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Existing Soundscapes and the Impact of Noise on the Welfare of Farmed Salmonids: A Review

Kathy Overton[1] | Tim Dempster[1] | Marco A. Vindas[2] | Frode Oppedal[3] | Luke T. Barrett[1]

[1]Sustainable Aquaculture Laboratory—Temperate and Tropical (SALTT), Queenscliff Marine Science Centre, Deakin University, Melbourne, Australia | [2]Department of Preclinical Sciences, Faculty of Veterinary Medicine, Norwegian University of Life Sciences, Ås, Norway | [3]Animal Welfare Research Group, Institute of Marine Research, Matredal, Norway

Correspondence: Kathy Overton (k.overton@deakin.edu.au)

Received: 14 August 2025 | **Revised:** 1 February 2026 | **Accepted:** 20 February 2026

Keywords: anthropogenic | Atlantic salmon | behavioural | Oncorhynchus | physiological | response | Salmo | sound | trout

ABSTRACT

Understanding how farmed salmonids sense and respond to their environment is key to securing animal welfare and efficient production. However, hearing has rarely received attention, despite the omnipresence of underwater sound and its potential effects. We describe how and what salmonids hear, and explore how hearing may differ between wild and farmed conspecifics. We then conduct two systematic reviews, to: (1) understand the existing soundscapes experienced by farmed salmonids; and (2) identify potential short- and long-term impacts of sound on salmonid behaviour and physiology. Sound can be measured via pressure changes or particle motion; pressure levels are commonly reported, whilst particle motion is rarely measured due to logistical challenges. Salmonids have an open, physostomous swim bladder, relying primarily on their lateral line to sense sound via particle motion. Because of this, they are most sensitive to low frequencies, with startle responses most apparent between 7 and 400 Hz. Few studies have tested for effects of sound on salmonid physiology, although there is evidence that some sound exposure regimes lead to chronic stress, whilst very loud sounds (e.g., cumulative sound exposure level > 216 dB re 1 μPa^2a) can cause fatal injuries. Quantifying salmonid aquaculture soundscapes, their potential welfare impacts, and strategies to mitigate these impacts should form a new frontier in salmonid aquaculture research. We make a series of recommendations, specifically: (1) conduct targeted research to fill knowledge gaps; (2) develop a standardised protocol to measure and report sound in salmonid aquaculture; and (3) apply mitigation strategies to reduce impacts of noise.

1 | Introduction

Hearing is a key sense and is crucial in all aspects of the lives of fish, including communication, detecting food and predators, as well as during mating [1–6]. Natural and anthropogenic factors can interfere with a fish's ability to detect and respond to biologically relevant sounds, which can impact their survival and fitness [7–10].

Sound is vibratory energy that propagates through a medium as a wave. Sound waves consist of both particle motion and pressure changes. The particles in the medium do not travel with the wave, but pass on their vibratory motion to neighbouring particles. A pressure wave accompanies the particle motion as particles are compressed together and then return to their original state. At a given point in space, the pressure will increase above and then below the ambient hydrostatic pressure as the wave moves past [11, 12]. At a specified frequency or frequency range, sound can be measured via pressure changes or particle motion, usually expressed as decibels (dB) relative to a universal reference level. Appropriate metrics depend on the temporal duration and purpose [12]. For instance, continuous underwater sounds, such as those produced by an engine or pump, are usually represented by the

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root-mean-square of the sound pressure level (SPL_{RMS}) in units of dB re 1 μPa. Impulsive sounds, such as blasts or pile drives, are better represented by the peak SPL (SPL_{Peak}, dB re 1 μPa) and/or the cumulative Sound Exposure Level over the duration of the impulsive sound (SEL; dB re 1 $\mu Pa^2 s$) [13]. Particle motion can be measured as displacement (m), velocity ($m\,s^{-1}$), or acceleration ($m\,s^{-2}$) [12].

A fish's hearing capabilities, including the frequencies they are sensitive to, depend on their physiology. Swim bladder presence or absence, type, and proximity to their ears, which influences their sensitivity to different types and frequencies of sound [14]. In this context, physostomous fishes have open swim bladders that are connected to the digestive system, and fish expel or gulp air to change the volume of air within the swim bladder [14, 15]. In contrast, physoclistous fishes have closed swim bladders that rely on a gas gland to provide gas exchange via diffusion between the swim bladder and the blood [14, 15]. Due to these differences in their swim bladder physiologies, physostomous and physoclistous fish respond differently to the two components of sound: sound pressure and particle motion. Specifically, physostomous fish are typically known as sound non-specialists (or generalists) that are sensitive to particle motion and can only sense a narrow band of frequencies, whilst physoclistous fish are considered sound specialists that can sense all sound components and several frequencies, and may use or respond to sound in more complex ways [16].

The hearing capabilities of fish have been quantified across species through decades of fundamental research [8, 17–19], yet key knowledge gaps remain regarding how anthropogenic noise affects both wild and farmed fish [8]. There are multiple sources of anthropogenic noise in marine ecosystems, such as sonar, dredging, oil and gas exploration, farm noise, shipping and maritime industries, and construction [14, 20, 21]. Quantifying the impacts of noise has focused on wild marine species [7–9]. However, as aquaculture intensifies in coastal and marine ecosystems to meet the global demand for seafood, studies assessing the impact of anthropogenic noise on farmed fish have begun to appear [22–26]. Farms can be noisy environments, with noise sources and levels differing between farming systems (e.g., [22, 26, 27]) and locations (e.g., [26, 27]). Farmed fish are kept in industrial settings throughout their lifecycle, where they are exposed to both consistent and sporadic near-field noises generated by machinery, boats, and other equipment [22, 24, 26]. Because of this, the impacts of noise will differ according to site-specific noise levels and species-specific hearing thresholds and responses. Sensitivities of farmed fish may also differ from wild counterparts due to domestication, deformities [28, 29], and conditioning/habituation [30], meaning there is a need for research focused on farmed fish.

Many salmonids (Family: Salmonidae), such as Atlantic salmon (*Salmo salar*), rainbow trout (*Oncorhynchus mykiss*), coho (silver) salmon (*Oncorhynchus kisutch*), and chinook (king) salmon (*Oncorhynchus tshawytscha*) are intensively cultured throughout the world [31]. Atlantic salmon are the most farmed marine finfish species, accounting for 32.6% of global aquaculture production, with 2.7 million tonnes produced in 2020 [31]. Notably, the health and welfare of salmonids is a priority in commercial culture, with management and mitigation measures targeted to reduce production-related stressors [32–35], diseases (e.g., [36–38]), and parasites (e.g., [39–41]). In this context, the short- and long-term impacts of sound on behaviour and physiology, and their welfare impacts on farmed salmonids, is increasingly being considered (e.g., [24, 25, 42]).

In this review, we describe how salmonids hear, the range of frequencies they can detect, and explore how this might differ between wild and farmed conspecifics. We conduct two systematic reviews to: (1) understand the range of soundscapes experienced by farmed salmonids, and (2) identify potential short and long-term impacts of sound on the welfare of farmed salmonids. We summarise the existing literature and pinpoint knowledge gaps on the effect of anthropogenic sound on farmed salmonid welfare. Finally, we propose measures to mitigate the impact of noise on salmonid welfare and enhance production outcomes.

2 | Hearing Abilities of Salmonids

Whilst all fish taxa detect and use the particle motion component of sound [12, 43–45], only hearing 'specialists' (such as the family Gadidae) can detect sound pressure [8, 14]. Sound pressure is correlated with particle motion, although more closely in deep/open water than in shallow/confined water bodies. Whilst understanding the particle motion component of underwater soundscapes and its relevance to fish is critical, research has focused on sound pressure, with particle motion severely understudied [8, 14]. The main reason for this is that recording particle motion is complex and difficult (see [8, 12]), with only recent technological advances enabling the gradual incorporation and use of particle motion sensors into scientific research [12]. To our knowledge, no studies have recorded particle motion values in an aquaculture setting.

Salmonids are physostomous, and compared to other fish taxa, have relatively low sensitivity to sound pressure waves due to the lack of connection between the inner ear and the swim bladder [8]. Instead, salmonid hearing relies on sensing of particle motion by the lateral line, which is a mechanosensory system with small sensory organs distributed across the side of the fish's body [46]. The lateral line converts particle motion into electrical signals that stimulate the nervous system [6]. Otoliths are calcium carbonate structures found in the inner ear of vertebrates, and contribute to hearing, gravity sensation, balance, and linear acceleration in fish species [29, 47]. Salmonids also rely on the relative motion between their otoliths and sensory epithelium to stimulate mechanoreceptive hair cells, which in turn provide information about body position and the surrounding auditory environment [47, 48]. Salmonids are particularly sensitive to low frequencies, with peak hearing sensitivities around 160–250 Hz based on behavioural and brainstem responses in Atlantic and chinook salmon [48–50]. Notably, the hearing frequencies of salmonids have typically been quantified for fish that have either been hatchery-produced or hatchery raised, which allows for greater relevance within an aquaculture context (Figure 1A).

The hearing capabilities between wild and farmed salmon are thought to differ, with two potential explanations as to why. This first is due to environmental causes, either from loud sound exposure levels or due to differences in their calcium carbonate

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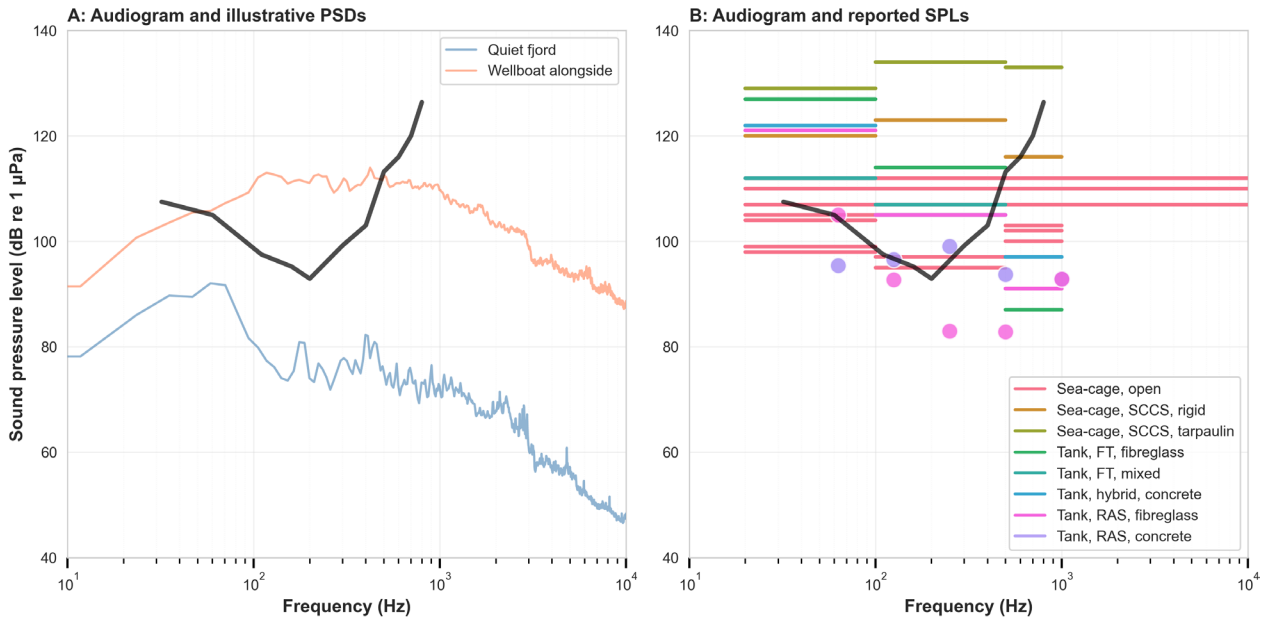

FIGURE 1 | Comparison of the Atlantic salmon audiogram (frequency-specific audible thresholds) with (panel A) illustrative power spectral densities of quiet and loud sea-cage farm conditions, and (panel B) sound pressure levels (SPLs) reported by studies of commercial salmon aquaculture settings. The audiogram, indicated by the black line, is based on minimum reported values for farmed and wild salmon [49, 50]. Two power spectral density (PSD) curves are shown in panel A, representing aquaculture environments surveyed by Barrett and Oppedal [27]. The quieter (blue) PSD was recorded at midnight at a fjord farm site, representing a near-natural sound level, whilst the louder (orange) PSD was recorded at a sea-cage site with a wellboat operating alongside. PSDs were calculated using the Welch method in Python (scipy module), with a Hanning window, 50% segment overlap, and 4096 samples per segment at a sampling rate of 48 kHz, yielding a frequency resolution of 11.7 Hz. The coloured horizontal lines in panel B indicate observed mean sound pressure levels (SPL) from Terhune et al. [51], Radford and Slater [26], and Barrett and Oppedal [27]. The horizontal line indicates the frequency range over which the SPL was measured, whilst points are used where a primary or peak frequency was reported rather than a frequency range. Data are coloured according to the type of aquaculture system (see legend; SCCS: Semi-closed containment system; FT: Flowthrough aquaculture system; RAS: Recirculating aquaculture system).

otolith composition resulting from environmental exposure [28, 29, 48, 52]. Over half of Norwegian farmed Atlantic salmon have vateritic otoliths, far above the incidence in wild fish [53]. Mechanistic modelling suggests that this deformity decreases hearing sensitivity by 28%–50% across the known hearing range [29] and can be attributed to fast growth in the hatchery stage [52]. Another reason why hearing in farmed and wild salmonids may differ is due to selection for performance in an aquaculture setting, which may be inadvertently selecting for individuals with lower sensitivity and/or reactivity if those individuals are less stressed and more productive. However, there is no evidence that supports this yet.

3 | Noise Sources and Soundscapes in Salmonid Aquaculture

Fish farms can be noisy environments, especially with the mechanisation of modern farming systems. To understand the soundscapes experienced in salmonid aquaculture, we conducted a systematic review following Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines [54] in Web of Science on 18/12/2025 using the search term (all fields): '(salmo* OR trout* OR charr* OR "oncorhynchus" OR "salvelinus") AND ("aquaculture" OR "hatchery" OR "hatcheries") AND (sound* OR noise* OR audit* OR acoustic* OR hear* NOT heart*)'. This returned 1677 results, which were each individually screened by title and abstract for relevance to ensure that they: (1) were relevant to a species of salmonid; and (2) was conducted within the context of farming/aquaculture. This initial relevancy screening yielded 29 studies (Figure S1). These 29 studies were then thoroughly screened to ensure that the study quantified an ambient soundscape within a salmonid farming system and provided a measure of sound level at specified frequencies or frequency bands/ranges. Studies that did not measure the ambient soundscape (e.g., [55]) or reported values that were not easily extractable (e.g., [56]) were excluded from the paper. Reported sound metrics that were not in this format (i.e., [55, 56]) were excluded as they could not be compared across studies. After applying these criteria, we identified three relevant studies in total, with two additional studies identified from the reference lists [22, 51].

In intensive commercial-scale aquaculture systems, equipment and machinery used throughout production can produce loud and potentially stressful noises. Land-based hatcheries rely on either flow-through or recirculating systems where water is pumped into concrete or fibreglass tanks (Figure 1B; Table S1). Equipment used can include filtration systems, air and water pumps, aerators, harvesters, and blowers [57, 58]. Through our systematic review of studies in onshore systems, we found that tank soundscapes were broadly similar across associated infrastructure (Figure 1B; Table S1). Tank material had study-specific effects in flow-through systems, although SPL_{RMS} was broadly

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between 110 and 124 dB re 1 μPa ([23]; Figure 1B; Table S1). Similar SPL_{RMS} values were also reported in recirculating systems (i.e., 83–127 dB re 1 μPa; Figure 1B; Table S1) across a range of frequencies [22, 27, 51].

At sea-cage or net-pen farms in coastal waters, farmed salmonids are frequently exposed to external sources of noise from motorised vessels [59, 60], and can also occasionally be exposed to seismic surveys, pile driving, and naval sonar [6, 61]. Aquaculture sites also generate their own noise through on-site workboats, and large vessels delivering feed, harvesting fish, or treating fish for diseases or parasites [26, 27]. Our systematic review identified two studies that quantified soundscapes at sea-cage or net-pen farm sites in coastal waters (Figure 1B; Table S1). Radford and Slater [26] recorded SPL_{RMS} between 107 and 112 dB re 1 μPa at a chinook (king) salmon farm in New Zealand (Figure 1B; Table S1), noting that potential sound sources included access vessels, feed barges, and the temporary handling facility linked to the site. Further, 65% of sound recordings made, contained boat noise, suggesting that boats are a significant source of sound [26]. Barrett and Oppedal [27] recorded SPL_{RMS} at six Atlantic salmon farms in Norway, and reported that open sea-cages were quieter (91–105 dB re 1 μPa across 20–1000 Hz) compared to fully enclosed sea-cages (i.e., tarpaulin cages: 129–134 dB re 1 μPa across 20–1000 Hz; rigid composite sea-cages: 116–123 dB re 1 μPa across 20–1000 Hz; Figure 1B; Table S1).

4 | The Impact of Aquaculture Soundscapes on Farmed Salmonid Welfare

Exposure to anthropogenic sounds can cause physical or physiological damage, mask biologically significant sounds (i.e., for prey detection, predator avoidance, orientation and navigation), and drive behavioural changes in a range of fish species. This can influence the growth and survival (and hence fitness) of individuals and have population-level consequences [14, 17]. Specifically, exposure to different types of noise (broadband white noise or pure tones) at sound pressure levels that range from 142 to 170 dB re 1 μPa can induce short- and long-term hearing loss in fish [58, 62–65].

Within a salmonid aquaculture context, the physiological and behavioural impacts of noise are critical to understand given potential welfare and health implications. To understand the impact of noise on farmed salmonids, we conducted a systematic review following PRISMA guidelines [54] in Web of Science on 18/12/2025 using the search term (all fields): '(salmo* OR trout* OR charr* OR "oncorhynchus" OR "salvelinus") AND (sound* OR noise* OR audit* OR acoustic* OR hear* NOT heart*) AND (welfare OR behav* OR physiolog* OR respon* OR effect* OR impact*)'. This returned 3774 results, which were each individually screened by title and abstract for relevance, yielding 42 studies (Figure S2). These 42 studies were then thoroughly screened to ensure that quantified impacts of noise (behavioural or physiological) were specific to salmonid species, yielding 20 relevant studies. Seven additional studies [49, 66–71] were identified by looking through the reference lists of the thoroughly screened articles, bringing the total number of relevant studies to 27 (Figure S2).

4.1 | Physiological Impacts of Noise

Eight studies identified in our systematic review assessed the short-term physiological impacts of sound exposure on salmonids (Figure 2D; Table S2), with most (6 studies) on farmed rainbow trout (Table S2). Of these, Kane et al. [72], Halvorsen et al. [67], Oestman and Earle [73], and Popper et al. [71] found no evidence of short-term physiological impacts of sound exposure (ranging from unreported SPL at 100, 200 and 400 Hz; SPL_{RMS}: 135–193 dB re 1 μPa at 170–320 and unspecified Hz; and SPL: 163–188 dB re 1 μPa at unspecified frequencies) at frequencies > 100 Hz across a range of size classes of hatchery-reared rainbow trout (Figure 2D; Table S2). In contrast, Narnaware et al. [74] found a physiological effect on rainbow trout, with phagocytosis in macrophages (which plays an important role in immune responses) impacted and cortisol levels increased after exposure to an unspecified noise level generated by a small electric motor that vibrated against the side wall of a bin for 1 h (Table S2). Harding et al. [49] found no evidence difference in oxygen consumption when wild and farmed Atlantic salmon adults were played a recording of pile driving noise (149–164 dB re 1 μPa at 2–30,000 Hz; Figure 2D; Table S2). For chinook salmon, Halvorsen et al. [66] reported that whilst the structural integrity of the olfactory epithelium of fish exposed to noise associated with barging (SPL_{RMS}: 129–135 dB re 1 μPa at 0–400 Hz) was similar compared to control fish, barged fish experienced temporary threshold shifts 7 days post-barging at 100, 200, 400 and 600 Hz (Figure 2D,I; Table S2). Halvorsen et al. [15] is the only study identified in our systematic review that resulted in severe physical injury for salmonids after sound exposure (Figure 2F). Cumulative SELs ≥ 216 dB re 1 μPa^2s resulted in mortal injuries (indicated by haemorrhaging of organs, laceration of the swim bladder or organs) or death an hour post-sound exposure (Figure 2F,G; Table S2).

Long-term studies have only tested the effects of sound exposure on Atlantic salmon and rainbow trout, with generally minor physiological impacts (Figure 2E; Table S2). Slater et al. [42] observed similar physiological conditions between ambient (96 dB re 1 μPa) and sound exposure (127 dB re 1 μPa) groups after 8 weeks in recirculating aquaculture system tanks (Figure 2E; Table S2). Terhune et al. [51] observed slightly higher smoltification rates in one out of 3 year classes in fibreglass tanks (83–105 dB re 1 μPa), which experienced different sound levels compared to concrete tanks (93–99 dB re 1 μPa). Oppedal et al. [25] tested the physiological impacts of low frequency (5–15 Hz) sound exposure ranging from 142 to 146 dB re 1 μPa over 42 days. They found a physiological response to stress that either diminished (cortisol levels) or increased (monoamine neurochemistry and neural activity) with time, indicating that sound is a chronic stressor ([25]; Figure 2E; Table S2). Solé et al. [75] reported no effect on a range of physiological parameters in salmon exposed to daily sound hair cells in 4 and 12 week trials (Figure 2E; Table S2). Davidson et al. [23], Wysocki et al. [58], and Papoutsoglou et al. [76] quantified physiological impacts of long-term sound exposure on rainbow trout, and were the only studies to assess impacts on growth (Figure 2H; Table S2). Davidson et al. [23] and Wysocki et al. [58] found similar physiological parameters across treatments (Figure 2H; Table S2), with no effect on growth. In contrast, Papoutsoglou et al. [76] found that rainbow trout that were played classical music had higher

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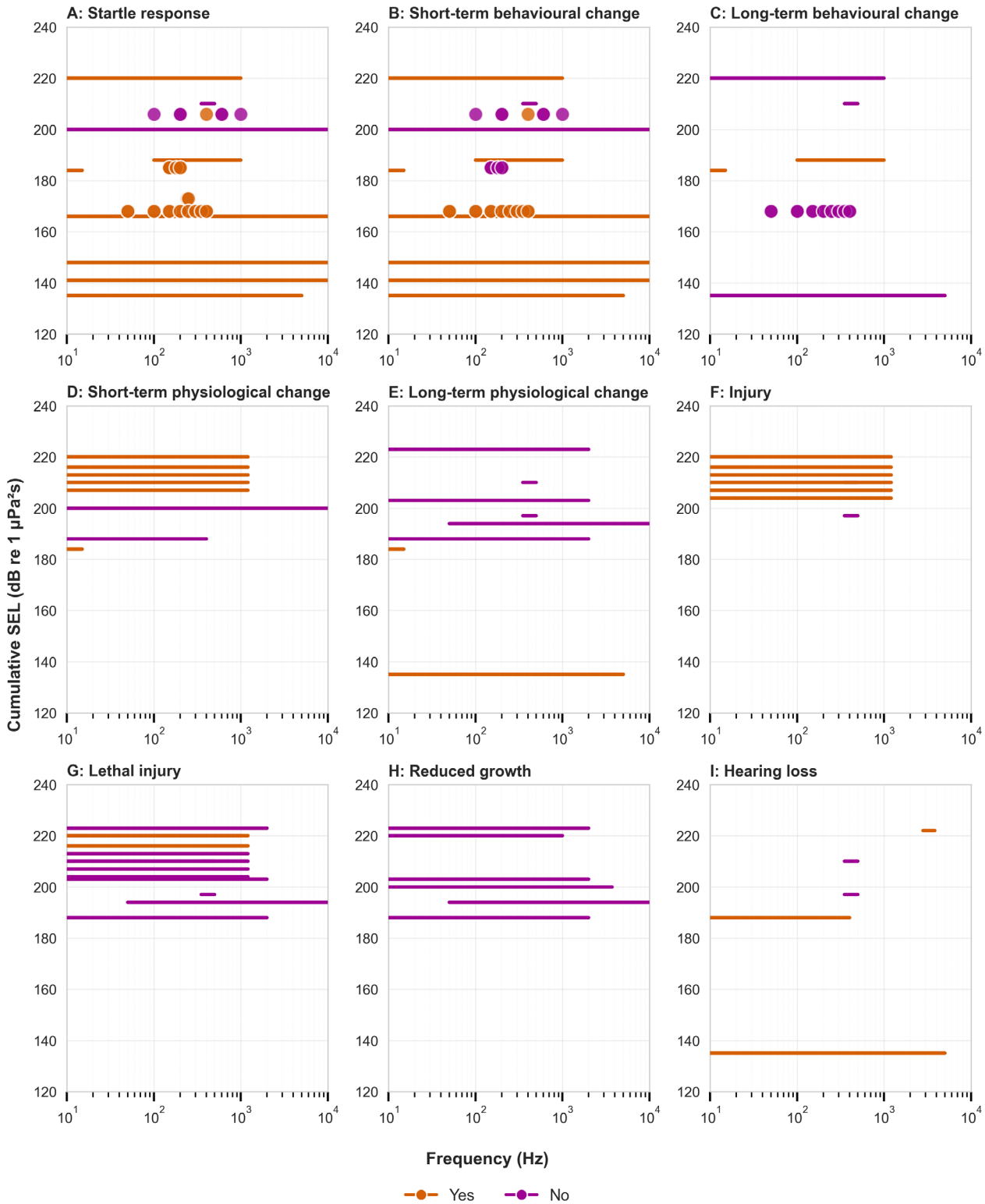

FIGURE 2 | Impacts of specified cumulative sound exposure levels (SEL) on salmonids based on a literature review. Categories of impacts are plotted separately (panels A-I). Startle responses were scored immediately upon first exposure, 'short-term' responses were scored over hours to days (< 1 week), and 'long-term' responses were scored over weeks to months (> 1 week), often with constant or repeated exposure over that timeframe. Sound exposure treatments are characterised by horizontal lines or points indicating the frequency range (or single frequency) corresponding to the reported SEL. The outcome ('Yes' or 'No') is indicated by the colour (orange and purple, respectively). Cumulative SELs were either used as reported, or else calculated based on the sound pressure level (SPL), duration, and number of exposures over the experiment. Studies that reported impulsive sounds in SPL units without a corresponding duration could not be converted to SEL and are not plotted.

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growth rates compared to ambient and white-noise tanks, although there was no effect on other physiological parameters (Figure 2H; Table S2). Studies of long-term sound exposure on salmonid growth have been limited to a single species (rainbow trout) in tanks.

4.2 | Behavioural Impacts of Noise

Studies that quantified behavioural impacts of noise frequently reported initial startle response after noise treatments began (Figure 2A). Ten studies have assessed the short-term behavioural impacts of noise on salmonids, with generally similar behavioural responses across taxa when exposed to similar frequencies, with salmonids most responsive to infrasound (Figure 2B). Knudsen et al. [77] found that juvenile Atlantic salmon exposed to noise from a piston running at 5, 10, 60, or 150 Hz exhibited stronger responses to lower frequencies, despite lower particle motion velocities at lower frequencies (< 10 Hz: 2×10^{-5} ms^{-2}; ~150 Hz: 10^{-4} ms^{-2}; Figure 2B). Moreover, whilst fish were aware of the 150 Hz stimulus, it did not evoke an avoidance response, unlike lower frequencies (Figure 2B) [77]. Bui et al. [78] quantified short-term changes in farmed Atlantic salmon behaviour held in small sea cages after close exposure to an unspecified SPL from an infrasound source played at a frequency of 12.5 Hz, finding that Atlantic salmon swam erratically after exposure to sound, with increased swimming speeds (3× faster than control group; Figure 2B; Table S2). Knudsen et al. [30] tested if wild Atlantic salmon smolts reacted to sounds played at 10 and 150 Hz and found that whilst they moved away from the sound source at 10 Hz, no behavioural response was observed at 150 Hz (Figure 2B; Table S2). Similarly, Harding et al. [49] found no evidence of a startle response when wild and farmed Atlantic salmon adults were played a recording of pile driving noise (149–164 dB re 1 μPa at 2–30,000 Hz; Figure 2B; Table S2), with behavioural (swimming activity level) impacts also similar between both groups (Figure 2B; Table S2). In contrast, Zhang et al. [79] reported salmon in sea-cages only had strong behavioural responses to SPL 180 dB re 1 μPa noise played at 400 Hz, with no responses recorded at 100 Hz, 200 Hz, 600 Hz, and 1000 Hz.

Juvenile rainbow trout and chinook salmon responded to infrasound when particle motion exceeded 10^{-2} ms^{-2} at frequencies of 7–10 Hz, invoking flight and avoidance responses ([80]; Table S2). A subsequent study found that juvenile rainbow trout and chinook salmon suddenly exposed to low frequency (10 Hz) noise for 5 s from a similar piston displayed a strong flight response that moderated but did not cease with acclimation ([69]; Table S2). Mueller et al. [80] also found that farmed and wild chinook salmon fry had a stronger initial response to infrasound played at 7–14 Hz (SPL_{RMS}: 155 dB re 1 μPa) than at 160, 180, or 200 Hz (Figure 2B; Table S2). Interestingly, Mueller et al. [70] reported that wild chinook salmon displayed a stronger behavioural response than farmed conspecifics to infrasound at 10–14 Hz (Figure 2B; Table S2). In contrast, exposed juvenile chinook and eastern brook trout (*Salvelinus fontinalis*) to 10–14 Hz infrasound and found no effect ([70]; Figure 2B; Table S2).

Nedwell et al. [81] tested the effect of pile driving on caged brown trout (*Salmo trutta*) across various distances from the sound source and observed no startle response from piles driven by vibropiling or impact driven piles (Figure 2B; Table S2). Finally, van der Knapp et al. [82] tested the behavioural responses of juvenile pink (*Oncorhynchus gorbuscha*) and chum (*Oncorhynchus keta*) salmon to noises generated by small (118.5 dB re 1 μPa), medium (125.2 dB re 1 μPa), and large (143.6 dB re 1 μPa) vessels; both species' behavioural responses increased as sound pressure level increased (Figure 2B; Table S2).

Long-term studies have only tested the behavioural effects of sound exposure on Atlantic salmon and rainbow trout, with generally minor impacts (Figure 2C; Table S2). For Atlantic salmon, Solé et al. [75] reported no behavioural impacts of sound exposure (Figure 2C; Table S2). Larger farmed salmon (20–40 cm length) exposed to 134 dB in 50 Hz intervals from 50 to 400 Hz displayed initial startle responses across this frequency but acclimated with no startle response observed within 2–3 days ([83]; Figure 2C; Table S2). Karikoski [68] found that adult salmon exposed to control (SPL_{RMS}: 110–120 dB re 1 μPa at 100–1000 Hz) and ship noise (SPL_{RMS}: 117–148 dB re 1 μPa at 100–1000 Hz) for 31 days had slight variations in behaviour (e.g., erratic movements, freezing observations, swimming activity), although swimming activity and erratic movement observations increased through time in both groups (Figure 2C). Oppedal et al. [25] found that salmon exposed to low frequency (5–15 Hz) sound exposure ranging from 142 to 146 dB re 1 μPa over 42 days initially changed swimming behaviour, but this response decreased through time (Figure 2C; Table S2). The only study that has quantified behavioural impacts in rainbow trout is Davidson et al. [23] (Table S2). In a 5-month trial, they exposed rainbow trout to SPL_{RMS} 149 dB re 1 μPa and found an initial startle response followed by a return to normal swimming behaviour after a few hours (Figure 2C; Table S2). For brook trout, Beach et al. [84] reported a strong startle response for fish exposed to SPL_{RMS} 135 dB re 1 μPa at 10–5000 Hz, with increased swimming distance and velocity (Figure 2C; Table S2). After 2 weeks, fish were less responsive to noise compared to control fish.

Habituation has previously been defined as 'a behavioural response decrement that results from repeated stimulation and that does not involve sensory adaptation/sensory fatigue or motor fatigue' [85]. In this context, repeated sound exposure may result in a gradual decrease of the fish's response in either frequency and/or magnitude. In this context, Knudsen et al. [77] reported that salmon habituate (in terms of their bradycardia response) to 5–10 Hz sound over 6 times but need only one time to habituate to 150 Hz sound exposure. Furthermore, habituation is quick when presented within short intervals (35 s) in small enclosures (i.e., acoustic tubes) but lasted several hours when presented every 10 min in a pool. However, wild migrating Atlantic salmon smolts showed no behavioural habituation to a 10 Hz sound source placed at a hydroelectric power plant [30]. Similarly, hatchery reared juvenile spring chinook and rainbow trout showed avoidance, but not habituation, to a 10 Hz sound source in outdoor holding 3 m outdoor experimental tanks [69]. Finally, Tlusty et al. [83] found that farmed rainbow trout and Atlantic salmon juveniles maintained a conditioned response to sound played at 250 Hz and 134 dB for over 7 months (Table S2). Taken together, this research suggest that salmonids respond with avoidance, but not habituation to repeated infrasound exposure, particularly over large volume areas. This highlights

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possible welfare issues regarding sound exposure for farmed salmon during the seawater stage.

5 | Recommendations

5.1 | More Research Required to Fill Significant Knowledge Gaps

Targeted research is required to establish acceptable limits for long-term and short-term noise in salmonid aquaculture and inform approaches to mitigate problematic sounds. We highlight the following knowledge gaps regarding the impacts of sound on the health and welfare of farmed salmonids:

1. What are the welfare implications of hearing loss in farmed salmonids? What level of sound exposure, both short- and long-term, results in hearing loss in farmed salmonids, how long does hearing loss persist, and are affected fish more or less stressed as a result? What effect do rearing conditions and developmental deformities such as vateritic otoliths have on relevant thresholds later in life? Each of these questions has been studied to some extent (e.g., [28, 29, 48, 52, 58, 66]), but there is not yet sufficient support to establish acceptable thresholds.
2. Most studies of long-term sound exposure have compared the effects of sound levels representative of those that occur in commercial aquaculture, for example by comparing behaviour and performance of fish farmed in the quietest and loudest tanks at a given farm site (e.g., [58, 66, 68, 71, 76]). However, it may be that effects of long-term sound exposure are equally present across this range of sound levels, and quieter baseline conditions (more representative of natural environments) are needed to detect an effect of farm noise on fish.
3. There has been minimal consideration of particle motion in studies of aquaculture soundscapes. Whilst the practical challenges involved in measuring particle motion [8, 12] may preclude its widespread use as a metric, targeted use may be beneficial to establish whether—or in which settings—sound pressure level measurements reliably identify stressful sound levels for fishes that primarily sense particle motion.
4. Soundscapes associated with emerging farming systems and technologies should be assessed, ideally during the development stage, to ensure that any required mitigations can be integrated before deployment. Further, as land-based aquaculture systems continue to develop globally, it is important to consider the welfare implications of ongoing construction noises on farmed fish (e.g., adjacent blasting works; [27]).

5.2 | Create Standardised Protocols to Measure and Report Sound in Salmonid Aquaculture

Sound pressure levels are reported inconsistently across studies, which makes it challenging to make comparisons and synthesise research. For instance, even amongst studies that report root-mean-square sound pressure level, some researchers report levels within defined frequency bands, others at a peak frequency (i.e., highest power spectral density), whilst others report broadband levels that are specific to the frequency response curve of the equipment used. Whilst beyond the scope of this study, we encourage the development of a standardised protocol and terminology for assessment of aquaculture soundscapes (see [86, 87]).

5.3 | Potential Mitigations

Whilst substantial knowledge gaps remain, noise in aquaculture can reach levels that stress salmonids. Farmers can apply a range of mitigation strategies to dampen these sounds. For example, in onshore systems, acoustic isolation can be improved between machinery and tanks to substantially reduce sound levels in the water column [24, 88] either during the design and construction of facilities (e.g., locating pump room away from tanks), or deploying mitigation measures to reduce noise in existing facilities (e.g., installing vibration dampening pads, reducing noise from outflow). Mitigating noise exposure in open sea-cages is challenging as anthropogenic sounds are not always related to production [24, 26, 27]. However, noise can be mitigated by transitioning to quieter, fully electric workboats. From a spatial management/planning perspective, we can also avoid placing farms in busy waterways to minimise potential exposure to loud noises [24].

Author Contributions

Kathy Overton: conceptualisation, data curation, formal analysis, investigation, methodology, visualisation, writing – original draft preparation. **Tim Dempster:** conceptualisation, funding acquisition, methodology, writing – reviewing and editing. **Marco A. Vindas:** conceptualisation, funding acquisition, methodology, writing – reviewing and editing. **Frode Oppedal:** conceptualisation, funding acquisition, project administration, methodology, writing – reviewing and editing. **Luke T. Barrett:** conceptualisation, data curation, formal analysis, investigation, methodology, visualisation, writing – reviewing and editing.

Acknowledgements

Open access publishing facilitated by Deakin University, as part of the Wiley - Deakin University agreement via the Council of Australasian University Librarians.

Funding

This research was funded by the Norwegian Seafood Research Fund (FHF#901744), Institute of Marine Research (IMR#14597-17)—Soundscape in salmon aquaculture—mapping, behavioural and welfare impacts and risk considerations (Salmon Soundscape), and funding from Deakin Centre for Marine Science. Open access publishing facilitated by Deakin University, as part of the Wiley—Deakin University agreement via the Council of Australian University Librarians.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Data S1:** Supporting Information.

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