*Embedding a fish hook is comparable with the mechanical tissue damage caused by embedding a needle of similar size, but without the saline injection*”. The above cited studies which demonstrate a minimal and often even no impact of fish hooks on fishes represent a consistent body of evidence that debunks the theory of fish pain from hooking. This evidence also calls into question any definition which accepts pain as “an animal’s response to stimuli that would be painful for a human” (e.g., see Fiorito et al. 2015). The latter is clearly a “double standard”, especially considering that invertebrate taxa like crustaceans and cephalopods naturally undertake behaviors that are completely alien to humans, such as autotomy (shedding of limbs), autophagy (eating ones’ own body parts), auto-mutilation during essential processes such as reproduction (e.g., Budelmann 1998), as well as regrowth of lost limbs (Murayama et al. 1994; Mariappan et al. 2000).

To summarize, quality evidence-based decision-making weighs all scientific evidence for a particular hypothesis in a rigorous, critical, balanced, transparent, and systematic manner. It does not overinterpret context-specific findings (Rose et al. 2014; Hart 2023), exclude valid studies that report contradictory outcomes (Eckroth et al. 2014; Pullen et al. 2017; Hlina et al. 2021), or fail to consider alternative well-established neurological or behavioral mechanisms which are often not controlled for, yet could also explain the results obtained (Diggles et al. 2017; Walters 2018a; Diggles 2019; Kuuspalu et al. 2022; Chang and Hale 2023). Nor does it recognize as valid

studies that have fundamental experimental design flaws such that their conclusions are not warranted (Cooke 2016; Smaldino and McElreath 2016; Key et al. 2017).

iii. Lack of replicable empirical evidence

High quality scientific research produces results that are replicable and independently verifiable by multiple research groups. The “replication crisis” (Ioannidis 2005; Camerer et al. 2018; Clark et al. 2020; Yang et al. 2020, 2023) is also relevant to the fish and invertebrate welfare literature (Rose et al. 2014; Browman et al. 2019; Diggles 2019; Walters 2022; Hart 2023).

In the crustacean welfare literature, a typical example of replication failure was demonstrated by Puri and Faulkes (2010). These researchers failed to replicate an earlier study by Barr et al. (2008) who described grooming and rubbing of prawn antennae exposed to acids (vinegar), bases and an anesthetic as “*consistent with the idea of pain*”. Indeed, Puri and Faulkes (2010) failed to find any evidence that crayfish or shrimp antennae even had nociceptors that detect acids or bases, suggesting that Barr et al. (2008) had mischaracterized normal grooming (Bauer 1981; Puri and Faulkes 2010), or even other behaviors normally initiated by chemosensors (such as olfaction or gustation, see Johnson and Ache 1978; Derby and Weissburg 2014; Diggles 2019) as evidence of nociception and “pain”. It is notable that this lack of verification did not dissuade Birch et al. (2021) from retaining grooming as a welfare criterion for crustaceans, or even acknowledging the ambiguity of the interpretation of Barr et al. (2008). Similar experimental methods and behavioral “pain criteria” have also been applied to cephalopods (e.g., Crook 2021), however the relatively nascent state of research on cephalopod nociception means that the conclusions of Crook et al. await confirmation by other research groups. This is particularly important because all of the same issues and problems with interpretation and replication discussed above for crustaceans (and below for fishes) also apply to cephalopods, especially considering that it is well known that individual cephalopods can react to the same stimulus with quite different responses (Borrelli et al. 2020).

In the case of fishes, Newby and Stevens (2008, 2009) failed to replicate several key results of early fish “pain” research conducted by Sneddon (2003) and Sneddon et al. (2003), something that continues to be ignored by some (e.g., Elwood 2021; Sneddon and Roques 2023). More recently, Rey et al. (2015)

claimed that they found evidence for “emotional fever” (stress induced hyperthermia, SIH) in zebrafish (*Danio rerio*) and stated that “... *this finding removes a key argument for lack of consciousness in fishes*”. Although these extraordinary claims received considerable media coverage at the time, many technical and interpretational problems meant that the study failed to provide the evidence required to support such claims (Key et al. 2017). The concerns of Key et al. (2017) were later confirmed by Jones et al. (2019), who found no evidence of stress-induced hyperthermia in zebrafish. Importantly, a recent study that used the same tank array as Rey et al. (2015) also failed to replicate stress induced hyperthermia in zebrafish (Vera et al. 2023), while curiously not citing the critical work by Jones et al. (2019). It is notable that the scientific self-correction process that rectified the wildly overinterpreted claims of Rey et al. (2015) took nearly five years. It is relatively easy to make an unfounded claim, but usually far more difficult to scientifically refute it through further experimentation. This demonstrates the asymmetry of this process, especially in the spotlight of the modern media cycle where the initial headlines vastly overshadow the small font used for any eventual correction or retraction.

Rose et al. (2014), Browman et al. (2019) and Diggles (2019) provide many other examples from the fish and invertebrate welfare literature where subsequent studies failed to replicate earlier results obtained through use of unverified and unvalidated welfare indicators. Efforts to draw attention to these instances of overinterpretation are notable because the research community can usually predict which results are unlikely to be replicable (Camerer et al. 2018), because they can identify “*low-powered research coupled with bias selecting for significant results for publication*” (Camerer et al. 2018; see also Clark et al. 2020; Clements et al. 2022; Yang et al. 2023).

In summary, it is vitally important that any new operational welfare indicators used to underpin legislation which defines best practice guidelines for the welfare of fish and invertebrates are valid, robust, measurable, consistent under varying environmental conditions (particularly in the real world outside the laboratory) and independently replicable and verifiable (Table 2).

iv. Ad hominem attacks on skeptics

Ad hominem attacks, while common, are a fallacious form of argumentation that should not be part of science. When the evidence for fish and invertebrate

pain was found wanting (see Reasons 2 and 3 for selected examples), some of the researchers who conclude that fish are sentient and feel pain attempted to direct attention away from the evidence that contradicted their assertions by discrediting skeptical scientists and labeling them “deniers” (see Diggles and Browman 2018), “creationists” (Sneddon 2013) or even “racists” (Vettese et al. 2020). Demeaning and factually incorrect attacks in pseudo-journals, online, or in the popular media are cleverly potent, because they are often repeated unquestioningly by those unfamiliar with the underlying science, particularly in social media forums, special interest groups and the press. Unfortunately, such activities also lead to completely unacceptable outcomes, including attempts at public shaming by activist groups, and even anonymous threats of violence and intimidation which create a climate of fear amongst skeptics, who understandably wish to avoid such constant attacks. Most concerning, however, is a recent example in an undergraduate textbook (Orth 2023) where several demonstrably false statements were attributed to “skeptics”, including that fish were “*incapable of complex cognitive abilities*”, and that skeptics “*oppose the need for regulations governing the welfare of fish*”. These fallacies are strawman arguments that distort an opposing position into an extreme or weakened version of itself, so that proponents can argue against the newly manufactured position.

Another example is a critique of evidence for fish pain (Key 2016a) in *Animal Sentience*, a publication established in 2015 by the Humane Society of the United States. Responses to Key’s invited critique from the readership of that publication included many attacks on the author, rather than his arguments. What is often misunderstood during these asymmetrical, *ad hominem* attacks and the subsequent unfounded claims of “scientific consensus” about fish pain, is that reproducible science eventually triumphs. Science does not advance simply by counting the number of attackers (also colloquially known as a “pile on” or the “bandwagon effect”, see Key 2016b) in order to claim “consensus” in an unrepresentative and unreviewed forum (Brown 2016). Instead, scientific advancement depends on the merits of solid, replicable evidence (Abbot et al. 2023).

Attempts to silence scientific debate over the need for reliable empirical evidence for decision making is a form of “cancel culture” which has increasingly pervaded public debate in recent years. An underlying cancel culture theme can be detected in the article by Crump et al. (2022) where they advocate for bans on cephalopod aquaculture and the sale of live decapod crustaceans to

private individuals, as a “*low-cost intervention to improve welfare*”. Logically, such a position would also result in legal problems for fishers possessing live cephalopods or crustaceans they have caught, and could initiate bans on sale of live crustaceans and cephalopods in the ornamental (pet) aquarium industry and in public aquaria. It is unfortunate to see calls for such bans being repeated in the literature (e.g., see Wuertz et al. 2023). If similar standards were applied to the handling of ornamental fishes, birds or mammals, it would eliminate these companion animal industries overnight, resulting in increased numbers of euthanized, stray or uncared-for animals, while depriving humans of the many health benefits arising from their pets (Beck and Meyers 1996; Brooks et al. 2018) in what could only be described as a “lose-lose” scenario for animals and humans alike. It is important to remember that often the most ardent supporters for welfare of animals are the users of those animals, which for aquatic animals includes recreational anglers (Shephard et al. 2023).

Indeed, banning certain animal uses as advocated by Crump et al. (2022) is a hallmark of the animal rights movement, which is intrinsically opposed to all animal use (Arlinghaus et al. 2009; Arlinghaus and Schwab 2011). Interrogating the ethics of how animals are treated by humans is a philosophical endeavor. In contrast, animal welfare is based on objective scientific evidence which enables principles to be derived that allow animal use for human benefit, whilst recognizing the need for ethical treatment of those animals. This is achieved by providing people and industries with the tools and guidelines to maximize animal welfare (Arlinghaus and Schwab 2011; Stoner 2012; Fiorito et al. 2014, 2015; Diggles 2016). True animal welfare thus provides the potential to develop “win-win” scenarios that benefit both humans and animals, unlike the high potential for generating “lose-lose” scenarios inherent in the application of animal rights ideology. Therefore, to avoid far-reaching “lose-lose” consequences of adopting an animal rights approach to cephalopod aquaculture and the handling of live crustaceans, a more balanced science-based welfare-oriented approach provides advice to industry and consumers on best practice for rearing, handling and dispatch methods for these taxa (as has already been done for fishes, e.g., Cooke et al. 2013; Cook et al. 2015; Diggles 2016). The latter approach certainly has a lower cost to the economy and livelihoods, while supporting the human right to avoid hunger (Golden et al. 2021; FAO 2022; <https://www.un.org/sustainabledevelopment/hunger/>), all without adding unnecessary burden to handling or processing of fresh seafood.

v. Testing of unfalsifiable hypotheses

As was emphasized at the start of this article, an important cornerstone of the self-corrective aspect of the scientific method is hypothesis falsifiability (Popper 1963). This is an important point, because most of the research conducted on fish and invertebrate sentience, pain and suffering tests hypotheses that are unfalsifiable (Browman and Skiftesvik 2011). For example, Sneddon and Roques (2023) state that “*Responses to “painful treatment” will differ between species and between individuals*”. Sneddon and Roques (2023) also state:

General indicators, such as the overall physical condition of the fish, the presence of lesions, demeanor, and body or fin posture, make a contribution to the assessment of pain, but they alone do not determine whether the animal is in pain. Pain is inherently stressful and, as such, physiologic indicators of stress can assist in understanding the extent to which pain affects welfare and homeostasis. More importantly, changes in biological function traits can be used more effectively to determine if an animal is pain-free; if the animals exhibit normal behavior and demeanor, no significant stress responses, are healthy and disease-free, reproduce normally, and grow normally, then there is likely no pain.

These statements suggest that, by these definitions, virtually any behavioral changes in fish could be interpreted as indicating “pain”, whether from a specific noxious stimulus or otherwise. This position ignores important differences between nociception, stress, and pain (Stevens et al. 2016, also see Reason 1) and makes the question of pain in fishes a non-falsifiable hypothesis. In other words, Sneddon and Roques (2023) argue that any deviation from what an observer believes is “normal” behavior for that particular individual fish is a result of pain. This approach basically assumes that all “normal” behaviors in each fish species are known and quantifiable, that there are known ranges of “normal” and “painful” behavior for individual fish, and that there are no explanations other than pain for any behavioral deviations from “normal”.

The same problems also occur in the crustacean literature where, for example, some behaviors deemed “*consistent with the idea of pain*” (Barr et al. 2008; Elwood 2021) are most likely an overinterpretation or misrepresentation of normal grooming or chemosensory behaviors (Puri and Faulkes 2010; Diggles 2019). Experiments on cephalopods have also revealed a tendency for individual animals to react to the same stimulus with quite different responses, such that standardization of testing protocols is urgently required (Borrelli et al. 2020) if there is to be any chance of

consistent application of the scientific method toward validating welfare criteria for these animals.

This is not a trivial issue. If unfalsifiable hypotheses based on unvalidated criteria are used as the basis for drafting welfare legislation encompassing fishes, crustaceans and other invertebrates, any activities that an observer believes deviates from their qualitative idea of “normal” behavior could be interpreted as “painful”, and hence could meet legislative criteria for infringement and prosecution. Similarly, if unfalsifiable criteria are used to judge whether organisms are sentient or feeling pain, it is difficult to see how any organism would fail to meet criteria requiring their protection under welfare legislation, unless the criteria were arbitrarily applied.

vi. Arbitrary application of criteria

The criteria advocated by Birch et al. (2021) to ascribe sentience to animals are being applied arbitrarily. For example, Birch et al. (2021) argue, based on their criteria, that all cephalopods and decapod crustaceans should now be considered “sentient beings”, yet within the Mollusca they do not extend their analyses to other groups such as bivalves (e.g., scallops, oysters) and gastropods (e.g., abalone, snails). These taxa also react in response to visual, chemical, noxious and environmental cues (e.g., Barnhart et al. 2008; Wesołowska and Wesołowski 2014; Siemann et al. 2015; Hochner and Glanzman 2016; Walters 2018b, 2022) including alleged “avoidance learning” (Selbach et al. 2022), and share similar neuroanatomical networks to the Cephalopoda. Moreover, within the Crustacea, members of the Copepoda have similar physiology and neurological networks to the Decapoda and also react in response to visual, chemical, noxious and environmental cues. Based on the criteria of Birch et al. (2021), copepods, bivalves, and gastropods would appear to satisfy at least three or four of their eight criteria with reasonably high certainty, leading to a potentially erroneous conclusion of “some evidence” or “substantial evidence” of sentience in these groups (Walters 2022).

Perhaps these criteria are being applied arbitrarily because taking their consistent application to its logical conclusion would be extremely problematic. For example, sea lice (*Lepeophtheirus* spp., *Caligus* spp.) are ectoparasitic copepods that cost the global salmon farming industry hundreds of millions of dollars annually to control (Abolofia 2017; Stene et al. 2022). This cost is incurred in large part to satisfy animal welfare concerns over the impact of lice infestation on the welfare of wild and cultured salmon (Macaulay

et al. 2022), but without any regard for the impact of the treatments on the welfare of the sea lice (Moccia et al. 2020). Similarly, extending the same sentience analysis to bivalve molluscs could result in bans on the consumption of fresh, live oysters.

The problems with the criteria of Birch et al. (2021) do not stop there. Single cell protozoans exhibit nociception yet they have no cell-based nervous system; changes in behavior during predator avoidance are triggered by changes in bioelectrical activity within cell membranes (Naitoh 1974; Valentine and Van Houten 2022) or by response to chemical gradients (King and Insall 2009). Even bacteria exhibit not only quorum sensing but also learning behavior “*similar to Pavlovian conditioning*” (Hopkin 2008), while slime molds are alleged to exhibit learning and problem-solving behaviors (Bonner 2010; Boussard et al. 2019). Indeed, such behavior is not restricted to microorganisms from the animal kingdom, given that plants make sounds when stressed by dehydration (Khait et al. 2023; Marris 2023).

Essentially, all of this means that if the criteria used by Birch et al. (2021) were universally applied, there is a high chance that few, if any, organisms would fail to meet their threshold for “some evidence of sentience” (Walters 2022). Such an outcome brings the utility and validity of the criteria themselves into serious question; if all organisms are considered “sentient”, this severely devalues the feelings-based welfare concept itself into irrelevance, because everything (and therefore nothing) is special all at the same time (Birch 2017). Thus, at some stage there would still be a need for further arbitrary decision making regarding which groups deserve welfare protection, and where or when exemptions must be applied to preserve the human population’s health and food supply systems (e.g., in wild capture fisheries, use of insecticides to protect crops or control mosquitoes to combat malaria or other vector-borne diseases). Sentience is a “hard problem” (Gray 2004; Humphrey 2022; Mason and Lavery 2022), and these severe shortcomings of the sentience criteria used by Birch et al. (2021) highlight why their utility is questionable, as is more broadly, application of the feelings-based suffering-centered approach to the welfare of fish and aquatic invertebrates. Instead of arbitrary application of intangible, context-dependent concepts that may selectively serve certain ethical positions (no use of animals at all) at the cost of others (sustainable use of animals), pragmatic functional or nature-based operational welfare indicators with quantifiable endpoints that are scientifically validated, reliable and straight-forward to interpret should be used

(Arlinghaus et al. 2009; Diggles et al. 2011; Barragán-Méndez et al. 2019; Browman et al. 2019; Table 2).

vii. Dilution/devaluation of the welfare concept

A broad definition of sentience is being extended from terrestrial vertebrates into not only fish, crustaceans, molluscs, and other invertebrates including insects (Crump et al. 2022, 2023; Gibbons et al. 2022), but also plants (Calvo et al. 2017; Chamovitz 2018; Baluška and Mancuso 2021) and cell cultures (Niikawa et al. 2022). Most of this discussion is philosophical in nature, since measuring “pleasure” and “pain” in these groups in any scientifically valid context remains challenging and riddled with inconsistencies, technical problems (e.g., Bennett et al. 2009; Borrelli et al. 2020) and subjective anthropomorphic assumptions (e.g., for fishes see Rose et al. 2014; Mason and Lavery 2022; Hart 2023; and for plants see Brown and Key 2021).

The major problems with assuming all animals (and increasingly plants) are sentient until proven otherwise were identified by Birch (2017) as being “*unscientific or anti-scientific*”, and that such a position would make “*the science of animal sentience more or less irrelevant to the scope of animal protection law: all animals would be assumed sentient unless proven otherwise, and it is hard to see how research could prove otherwise*” (Birch 2017). This proposition by Birch would require proving a negative, almost an impossibility, but properly done research could determine if a species failed to meet sound, testable criteria for sentience if they were to become available.

The argument that bees are sentient is illustrative of some of the problems of adopting this approach. If the potentially unfalsifiable hypothesis that bees are sentient is accepted (Gibbons et al. 2022; Crump et al. 2023), ignoring the fact that their behaviors can be replicated by robots (Adamo 2019), it follows that all insects are potentially sentient and should therefore be theoretically protected under welfare regulation. This situation would lead to widespread noncompliance with welfare legislation when farmers need to protect their crops from predatory insects. A likely (and presumably unintended) consequence of such an event would be severe constraints on crop production imposed by bans on insecticides to protect insects and regulation of tilling the soil because of all of the sentient animals displaced and killed in doing so. Issues would also arise when trying to protect bees. For example, parasitic mites (arachnid arthropods) have been implicated in the worldwide collapse of bee

colonies. Can mites be killed using allegedly “painful” procedures if it helps save bees? What if mites turn out to be more sentient than bees? (Reber 2017).

Given that arthropod parasites (including crustaceans) and other microorganisms are common disease agents (or vectors for diseases) of animals and humans, it appears extremely implausible that any laws would ever be passed to protect their welfare. What would be the impact on animal welfare of treatments for arthropod parasites such as bedbugs, mosquitoes, headlice, fleas, skin mites and ticks? If sentience, and therefore, welfare protection were extended to helminth parasites such as nematodes and cestodes, the deliberate poisoning of intestinal worms would raise ethical issues that would need to be ignored by those afflicted. As would the more mundane problems of killing tens of thousands of allegedly sentient beings when mowing the lawn or driving your car along a country road.

Less obvious threats to biodiversity would also arise. For example, the culture of the critically endangered freshwater mussel would raise animal ethics issues because the larval stage of this bivalve mollusc is an obligate parasite on the gills of freshwater fish (Barnhart et al. 2008). Is it still ethical to save the mollusc by deliberately exposing or directly infecting fish? The latter strategy has been widely accepted since the beginning of the twentieth century in an attempt to prevent loss of biodiversity (Buddensiek 1995).

If the intent of sentience proponents is to protect more animal taxa under welfare legislation, there is no need to dilute welfare concepts, and generate “lose-lose” situations for animals and humans while denigrating the scientific method in the process. As already pointed out, these taxa can be included in welfare frameworks under pragmatic functional or nature-based welfare definitions (Arlinghaus et al. 2009; Diggles et al. 2011) which can make welfare a “win-win” scenario for both animals and humans alike. Otherwise, how can welfare for fishes or invertebrates be considered in instances such as endocrine disruption, for example, where it has been demonstrated that entire populations of fishes can collapse (Kidd et al. 2007) when exposed to estrogenic chemical pollutants? Individual animals affected by endocrine disruption do not necessarily “suffer” in a conventional sense (Diggles et al. 2011), so a suffering centered approach to welfare will not suffice.

Poor water quality and damaged habitat can lead to complete loss of fish or invertebrate populations. No fish or invertebrates means no fish or invertebrate welfare. Solving this equation for fish and

invertebrates, however, yields the following: water quality and habitat = fish and invertebrate welfare, thus providing a potential “win-win” for both humans and animals. As demonstrated by the biodiversity crisis and endocrine disruption problems, in practice, workable animal welfare frameworks need to be able to align with ecological reality in the natural world. To achieve this in the Anthropocene, animal welfare needs to be reframed as ecological welfare with an integrated approach to general ethical principles that also encompass ecological, environmental and societal issues (Fox 2006) such as biodiversity protection, human and animal health and food security (Golden et al. 2021; FAO 2022; Macaulay et al. 2022; Troell et al. 2023; Allen et al. 2023). If food webs collapse, so will human society, at which point nothing is served by demanding a welfare status for an individual animal, be it a fish, crab, snail, cephalopod or insect. The “One Health” approach to sustainable food system design advocated by the World Health Organization appears to be an appropriate starting point signaling the way forward in this regard (Stentiford et al. 2020).

viii. High risk of unintended consequences

There are always risks of unintended consequences when governments regulate, and welfare legislation is no exception. A notable example followed the inclusion of decapod crustaceans in welfare regulations in Victoria, Australia in June 2019 (Supplement 1). In this case, Royal Society for Prevention of Cruelty to Animals (RSPCA) field officers threatened fines and prosecution of a restaurateur who was housing live mud crabs (*Scylla serrata*) in a display aquarium, because the crabs had their claws tied to their bodies. This was considered a breach of the *Prevention of Cruelty to Animals Act 1986* as the RSPCA inspector considered that the crabs “needed to be allowed to move their arms freely.” The tying method used had been implemented by the live mud crab industry for many decades based not only on occupational health and safety concerns (to prevent people from getting their fingers and hands crushed by crabs), but also the fact that free claws greatly increase claw autotomy rates and allows the mud crabs to injure, kill and eat other mud crabs held in the same display tanks due to their naturally cannibalistic nature.

This case study highlights how unvalidated, anthropomorphic, feelings-based welfare criteria applied to new animal groups under suffering-centered animal welfare legislation frameworks can result in retrograde “lose-lose” welfare outcomes for the animals involved,

as well as injury and prosecution of innocent people. Crump et al. (2022) appeal for “more research into appropriate stocking densities, environmental conditions, and methods to prevent aggression and injury” in captive decapod crustaceans. This is laudable, however they overlook the fact that decades of practical experience in “quality management” have already developed that information as well as many other reliable physiological, pathological, nutritional, and health related welfare indicators for holding live decapod crustaceans (e.g., Paterson and Spanoghe 1997; Davidson and Hosking 2004; Shields et al. 2006). This large body of existing evidence underpins animal health, survival and profitability in many fisheries and aquaculture industries; hence it should not be ignored in a rush for “new” feelings-based welfare criteria for decapod crustaceans.

Eyestalk ablation to boost larval production from penaeid shrimp broodstock has also emerged as a welfare issue in recent years. Diarte-Plata et al. (2012) suggested that ablation was “painful” based on tail flicking and leg or antennal rubbing as welfare indicators. Neither tail flicking nor rubbing are validated or reliable pain indicators in crustaceans, however, as shown by Puri and Faulkes (2010) in the case of rubbing and Weineck et al. (2018) who demonstrated that tail flicking is a reflex that also occurs in transected shrimp abdomens separated from the head. Nevertheless, eyestalk ablation affects several other easily quantifiable functional welfare metrics such as broodstock survival and larval quality; hence alternatives to ablation are used by the shrimp aquaculture industry when they are available (Magaña-Gallegos et al. 2018).

Recent studies of the shrimp *Penaeus vannamei* have found alternatives to eyestalk ablation that can result in equal or better quality and quantity of larvae for that species (Zacarias et al. 2019, 2021). This result is not universal, however, and to date no alternatives to ablation have been found for other important cultured shrimp species such as *Penaeus monodon* (see Uddin and Rahman 2015). Demands by certain interest groups to ban eyestalk ablation in all shrimp farming would result in the use of ten to twenty times more *P. monodon* broodstock to meet industry needs for post larvae. This would immediately have the unintended consequence of requiring many more *P. monodon* broodstock, another “lose-lose” situation as it conflicts with one of the basic 3Rs welfare principles of reduction of numbers of animals used. Such a move would also increase fishing pressure on wild stocks, while the lack of reliable larval supply would threaten entire aquaculture industries in countries where *P.*

vannamei is not available, threatening livelihoods and regional and/or global food security.

Similar issues have arisen in the regulation of commercial fishing in the European Union (EU). For example, attempts to increase gear selectivity and reduce the environmental impact of beam trawling for flatfishes in the Netherlands resulted in development of electric pulse trawling (Kraan et al. 2020; Penca 2022). Instead of using tickler chains which damage sensitive benthic habitats, the electric pulse trawl method uses a suspended hydrofoil generating pulsed electric fields (up to 60 volts, 30–45 Hz) within the net area to generate galvanotaxis of benthic fishes and increase the potential for their capture in the trawl net without interacting directly with the sediment (Kraan et al. 2020). Intensive scientific scrutiny found electric pulse trawling was more selective for flatfish and brown shrimp (Verschuere et al. 2019; Poos et al. 2020), reduced bycatch and benthic disturbance, and also reduced fishing time and fuel consumption/CO₂ emissions, resulting in higher sustainability scores compared to fishing with traditional beam trawls (Kraan et al. 2020; Penca 2022). Paradoxically, despite this, animal welfare concerns were amongst the reasons provided when electric pulse trawling was banned by the EU in 2019 (Court of Justice of the European Union 2021; Penca 2022).

The precautionary approach (see Reason 9 below) as well as political and socio-economic considerations relating to encroachment of the pulse trawl fleet into areas historically fished by low impact netting methods, were some of the main drivers of the decision (Penca 2022). Nevertheless, intense activity from activist NGOs also highlighted perceived welfare concerns for flatfish as well as larger Atlantic cod which may experience spinal damage during capture when exposed to the electric pulses (Kraan et al. 2020). Atlantic cod typically have a low survival rate if they are caught in trawls, so the issue of spinal damage was considered irrelevant from a fisheries sustainability perspective (Kraan et al. 2020), assuming of course that the fishery itself is appropriately managed. Nevertheless, the court decision was upheld upon appeal, supported by false and misleading claims by activist NGOs who “*compromised the basic principles of ethical conduct in scientific research*” (Kraan et al. 2020). Some aspects of this decision were considered likely to stifle technological innovation in the fisheries sector which would otherwise improve conservation, reduce overfishing, and improve fisheries sustainability (Kraan et al. 2020; Penca 2022).

Another “lose-lose” example is the banning of catch-and-release angling in some countries, such as

Germany and Switzerland. In both these countries, voluntary catch and release of legal-sized fish by anglers was considered by some members of the community to be unethical and cruel, as the caught fish could be eaten rather than released (Arlinghaus et al. 2012). After intensive lobbying by animal rights groups, mandatory catch-and-retain regulations were implemented, which result in more fish being killed by anglers (Arlinghaus et al. 2012). Increased fishing mortality can result in potential reductions of both recruitment and sustainability in fisheries which generate substantial socio-economic activity and provide a range of human health benefits (Arlinghaus et al. 2007). A mandatory catch-and-retain policy based on animal rights ideology therefore paradoxically results in reduction of not only the welfare of populations of fish (due to the removal of fish that would otherwise continue to live), but also a reduction in human welfare as well.

All of the above examples provide glimpses into the range of unintended consequences and potential “lose-lose” scenarios that could be expected if a suffering-centered approach, fueled by animal rights advocacy, is allowed to influence welfare legislation for fishes and aquatic invertebrates, and that legislation is subsequently enacted in the absence of a firm scientific basis.

ix. Dangers of the precautionary approach

Various definitions of the precautionary approach exist, using wording such as “*Where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent that damage*” (Principle 15 of the 1992 Rio Declaration). The decision to invoke the precautionary approach is generally associated with risk assessment of both the seriousness and magnitude of the supposed threat whilst considering any inherent uncertainties (Krebs 2011). As shown in Reasons 6–8, however, the precautionary approach is often invoked by activist NGOs in order to more aggressively weaponize their campaigns for change.

What needs to be understood by policy makers is when the precautionary approach is used to prioritize the welfare needs of individual (allegedly sentient) species which are ecologically lower in the food chain (such as smaller fishes and aquatic invertebrates which are natural prey items for larger predatory fishes or aquatic invertebrates), several predator/prey conundrums arise. In aquaculture, one issue is the use of live feeds. The use of crustacean

zooplankton (i.e., *Artemia*, copepods) as live feeds is an essential prerequisite for the health, welfare and survival of virtually all larval fish, decapod crustaceans and cephalopods. A pragmatic science and nature-based approach to fish and invertebrate welfare supports live feeding on the grounds that live feeds form the basis of natural food webs, and hence provide the best nutrition, health and welfare outcomes for larval fish and invertebrates. Provided that live feed cultures are biosecure, microbially clean and disease free, they are accepted as necessary and critical for replicating natural feeding processes that underpin the entire global aquaculture industry (Støttrup and McEvoy 2003).

In stark contrast, Crump et al. (2022) use what are essentially animal rights definitions to identify live feed as a welfare problem for the prey animals. This shows how the precautionary use of a suffering-centered welfare framework does not mirror reality in any predator/prey situation that supports natural trophic pathways (i.e., in natural environments, wild fisheries or aquaculture nurseries), because it only recognizes the needs of individual animals (“dots”), but it is unable to “join the dots” together *via* trophic pathways into a coherent working ecosystem (Fox 2006). “Joining the dots” also involves humans, who are part of the same natural world where we are all inextricably linked to the other dots through our health, welfare and food security needs (Allen et al. 2023). Regulating live feeding for fisheries or aquaculture under a suffering-centered welfare framework, usually leads to circular arguments about benefits for predators versus prey. This argument is eventually self-limiting, however, because animal rights definitions eventually conclude that to resolve the conundrum the solution is to humanely kill all predators (Fox 2006; Bramble 2021), or genetically engineer them to become vegetarian (Fox 2006). Of course, in the real world, both so called “solutions” would undermine essential trophic and evolutionary processes and risk global ecological collapse (Allen et al. 2023).

Similar animal rights-based arguments are also being made against fish feeds based on insect meal¹, despite this natural protein source resulting in better welfare for carnivorous fish than feeding them terrestrial plant-based diets (Alfiko et al. 2022). Recent calls by animal rights groups and others to ban farming of octopus and other cephalopods, allegedly based on welfare grounds (Schnell et al. 2022), also invoke the precautionary approach, to the arguable detriment of

overexploitation of wild cephalopod populations². Utilizing the precautionary approach to advocate for banning aquaculture production of predatory fish and invertebrates based on perceived welfare issues with live feeds under suffering-centered welfare frameworks would result in immediate global food insecurity (Golden et al. 2021; Tigchelaar et al. 2022; Troell et al. 2023). On the other hand, playing devil’s advocate with the very same precautionary approach could lead to an argument that to reduce these clear risks to global food security and avoid other presumably unintended consequences, all aquatic taxa should be removed from all animal welfare protection. Of course, this extreme example would likely be unacceptable to society, as well as potentially counterproductive to the health and welfare of aquatic animals. But as pointed out by Arlinghaus and Schwab (2011), the precautionary approach or “benefit of the doubt”, can neutralize everything, including common-sense.

x. The need for organized skepticism and critical thinking

The scientific method is based upon observations, hypotheses to test and in turn understand the observations, data collection, and analysis of repeatable empirical evidence for or against the hypotheses. The method then requires rigorous skepticism regarding the empirical evidence (Huxley 1866; Popper 1963), and self-correction through defining specific criteria for falsifying the hypotheses (Trevors 2010; Abbot et al. 2023). As such, science is best seen as organized skepticism: “a journey, over time, toward contingent understanding guided by experimental tests and skeptical questioning” (May 2011).

The examples in the previous nine points demonstrate that the scientific method is being regularly misused, misinterpreted, or ignored in the fish and invertebrate sentience and pain literature. Moreover, some of this literature (and other associated publication activities) contains evidence of organized activism. The strategies being used by some groups to advocate for legislative changes ignore several of the Mertonian principles of science (Abbot et al. 2023). This pathway usually leads to pseudoscience, which if left unchallenged, promotes Lysenkoism-like activity (Gordin 2012; Kolchinsky et al. 2017) leading to a slippery slope which unravels the fundamentals of all sciences, regardless of discipline.

¹<https://thefishsite.com/articles/anti-insect-ingredient-farmed-salmon-standard-tops-new-welfare-benchmark>

²<https://www.theguardian.com/environment/2023/jun/25/a-symbol-of-what-humans-shouldnt-be-doing-the-new-world-of-octopus-farming>

One of the most important defenses against pseudo-science is critical thinking. A good way to explain critical thinking is *via* a worked example. Imagine Ms. B. Leave and Ms. A. Gainst are engaged in a discussion about the existence of the tooth fairy. Ms. B. Leave starts by affirming the existence of the tooth fairy with evidence that her teeth placed on the bedside table at night are replaced with a gold coin the next morning. This didn't happen only once, but many times, and was also verified by other friends who experienced similar events. Wanting direct proof, Ms. A. Gainst proposed to stay awake overnight and witness the tooth fairy for herself, however, Ms. B. Leave exclaimed that the tooth fairy will never come if there is a chance it will be seen. Not surprisingly, Ms. A. Gainst remained skeptical of this non-falsifiable hypothesis. She suggested perhaps there was a more parsimonious explanation, that being Ms B. Leaves' parents were the entities responsible for the tooth/coin swap.

The above scenario reveals how four important questions can help guide critical thinking: first, what

is the proposed hypothetical mechanism underpinning the phenomenon? i.e., the tooth fairy replaces the tooth with a gold coin. Second, does the evidence support the mechanism? – neither the gold coin nor hearsay is evidence for the tooth fairy. Third, is the mechanism biologically or physically plausible? – flying fairies carrying gold coins are inconsistent with known scientific principles; and fourth, are there other more parsimonious alternative explanations for the phenomenon? e.g., the tooth fairy is instead a real person. These four questions demonstrate the basis of organized skepticism.

Application of organized skepticism and critical thinking to the various scientific issues highlighted here is vitally important if policy makers are to interpret the limited data available (Sutherland et al. 2013) and develop sound policies which avoid the potential “lose-lose” situations and unintended consequences which could otherwise arise (Figure 1). In this age of internet misinformation, “alternative facts” and

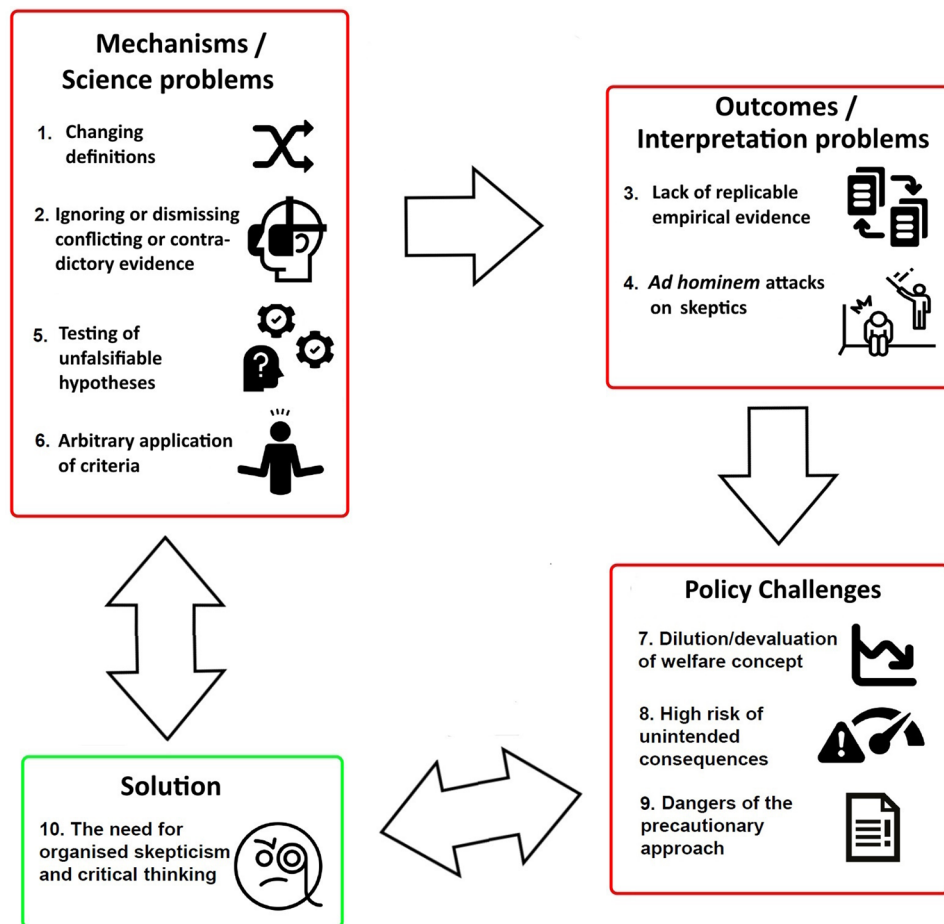


Figure 1. Conceptual diagram of the interactions between the ten reasons to be skeptical about fishes and aquatic invertebrates being sentient and feeling pain. Problems with scientific rigor hinder interpretation of the outcomes, which results in significant policy challenges during development of legislation regulating welfare. To avoid the potential dangers and unintended consequences which can arise from these issues, organized skepticism and critical thinking must be applied to the underlying scientific problems and policy challenges that arise.

Artificial Intelligence (AI) written research which fabricates its own references (Davinack 2023), it is also important to maintain and cultivate in our schools and higher education systems a scientific culture of healthy, rigorous, organized skepticism, to protect us from pseudoscience so scientists can continue to generate reliable empirical evidence upon which to base important decisions that affect the future of human-kind and animal life (Krebs 2011; May 2011; O'Brien et al. 2021; Abbot et al. 2023). Clearly, the current uncertain state of fish and invertebrate welfare science demands a skeptical view (Mason and Lavery 2022; Hart 2023) to ensure that the scientific record generates reliable knowledge to support evidence-based decision making on this issue of global importance.

Conclusion – a suggested way forward

The ten reasons outlined above emphasize why any new operational welfare indicators used to define best practice guidelines for fish and aquatic invertebrates under suffering-centered welfare frameworks need to be closely scrutinized for their scientific robustness, relevance and applicability. This means they should be held to a scientifically validated evidential standard which makes them measurable, replicable under all conditions (rather than being specific to certain laboratory contexts), reliable and hence equivalent to the well-established physiological, pathological, nutritional, and health-related welfare indicators already used to define current best practice for these animals under the pragmatic animal welfare approach (Table 2). If they are not, it is doubtful that inclusion of fish and invertebrates in animal welfare legislation will generate any meaningful welfare improvement for these animals, at a high risk of “lose-lose” scenarios involving retrograde welfare outcomes and unintended consequences to both humans and aquatic animals alike.

Extending legal protection to fish and aquatic invertebrates is a societal choice (Browman et al. 2019) and politics is the method used in Western democracies to influence that choice (Krebs 2011; Moylan 2022). Nevertheless, science, not politics, is the method best equipped to identify reliable, replicable, and effective operational welfare indicators that can improve welfare outcomes for fish and invertebrates. Effective welfare can be a “win-win” scenario for both aquatic animals and humans alike. Yet without application of organized skepticism, verification and critical thinking to this subject, there is a high risk of invoking a rapid downward spiral in scientific rigor, with potentially significant unintended consequences. This situation would be at odds with the high evidential bar historically

applied to the majority of science underpinning development of modern aquaculture and fisheries science and management. With global food security, livelihoods, and the human right to be free from hunger and poverty in play, the stakes are very high. To paraphrase Sir Winston Churchill,

Never before in the field of human food security, has so much been put at risk for so many, based on so few verifiable facts

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Author contributions

Conceptualization: SJ Cooke, R Arlinghaus.

Writing, figures - HI Browman, SJ Cooke, BK Diggles, PJB Hart, JB Jones, B Key, DC Rogers, A Schwab, JD Shields, AB Skiftesvik, ED Stevens.

Review and editing: R Arlinghaus, HI Browman, SJ Cooke, RL Cooper, IG Cowx, CD Derby, SW Derbyshire, BK Diggles, PJB Hart, JB Jones, AO Kasumyan, B Key, JG Pepperell, DC Rogers, JD Rose, JD Shields, A Schwab, AB Skiftesvik, ED Stevens, C Watson.

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ORCID

Brian Key  <http://orcid.org/0000-0002-1150-3848>

References

- Abbot D, Bikfalvi A, Bleske-Rechek AL, Bodmer W, Boghossian P, Carvalho CM, Ciccolini J, Coyne JA, Gauss J, Gill PMW, et al. 2023. In defense of merit in science. *Controversial Ideas* 3(1):1. doi:10.35995/jci03010001.
- Abolofia J, Asche F, Wilen JE. 2017. The cost of lice: quantifying the impacts of parasitic sea lice on farmed salmon. *Mar Res Econ.* 32(3):329–349. doi:10.1086/691981.

- Adamo SA. 2019. Is it pain if it does not hurt? On the unlikelihood of insect pain. *Can Entomol. Entomol.* 151(6):685–695. doi:10.4039/tce.2019.49.
- Allen BL, Bobier C, Dawson S, Fleming PJS, Hampton J, Jachowski D, Kerley GIH, Linnell JDC, Marnewick K, Minnie L, et al. 2023. Why humans kill animals and why we cannot avoid it. *Sci Total Environ.* 896:165283. doi:10.1016/j.scitotenv.2023.165283.
- Alfiko Y, Xie D, Astuti RT, Wong J, Wang L. 2022. Insects as a feed ingredient for fish culture: status and trends. *Aquacult Fish.* 7(2):166–178. doi:10.1016/j.aaf.2021.10.004.
- Arlinghaus R, Schwab A. 2011. Five ethical challenges to recreational fishing: What they are and what do they mean? *Amer Fish Soc Symp.* 75:219–234.
- Arlinghaus R, Cooke SJ, Lyman J, Policansky D, Schwab A, Suski C, Sutton SG, Thorstad EB. 2007. Understanding the complexity of catch-and-release in recreational fishing: An integrative synthesis of global knowledge from historical, ethical, social, and biological perspectives. *Rev Fish Sci.* 15(1–2):75–167. doi:10.1080/10641260601149432.
- Arlinghaus R, Cooke SJ, Schwab A, Cowx IG. 2009. Contrasting pragmatic and suffering-centred approaches to fish welfare in recreational fishing. *J Fish Biol.* 75(10):2448–2463. doi:10.1111/j.1095-8649.2009.02466.x.
- Arlinghaus R, Schwab A, Riepe C, Teel T. 2012. A primer on anti-angling philosophy and its relevance for recreational fisheries in urbanized societies. *Fisheries.* 37(4):153–164. doi:10.1080/03632415.2012.666472.
- Aromataris E, Pearson A. 2014. The systematic review: an overview. *Am J Nurs.* 114(3):53–58. doi:10.1097/01.NAJ.0000444496.24228.2c.
- Ayali A. 2009. The role of the arthropod stomatogastric nervous system in moulting behaviour and ecdysis. *J Exp Biol.* 212(Pt 4):453–459. doi:10.1242/jeb.023879.
- Baluška F, Mancuso S. 2021. Individuality, self and sociality of vascular plants. *Philos Trans R Soc Lond B Biol Sci.* 376(1821):20190760. doi:10.1098/rstb.2019.0760.
- Barnhart MC, Haag WR, Roston WN. 2008. Adaptations to host infection and larval parasitism in Unionoida. *J Nth Amer Benthol Soc.* 27(2):370–394. doi:10.1899/07-093.1.
- Barr S, Laming PR, Dick JT, Elwood RW. 2008. Nociception or pain in a decapod crustacean? *Anim Behav.* 75(3):745–751. doi:10.1016/j.anbehav.2007.07.004.
- Barragán-Méndez C, Sobrino I, Marín-Rincón A, Fernández-Boo S, Costas B, Mancera JM, Ruiz-Jarabo I. 2019. Acute-stress biomarkers in three Octopodidae species after bottom trawling. *Front Physiol.* 10:784. doi:10.3389/fphys.2019.00784.
- Bauer RT. 1981. Grooming behavior and morphology in the decapod Crustacea. *J Crust Biol.* 1(2):153–173. doi:10.2307/1548154.
- Beall J. 2017. What I learned from predatory publishers. *Biochem Med.* 27(2):273–278. doi:10.11613/BM.2017.029.
- Beck AM, Meyers NM. 1996. Health enhancement and companion animal ownership. *Annu Rev Public Health.* 17(1):247–257. doi:10.1146/annurev.pu.17.050196.001335.
- Bennett CM, Miller M, Wolford G. 2009. Neural correlates of interspecies perspective taking in the post-mortem Atlantic salmon: an argument for multiple comparisons correction. *Neuroimage.* 47:S125. doi:10.1016/S1053-8119(09)71202-9.
- Beukema JJ. 1970a. Angling experiments with carp (*Cyprinus carpio* L.) II. Decreasing catchability through one-trial learning. *Neth J Zool.* 20(1):81–92. doi:10.1163/002829670X00088.
- Beukema JJ. 1970b. Acquired hook-avoidance in the pike *Esox lucius* L. fished with artificial and natural baits. *J Fish Biol.* 2:155–160. doi:10.1111/j.1095-8649.1970.tb03268.x.
- Birch J. 2017. Animal sentience and the precautionary principle. *Anim Sent.* 2(16):1200. doi:10.51291/2377-7478.1200.
- Birch J, Burn C, Schnell A, Browning H, Crump H. 2021. Review of the evidence of sentience in cephalopod molluscs and decapod crustaceans. Report by the London School of Economics and Political Science. <https://www.lse.ac.uk/business/consulting/reports/review-of-the-evidence-of-sentiences-in-cephalopod-molluscs-and-decapod-crustaceans>.
- Bolgan M, O'Brien J, Gammell M. 2015. The behavioural repertoire of Arctic charr (*Salvelinus alpinus* (L.)) in captivity: a case study for testing ethogram completeness and reducing observer effects. *Ecol Freshw Fish.* 25(2):318–328. doi:10.1111/eff.12212.
- Bonner JT. 2010. Brainless behavior: a myxomycete chooses a balanced diet. *Proc Natl Acad Sci USA.* 107(12):5267–5268. doi:10.1073/pnas.1000861107.
- Borrelli L, Chiandetti C, Fiorito G. 2020. A standardized battery of tests to measure *Octopus vulgaris*' behavioural performance. *Invert Neurosci.* 20(1):4. doi:10.1007/s10158-020-0237-7.
- Boussard A, Delescluse J, Perez-Escudero A, Dussutour A. 2019. Memory inception and preservation in slime moulds: the quest for a common mechanism. *Philos Trans R Soc Lond B Biol Sci.* 374(1774):20180368. doi:10.1098/rstb.2018.0368.
- Bouwma PE, Herrnkind WF. 2009. Sound production in Caribbean spiny lobster *Panulirus argus* and its role in escape during predatory attack by *Octopus briareus*. *NZ J Mar FW Res.* 43(1):3–13. doi:10.1080/00288330909509977.
- Bramble B. 2021. Painlessly killing predators. *J Applied Philosophy.* 38(2):217–225. doi:10.1080/00288330909509977.
- Brooks HL, Rushton K, Lovell K, Bee P, Walker L, Grant L, Rogers A. 2018. The power of support from companion animals for people living with mental health problems: a systematic review and narrative synthesis of the evidence. *BMC Psychiatry.* 18(1):31. doi:10.1186/s12888-018-1613-2.
- Browman HI, Skiftesvik AB. 2011. Welfare in aquatic organisms – is there some faith-based HARKing going on here? *Dis Aquat Organ.* 94(3):255–257. doi:10.3354/dao02366.
- Browman HI, Cooke SJ, Cowx IG, Derbyshire SWG, Kasumyan A, Key B, Rose JD, Schwab A, Skiftesvik AB, Stevens ED, et al. 2019. Welfare of aquatic animals: where things are, where they are going, and what it means for research, aquaculture, recreational angling, and commercial fishing. *ICES J Mar Sci.* 76(1):82–92. doi:10.1093/icesjms/fsy067.
- Brown C. 2016. Fish pain: an inconvenient truth. *Anim Sent.* 2016:058.
- Brown D, Key B. 2021. Plant sentience, semantics, and the emergentist dilemma. *J Consci Stud.* 28:155–183.
- Buddensiek V. 1995. Culture of juvenile freshwater pearl mussels *Margaritifera margaritifera* L. in cages: a contribution to conservation programmes and the knowledge of habitat requirements. *Biol Conserv.* 74(1):33–40. doi:10.1016/0006-3207(95)00012-S.

- Budelmann BU. 1998. Autophagy in *Octopus*. *S Afr J Mar Sci.* 20(1):101–108. doi:10.2989/025776198784126502.
- Calvo P, Sahi VP, Trewavas A. 2017. Are plants sentient? *Plant Cell Environ.* 40(11):2858–2869. doi:10.1111/pce.13065.
- Camerer CF, Dreber A, Holzmeister F, Ho T-H, Huber J, Johannesson M, Kirchler M, Nave G, Nosek BA, Pfeiffer T, et al. 2018. Evaluating the replicability of social science experiments in *Nature* and *Science* between 2010 and 2015. *Nat Hum Behav.* 2(9):637–644. doi:10.1038/s41562-018-0399-z.
- Chamovitz DA. 2018. Plants are intelligent; Now what? *Nat Plants.* 4(9):622–623. doi:10.1038/s41477-018-0237-3.
- Chang W, Hale ME. 2023. Mechanosensory signal transmission in the arms and the nerve ring, an interarm connective, of *Octopus bimaculoides*. *iScience.* 26(5):106722. doi:10.1016/j.isci.2023.106722.
- Cholmondeley-Pennell H. 1870. Can fish feel pain? The question considered analogically and physiologically with a few words on the ethics of angling. London: Fredrick Warne and Co.
- Clark TD, Raby GD, Roche DG, Binning SA, Speers-Roesch B, Jutfelt F, Sundin J. 2020. Ocean acidification does not impair the behaviour of coral reef fishes. *Nature.* 577(7790):370–375. doi:10.1038/s41586-019-1903-y.
- Clements JC, Sundin J, Clark TD, Jutfelt F. 2022. Meta-analysis reveals an extreme “decline effect” in the impacts of ocean acidification on fish behavior. *PLoS Biol.* 20(2):e3001511. doi:10.1371/journal.pbio.3001511.
- Conte F, Voslarova E, Vecerek V, Elwood RW, Coluccio P, Pugliese M, Passantino A. 2021. Humane slaughter of edible decapod crustaceans. *Animals.* 11(4):1089. doi:10.3390/ani11041089.
- Cook KV, Lennox RJ, Hinch SG, Cooke SJ. 2015. Fish out of water: How much air is too much? *Fisheries.* 40(9):452–461. doi:10.1080/03632415.2015.1074570.
- Cooke SJ. 2016. Spinning our wheels and deepening the divide: call for an evidence-based approach to the fish pain debate. *Anim Sent.* 2016:42.
- Cooke SJ, Donaldson MR, O'connor CM, Raby GD, Arlinghaus R, Danylchuk AJ, Hanson KC, Hinch SG, Clark TD, Patterson DA, et al. 2013. The physiological consequences of catch-and-release angling: perspectives on experimental design, interpretation, extrapolation and relevance to stakeholders. *Fish Manag Ecol.* 20(2–3):268–287. doi:10.1111/j.1365-2400.2012.00867.x.
- Court of Justice of the European Union. 2021. Press Release No 59/21. Case C-733/19, Kingdom of the Netherlands v Council of the European Union and European Parliament. <https://curia.europa.eu/jcms/upload/docs/application/pdf/2021-04/cp210059en.pdf>.
- Crook RJ. 2021. Behavioral and neurophysiological evidence suggests affective pain experience in octopus. *iScience.* 24(3):102229. doi:10.1016/j.isci.2021.102229.
- Crosetto P. 2021. Is MDPI a predatory publisher? [accessed 2023 Jan 1]. <https://paolocrosetto.wordpress.com/2021/04/12/is-mdpi-a-predatory-publisher/>.
- Crump A, Browning H, Schnell AK, Burn C, Birch J. 2022. Invertebrate sentience and sustainable seafood. *Nat Food.* 3(11):884–886. doi:10.1038/s43016-022-00632-6.
- Crump A, Gibbons M, Barrett M, Birch J, Chittka L. 2023. Is it time for insect researchers to consider their subjects' welfare? *PLoS Biol.* 21(6):e3002138. doi:10.1371/journal.pbio.3002138.
- Czapla P, Wallerius ML, Monk CT, Cooke SJ, Arlinghaus R. 2023. Re-examining one-trial learning in common carp (*Cyprinus carpio*) through private and social cues: no evidence for hook avoidance lasting more than seven months. *Fish Res.* 259:106573. doi:10.1016/j.fishres.2022.106573.
- Davidson GW, Hosking WW. 2004. Development of a method for alleviating leg loss during post-harvest handling of rock lobsters. Fisheries Research and Development Corporation Project No. 2000/251. <https://www.frdc.com.au/development-method-alleviating-leg-loss-during-post-harvest-handling-rock-lobsters>.
- Davinack AA. 2023. Can ChatGPT be leveraged for taxonomic investigations? Potential and limitations of a new technology. *Zootaxa.* 5270(2):347–350. doi:10.11646/zootaxa.5270.2.12.
- Dawkins MS. 2006. A user's guide to animal welfare science. *Trends Ecol Evol.* 21(2):77–82. doi:10.1016/j.tree.2005.10.017.
- Derby CD, Weissburg MJ. 2014. The chemical senses and chemosensory ecology of crustaceans. In: Derby C, Thiel M, editors. *Nervous Systems and Control of Behavior, Vol. 3 of The Natural History of the Crustacea* (editor-in-chief, M. Thiel). New York: Oxford University Press; pp. 263–292.
- Derby C, Thiel M. (editors). 2014. *Nervous systems and control of behavior Vol. 3 of The Natural History of the Crustacea* (editor-in-chief, M. Thiel). Oxford University Press, New York. ISBN 978-0-19-979171-2.
- Derbyshire SW. 2016. Fish lack the brains and psychology for pain. Commentary on Key on Fish Pain. *Animal Sent.* 2016:025.
- Diarte-Plata G, Sainz-Hernández JC, Aguiñaga-Cruz JA, Fierro-Coronado JA, Polanco-Torres A, Puente-Palazuelos C. 2012. Eyestalk ablation procedures to minimize pain in the freshwater prawn *Macrobrachium americanum*. *Appl Anim Behav Sci.* 140(3–4):172–178. doi:10.1016/j.applanim.2012.06.002.
- Dickerson HW. 2006. Chapter 4. *Ichthyophthirius multifiliis* and *Cryptocaryon irritans* (Phylum Ciliophora). In: Woo PTK, editor. *Fish Diseases and Disorders Volume 1*. CAB International, p. 116–153.
- Diggles BK. 2016. Development of resources to promote best practice in the humane dispatch of finfish caught by recreational fishers. *Fish Manag Ecol.* 23(3–4):200–207. doi:10.1111/fme.12127.
- Diggles BK. 2019. Review of some scientific issues related to crustacean welfare. *ICES J Mar Sci.* 76(1):66–81. doi:10.1093/icesjms/fsy058.
- Diggles BK, Browman HI. 2018. Denialism and muddying the water or organized skepticism and clarity? THAT is the question. *Anim Sent.* 21(10):139. doi:10.51291/2377-7478.1349.
- Diggles BK, Cooke SJ, Rose JD, Sawynok W. 2011. Ecology and welfare of aquatic animals in wild capture fisheries. *Rev Fish Biol Fisheries.* 21(4):739–765. doi:10.1007/s11160-011-9206-x.
- Diggles BK, Arlinghaus R, Browman HI, Cooke SJ, Cowx IG, Kasumyan AO, Key B, Rose JD, Sawynok W, Schwab A, et al. 2017. Responses of larval zebrafish to low pH immersion assay. Comment on Lopez-Luna et al. *J Exp Biol.* 220(Pt 17):3191–3192. doi:10.1242/jeb.162834.

- Dobrow MJ, Goel V, Upshur RE. 2004. Evidence-based health policy: context and utilisation. *Soc Sci Med.* 58(1):207–217. doi:10.1016/s0277-9536(03)00166-7.
- Eckroth JR, Aas-Hansen Ø, Sneddon LU, Bichão H, Døving KB. 2014. Physiological and behavioural responses to noxious stimuli in the Atlantic Cod (*Gadus morhua*). *PLoS One.* 9(6):e100150. doi:10.1371/journal.pone.0100150.
- Eisemann CH, Jorgensen WK, Merritt DJ, Rice MJ, Cribb BW, Webb PD, Zalucki MP. 1984. Do insects feel pain? A biological view. *Experientia.* 40(2):164–167. doi:10.1007/BF01963580.
- Elwood RW. 2021. Potential pain in fish and decapods: Similar experimental approaches and similar results. *Front Vet Sci.* 8:631151. doi:10.3389/fvets.2021.631151.
- FAO. 2022. The State of World Fisheries and Aquaculture 2022. Towards Blue Transformation. Rome: FAO. doi:10.4060/cc0461en.
- Fiorito G, Affuso A, Anderson DB, Basil J, Bonnaud L, Botta G, Cole A, D'Angelo L, De Girolamo P, Dennison N, et al. 2014. Cephalopods in neuroscience: regulations, research and the 3Rs. *Invert Neurosci.* 14(1):13–36. doi:10.1007/s10158-013-0165-x.
- Fiorito G, Affuso A, Basil J, Cole A, de Girolamo P, D'Angelo L, Dickel L, Gestal C, Grasso F, Kuba M, et al. 2015. Guidelines for the care and welfare of cephalopods in research – a consensus based on an initiative by CephRes, FELASA and the Boyd Group. *Lab Anim.* 49(2 Suppl):1–90. doi:10.1177/0023677215580006.
- Fox W. 2006. Human relationships, nature, and the built environment: problems that any general ethics must be able to address. The MIT Press. http://www.warwickfox.com/files/2007_sage_-_probs_for_ge.pdf.
- Gibbons M, Crump A, Barrett M, Sarlak S, et al. 2022. Can insects feel pain? A review of the neural and behavioural evidence. *Adv Insect Physiol.* 63:155–229. doi:10.1016/bs.aiip.2022.10.001.
- Golden CD, Koehn JZ, Shepon A, Passarelli S, Free CM, Viana DF, Matthey H, Eurich JG, Gephart JA, Fluet-Chouinard E, et al. 2021. Aquatic foods to nourish nations. *Nature.* 598(7880):315–320. doi:10.1038/s41586-021-03917-1.
- Gordin MD. 2012. How Lysenkoism became pseudoscience: dobzhansky to velikovsky. *J Hist Biol.* 45(3):443–468. doi:10.1007/s10739-011-9287-3.
- Gray J. 2004. Consciousness. creeping up on the hard problem. Oxford: Oxford University Press.
- Grudniewicz A, Moher D, Cobey KD, Bryson GL, Cukier S, Allen K, Ardern C, Balcom L, Barros T, Berger M, et al. 2019. Predatory journals: no definition, no defence. *Nature Comment.* 576(7786):210–212. doi:10.1038/d41586-019-03759-y.
- Guo Y-C, Liao K-K, Soong B-W, Tsai C-P, Niu D-M, Lee H-Y, Lin K-P. 2004. Congenital insensitivity to pain with anhydrosis in Taiwan: a morphometric and genetic study. *Eur Neurol.* 51(4):206–214. doi:10.1159/000078487.
- Hart PJB. 2023. Exploring the limits to our understanding of whether fish feel pain. *J Fish Biol.* 102(6):1272–1280. doi:10.1111/jfb.15386.
- Hlina BL, Glassman DM, Chhor AD, Etherington BS, Elvidge CK, Diggles BK, Cooke SJ. 2021. Hook retention but not hooking injury is associated with behavioral differences in Bluegill. *Fish Res.* 242:106034. doi:10.1016/j.fishres.2021.106034.
- Hopkin M. 2008. Bacteria ‘can learn. *Nature* 2007:360. doi:10.1038/news.2007.360.
- Hochner B, Glanzman DL. 2016. Evolution of highly diverse forms of behavior in molluscs. *Curr Biol.* 26(20):R965–R971. doi:10.1016/j.cub.2016.08.047.
- Humphrey N. 2022. Sentience, The Invention of Consciousness. Oxford: Oxford University Press.
- Huxley TH. 1866. On the advisableness of improving natural knowledge. *Fortnight Rev.* 3:626–637. <https://www.gutenberg.org/files/2934-h/2934-h.htm>.
- IASP. 2020. IASP revises its definition of pain for the first time since 1979. <https://www.iasp-pain.org/publications/iasp-news/iasp-announces-revised-definition-of-pain/>.
- Ioannidis JP. 2005. Why most published research findings are false. *PLoS Med.* 2(8):e124. doi:10.1371/journal.pmed.0020124.
- Johnson BR, Ache BW. 1978. Antennular chemosensitivity in the spiny lobster, *Panulirus argus*: Amino acids as feeding stimuli. *Mar Behav Physiol.* 5(2):145–157. doi:10.1080/10236247809378530.
- Jones NA, Mendo T, Broell F, Webster MM. 2019. No experimental evidence of stress-induced hyperthermia in zebrafish (*Danio rerio*). *J Exper Biol.* 222:jeb192971.
- Key B. 2015. Fish do not feel pain and its implications for understanding phenomenal consciousness. *Biol Philos.* 30(2):149–165. doi:10.1007/s10539-014-9469-4.
- Key B. 2016a. Why fish do not feel pain. *Anim Sent.* 2016:003.
- Key B. 2016b. Burden of proof lies with proposer of celestial teapot hypothesis. Response III to Commentary on Key on Fish Pain. *Anim Sent.* 2016:079.
- Key B, Arlinghaus R, Browman HI, Cooke SJ, et al. 2017. Problems with equating thermal preference with “emotional fever” and sentience. Comment on Rey et al. (2015) Fish can show emotional fever: stress-induced hyperthermia in zebrafish. *Proc Roy Soc Lond B.* 284:20160681.
- Key B, Zalucki O, Brown DJ. 2021. Neural design principles for subjective experience: implications for insects. *Front Behav Neurosci.* 15:658037. doi:10.3389/fnbeh.2021.658037.
- Khait I, Lewin-Epstein O, Sharon R, Saban K, Goldstein R, Anikster Y, Zeron Y, Agassy C, Nizan S, Sharabi G, et al. 2023. Sounds emitted by plants under stress are airborne and informative. *Cell.* 186(7):1328–1336.e10. doi:10.1016/j.cell.2023.03.009.
- Kidd KA, Blanchfield PJ, Mills KH, Palace VP, Evans RE, Lazorchak JM, Flick RW. 2007. Collapse of a fish population after exposure to synthetic estrogen. *Proc Natl Acad Sci USA.* 104(21):8897–8901. doi:10.1073/pnas.0609568104.
- King JS, Insall RH. 2009. Chemotaxis: finding the way forward with *Dictyostelium*. *Trends Cell Biol.* 19(10):523–530. doi:10.1016/j.tcb.2009.07.004.
- Kolchinsky EI, Kutschera U, Hossfeld U, Levi GS. 2017. Russia's new Lysenkoism. *Curr Biol.* 27:R1037–R1059.
- Kraan M, Groeneveld R, Pauwelussen A, Haasnoot T, Bush SR. 2020. Science, subsidies and the politics of the pulse trawl ban in the European Union. *Mar Pol.* 118:103975. doi:10.1016/j.marpol.2020.103975.

- Krebs JR. 2011. Risk, uncertainty and regulation. *Philos Trans A Math Phys Eng Sci.* 369(1956):4842–4852. doi:10.1098/rsta.2011.0174.
- Kuuspalu A, Cody S, Hale ME. 2022. Multiple nerve cords connect the arms of octopuses, providing alternative paths for inter-arm signaling. *Curr Biol.* 32(24):5415–5421.e3. doi:10.1016/j.cub.2022.11.007.
- Macaulay G, Barrett LT, Dempster T. 2022. Recognising trade-offs between welfare and environmental outcomes in aquaculture will enable good decisions. *Aquacult Environ Interact.* 14:219–227. doi:10.3354/aei00439.
- Magaña-Gallegos E, Bautista-Bautista M, González-Zuñiga LM, Arevalo M, Cuzon G, Gaxiola G. 2018. Does unilateral eyestalk ablation affect the quality of the larvae of the pink shrimp *Farfantepenaeus brasiliensis* (Latreille, 1817) (Decapoda: Dendrobranchiata: Penaeidae)? *J Crust Biol.* 38(4):401–406. doi:10.1093/jcabi/ruy043.
- Mameli M, Bortolotti L. 2006. Animal rights, animal minds, and human mindreading. *J Med Ethics.* 32(2):84–89. doi:10.1136/jme.2005.013086.
- Mariappan P, Balasundaram C, Schmitz B. 2000. Decapod crustacean chelipeds: an overview. *J Biosci.* 25(3):301–313. doi:10.1007/BF02703939.
- Marris E. 2023. Stressed plants ‘cry’ – and some animals probably hear them. *Nature.* 616(7956):229–229. doi:10.1038/d41586-023-00890-9.
- Mason GJ, Lavery JM. 2022. What is it like to be a bass? Red herrings, fish pain and the study of animal sentience. *Front Vet Sci.* 9:788289. doi:10.3389/fvets.2022.788289.
- May RM. 2011. Science as organized skepticism. *Philos Trans A Math Phys Eng Sci.* 369(1956):4685–4689. doi:10.1098/rsta.2011.0177.
- Mettam JJ, Oulton LJ, McCrohan CR, Sneddon LU. 2011. The efficacy of three types of analgesic drugs in reducing pain in the rainbow trout, *Oncorhynchus mykiss*. *Appl Anim Behav Sci.* 133(3–4):265–274. doi:10.1016/j.applanim.2011.06.009.
- Michel M. 2019. Fish and microchips: on fish pain and multiple realization. *Philos Stud.* 176(9):2411–2428. <https://link.springer.com/article/10.1007/s11098-018-1133-4>.
- Moccia RD, Scarfe D, Duston J, Stevens ED, et al. 2020. Code of practice for the care and handling of farmed salmonids: review of scientific research on priority issues. NFACC Scientific Committee Report. 2020 Sep. https://www.nfacc.ca/pdfs/codes/scientists-committee-reports/farmed%20salmonids_SC%20Report_2020.pdf.
- Moylan L. 2022. The misanthropy of animal sentience. *Academy of Ideas: Letters on Liberty*, July 2022. <https://academyofideas.org.uk/letters-on-liberty/>.
- Mulrow CD. 1994. Systematic reviews: rationale for systematic reviews. *BMJ.* 309(6954):597–599. doi:10.1136/bmj.309.6954.597.
- Murayama O, Nakatani I, Nishita M. 1994. Induction of lateral outgrowths on the chelae of the crayfish *Procambarus clarkii* (Girard). *Crust Res.* 23(0):69–73. doi:10.2307/1549540.
- Nagel T. 1974. What is it like to be a bat? *Philos Rev.* 83(4):435–450. doi:10.2307/2183914.
- Naitoh Y. 1974. Bioelectric basis of behavior in Protozoa. *Am Zool.* 14(3):883–893. doi:10.1093/icb/14.3.883.
- Nelson JS, Grande TC, Wilson MVH. 2016. *Fishes of the World*, 5th ed., Hoboken (NJ): John Wiley and Sons.
- Newby NC, Stevens ED. 2008. The effects of the acetic acid “pain” test on feeding, swimming and respiratory responses of rainbow trout (*Oncorhynchus mykiss*). *Appl Anim Behav Sci.* 114(1–2):260–269. doi:10.1016/j.applanim.2007.12.006.
- Newby NC, Stevens ED. 2009. The effects of the acetic acid “pain” test on feeding, swimming, and respiratory responses of rainbow trout (*Oncorhynchus mykiss*): a critique on Newby and Stevens (2008) - response. *Appl Anim Behav Sci.* 116(1):97–99. doi:10.1016/j.applanim.2008.07.009.
- Niikawa T, Hayashi Y, Shepherd J, Sawai T. 2022. Human brain organoids and consciousness. *Neuroethics.* 15(1):5. doi:10.1007/s12152-022-09483-1.
- O’Brien TC, Palmer R, Albarracín D. 2021. Misplaced trust: When trust in science fosters belief in pseudoscience and the benefits of critical evaluation. *J Exper Soc Psych.* 96:104184. doi:10.1016/j.jesp.2021.104184.
- Orth DJ. 2023. Chapter 5. Pain, Sentience and Animal Welfare In: Orth DJ, editor. *Fish, Fishing, and Conservation*. Blacksburg: Virginia Tech Department of Fish and Wildlife Conservation. doi:10.21061/fishandconservation.
- Oviedo-García MA. 2021. Journal citation reports and the definition of a predatory journal: the case of the Multidisciplinary Digital Publishing Institute (MDPI). *Res Eval.* 30(3):405–419a. doi:10.1093/reseval/rvab020.
- Passantino A, Elwood RW, Coluccio P. 2021. Why protect decapod crustaceans used as models in biomedical research and in ecotoxicology? Ethical and legislative considerations. *Animals.* 11(1):73. doi:10.3390/ani11010073.
- Paterson BD, Spanoghe PT. 1997. Stress indicators in marine decapod crustaceans, with particular reference to the grading of western rock lobsters (*Panulirus cygnus*) during commercial handling. *Mar Freshwater Res.* 48(8):829–834. doi:10.1071/MF97137.
- Penca J. 2022. Science, precaution and innovation for sustainable fisheries: the judgement by the Court of Justice of the EU regarding the electric pulse fishing ban. *Mar Pol.* 135:104864. doi:10.1016/j.marpol.2021.104864.
- Poos JJ, Hintzen NT, van Rijssel JC, Rijnsdorp AD. 2020. Efficiency changes in bottom trawling for flatfish species as a result of the replacement of mechanical stimulation by electric stimulation. *ICES J Mar Sci.* 77(7–8):2635–2645. doi:10.1093/icesjms/fsaa126.
- Popper KR. 1963. *Conjectures and refutations The growth of scientific knowledge*. London: Routledge and Kegan Paul.
- Pullen CE, Hayes K, O’Connor CM, Arlinghaus R, Suski CD, Midwood JD, Cooke SJ. 2017. Consequences of oral lure retention on the physiology and behaviour of adult northern pike (*Esox lucius* L.). *Fish Res.* 186(3):601–611. doi:10.1016/j.fishres.2016.03.026.
- Puri S, Faulkes Z. 2010. Do decapod crustaceans have nociceptors for extreme pH? *PLoS One.* 5(4):e10244. doi:10.1371/journal.pone.0010244.
- Raja SN, Carr DB, Cohen M, Finnerup NB, Flor H, Gibson S, Keefe FJ, Mogil JS, Ringkamp M, Sluka KA, et al. 2020. The Revised IASP definition of pain: concepts, challenges, and compromises. *Pain.* 161(9):1976–1982. doi:10.1097/j.pain.0000000000001939.
- Reber AS. 2017. What if all animals are sentient? *Anim Sent.* 16(6):1225. doi:10.51291/2377-7478.1225.

- Rehnberg BG, Schreck CB. 1987. Chemosensory detection of predators by coho salmon (*Oncorhynchus kisutch*): behavioral reaction and the physiological stress response. *Can J Zool.* 65(3):481–485. doi:10.1139/z87-074.
- Rehnberg BG, Smith RJE, Sloley BD. 1987. The reaction of pearl dace (Pisces, Cyprinidae) to alarm substance: time-course of behavior, brain amines, and stress physiology. *Can J Zool.* 65(12):2916–2921. doi:10.1139/z87-442.
- Rey S, Huntingford FA, Boltaña S, Vargas R, Knowles TG, Mackenzie S. 2015. Fish can show emotional fever: stress-induced hyperthermia in zebrafish. *Proc R Soc B.* 282(1819):20152266. doi:10.1098/rspb.2015.2266.
- Rose JD, Arlinghaus R, Cooke SJ, Diggles BK, Sawynok W, Stevens ED, Wynne CDL. 2014. Can fish really feel pain? *Fish Fish.* 15(1):97–133. doi:10.1111/faf.12010.
- Rosemberg S, Marie SK, Kliemann S. 1994. Congenital insensitivity to pain with anhydrosis: morphological and morphometric studies on the skin and peripheral nerves. *Pediatr Neurol.* 11(1):50–56. doi:10.1016/0887-8994(94)90091-4.
- Schnell A, Browning H, Birch J. 2022. Octopus farms raise huge animal welfare concerns – and they're unsustainable too. <https://theconversation.com/octopus-farms-raise-huge-animal-welfare-concerns-and-theyre-unsustainable-too-179134>.
- Selbach C, Marchant L, Mouritsen KN. 2022. Mussel memory: Can bivalves learn to fear parasites? *R Soc Open Sci.* 9(1):211774. doi:10.1098/rsos.211774.
- Shephard S, List CJ, Arlinghaus R. 2023. Reviving the unique potential of recreational fishers as environmental stewards of aquatic ecosystems. *Fish Fish.* 24(2):339–351. doi:10.1111/faf.12723.
- Shields JD, Stephens FJ, Jones B. 2006. Pathogens, parasites and other symbionts. *Lobsters: biology, management, aquaculture and fisheries.* pp. 146–204.
- Siemann LA, Parkins CJ, Smolowitz RJ. 2015. Scallops caught in the headlights: swimming escape behaviour of the Atlantic sea scallop (*Placopecten magellanicus*) reduced by artificial light. *ICES J Mar Sci.* 72(9):2700–2706. doi:10.1093/icesjms/fsv164.
- Smaldino PE, McElreath R. 2016. The natural selection of bad science. *R Soc Open Sci.* 3(9):160384. doi:10.1098/rsos.160384.
- Smarandache-Wellmann CR. 2016. Arthropod neurons and nervous system. *Curr Biol.* 26(20):R960–R965. doi:10.1016/j.cub.2016.07.063.
- Smith ES, Lewin GR. 2009. Nociceptors: a phylogenetic review. *J Comp Physiol A Neuroethol Sens Neural Behav Physiol.* 195(12):1089–1106. doi:10.1007/s00359-009-0482-z.
- Sneddon LU. 2002. Anatomical and electrophysiological analysis of the trigeminal nerve in the rainbow trout, *Oncorhynchus mykiss*. *Neurosci Lett.* 319(3):167–171. doi:10.1016/s0304-3940(01)02584-8.
- Sneddon LU. 2003. The evidence for pain in fish. Use of morphine as an anaesthetic. *Appl Anim Behav Sci.* 83(2):153–162. doi:10.1016/S0168-1591(03)00113-8.
- Sneddon LU. 2013. Pain perception in fish: Why critics cannot accept the scientific evidence for fish pain? (Response to Rose et al. 2012 Can fish really feel pain?). https://www.liv.ac.uk/media/livacuk/iib/fish/Response_to_Rose_2012.pdf. - document since removed. Now available via wayback machine https://web.archive.org/web/20150923060224/https://www.liv.ac.uk/media/livacuk/iib/fish/Response_to_Rose_2012.pdf.
- Sneddon LU, Roques JA. 2023. Pain recognition in fish. *Vet Clin North Am Exot Anim Pract.* 26(1):1–10. doi:10.1016/j.cvex.2022.07.002.
- Sneddon LU, Braithwaite VA, Gentle MJ. 2003. Do fish have nociceptors? Evidence for the evolution of a vertebrate sensory system. *Proc Biol Sci.* 270(1520):1115–1121. doi:10.1098/rspb.2003.2349.
- Sneddon LU, Elwood RW, Adamo SA, Leach MC. 2014. Defining and assessing animal pain. *Anim Behav.* 97:201–212. doi:10.1016/j.anbehav.2014.09.007.
- Snow PJ, Plenderleith MB, Wright LL. 1993. Quantitative study of primary sensory neurone populations of three species of elasmobranch fish. *J Comp Neurol.* 334(1):97–103. doi:10.1002/cne.903340108.
- Stentiford GD, Bateman IJ, Hinchliffe SJ, Bass D, Hartnell R, Santos EM, Devlin MJ, Feist SW, Taylor NGH, Verner-Jeffreys DW, et al. 2020. Sustainable aquaculture through the One Health lens. *Nat Food.* 1(8):468–474. doi:10.1038/s43016-020-0127-5.
- Stevens ED, Arlinghaus R, Browman HI, Cooke SJ, Cowx IG, Diggles BK, Key B, Rose JD, Sawynok W, Schwab A, et al. 2016. Stress is not pain. Comment on Elwood and Adams (2015) Electric shock causes physiological stress responses in shore crabs, consistent with prediction of pain. *Biol Lett.* 12(4):20151006. doi:10.1098/rsbl.2015.1006.
- Stene A, Carrozzo Hellevik C, Fjortoft HB, Philis G. 2022. Considering elements of natural strategies to control salmon lice infestation in marine cage culture. *Aquacult Environ Interact.* 14:181–188. doi:10.3354/aei00436.
- Stoner AW. 2012. Assessing stress and predicting mortality in economically significant crustaceans. *Rev Fish Sci.* 20(3):111–135. doi:10.1080/10641262.2012.689025.
- Støttrup JG, McEvoy LA. 2003. Live feeds in marine aquaculture. Oxford: Blackwell Science Ltd. 318. pgs. doi:10.1002/9780470995143.
- Sutherland WJ, Spiegelhalter D, Burgman M. 2013. Policy: twenty tips for interpreting scientific claims. *Nature.* 503(7476):335–337. doi:10.1038/503335a.
- Tigchelaar M, Leape J, Micheli F, Allison EH, Basurto X, Bennett A, Bush SR, Cao L, Cheung WWL, Crona B, et al. 2022. The vital roles of blue foods in the global food system. *Glob Food Sec.* 33:100637. doi:10.1016/j.gfs.2022.100637.
- Tracey WD. 2017. Nociception. *Curr Biol.* 27(4):R129–R133. doi:10.1016/j.cub.2017.01.037.
- Trevors JT. 2010. The scientific method: use it correctly. *Water Air Soil Pollut.* 205(S1):1–1. doi:10.1007/s11270-009-0283-6.
- Troell M, Costa-Pierce B, Stead S, Cottrell RS, Brugere C, Farmery AK, Little DC, Strand Å, Pullin R, Soto D, et al. 2023. Sustainable development goals for improved human and planetary health. *J World Aquaculture Soc.* 54(2):251–342. doi:10.1111/jwas.12946.
- Uddin SA, Rahman MM. 2015. Gonadal maturation, fecundity and hatching performance of wild caught tiger shrimp *Penaeus monodon* using unilateral eyestalk ablation in captivity. *J Bangladesh Agric Univ.* 13(2):315–322. doi:10.3329/jbau.v13i2.28804.
- Valente C. 2022. Anaesthesia of decapod crustaceans. *Vet Anim Sci.* 16:100252.
- Valentine MS, Van Houten J. 2022. Ion channels of cilia: *Paramecium* as a model. *J Eukaryotic Microbiology.* 69(5):e12884. doi:10.1111/jeu.12884.

- Vera LM, de Alba G, Santos S, Szewczyk TM, Mackenzie SA, Sánchez-Vázquez FJ, Rey Planellas S. 2023. Circadian rhythm of preferred temperature in fish: behavioural thermoregulation linked to daily photocycles in zebrafish and Nile tilapia. *J Therm Biol.* 113:103544. doi:10.1016/j.jtherbio.2023.103544.
- Verschueren B, Lenoir H, Soetaert M, Polet H. 2019. Revealing the by-catch reducing potential of pulse trawls in the brown shrimp (*Crangon crangon*) fishery. *Fish Res.* 211:191–203. doi:10.1016/j.fishres.2018.11.011.
- Vettese T, Franks R, Jacquet J. 2020. The great fish pain debate. *Iss Sci Technol Summ.* 36:49–53. 2020
- Walters ET. 2018a. Defining pain and painful sentience in animals. *Anim Sent.* 21(14):1360. doi:10.51291/2377-7478.1360.
- Walters ET. 2018b. Nociceptive biology of molluscs and arthropods: evolutionary clues about functions and mechanisms potentially related to pain. *Front Physiol.* 9:1049. doi:10.3389/fphys.2018.01049.
- Walters ET. 2022. Strong inferences about pain in invertebrates require stronger evidence. *Anim Sent.* 32:14. doi:10.51291/2377-7478.1731.
- Weineck K, Ray AJ, Fleckenstein LJ, Medley M, Dzubuk N, Piana E, Cooper RL. 2018. Physiological changes as a measure of crustacean welfare under different standardized stunning techniques: cooling and electroshock. *Animals.* 8(9):158. doi:10.3390/ani8090158.
- Wesołowska W, Wesołowski T. 2014. Do *Leucochloridium* sporocysts manipulate the behaviour of their snail hosts? *J Zool.* 292(3):151–155. doi:10.1111/jzo.12094.
- Wisenden BD. 2015. Chapter 6. Chemical cues that indicate risk of predation In: Sorensen PW, Wisenden BD. *Fish Pheromones and Related Cues*. New York: John Wiley and Sons, p. 131–148. doi:10.1002/9781118794739.ch6.
- Wuertz S, Bierbach D, Bogner M. 2023. Welfare of decapod crustaceans with special emphasis on stress physiology. *Aquacult Res.* 2023(1307684):1–17. doi:10.1155/2023/1307684.
- Yang Y, Youyou W, Uzzi B. 2020. Estimating the deep replicability of scientific findings using human and artificial intelligence. *Proc Natl Acad Sci USA.* 117(20):10762–10768. doi:10.1073/pnas.1909046117.
- Yang Y, Sánchez-Tójar A, O'Dea RE, Noble DWA, Koricheva J, Jennions MD, Parker TH, Lagisz M, Nakagawa S. 2023. Publication bias impacts on effect size, statistical power, and magnitude (Type M) and sign (Type S) errors in ecology and evolutionary biology. *BMC Biol.* 21(1):71. doi:10.1186/s12915-022-01485-y.
- Zacarias S, Carboni S, Davie A, Little DC. 2019. Reproductive performance and offspring quality of non-ablated Pacific white shrimp (*Litopenaeus vannamei*) under intensive commercial scale conditions. *Aquacult.* 503:460–466. doi:10.1016/j.aquaculture.2019.01.018.
- Zacarias S, Fegan D, Wangsoontorn S, Yamuen N, Limakom T, Carboni S, Davie A, Metselaar M, Little DC, Shinn AP. 2021. Increased robustness of postlarvae and juveniles from non-ablated Pacific whiteleg shrimp, *Penaeus vannamei*, broodstock post-challenged with pathogenic isolates of *Vibrio parahaemolyticus* (VpAHPND) and white spot disease (WSD). *Aquacult.* 532:736033. doi:10.1016/j.aquaculture.2020.736033.
- Zullo L, Hochner B. 2011. A new perspective on the organization of an invertebrate brain. *Commun Integr Biol.* 4(1):26–29. doi:10.4161/cib.13804.