

RESEARCH REVIEW

Changing estuaries and impacts on juvenile salmon: A systematic review

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Funding information

Liber Ero Postdoctoral Fellowship
Program; Vanier Canadian Graduate
Scholarship; American Fisheries Society:
Michael Stevenson Scholarship; American
Fisheries Society: Steven Berkeley Marine
Conservation Fellowship; Liber Ero Research
Chair in Coastal Science and Management

Abstract

Estuaries are productive ecosystems providing important habitat for a diversity of species, yet they also experience intense levels of anthropogenic development. To inform decision-making, it is essential to understand the pathways of impacts of particular human activities, especially those that affect species such as salmon, which have high ecological, social-cultural and economic values. Salmon systems provide an opportunity to build from the substantial body of research on responses to estuary developments and take stock of what is known. We conducted a systematic English-language literature review on the responses of juvenile salmon to anthropogenic activities in estuaries and nearshore areas asking: what has been studied, where are the major knowledge gaps and how do stressors affect salmon? We found a substantial body of research ($n = 167$ studies; 1,369 comparative tests) to help understand responses of juvenile salmon to 24 activities and their 14 stressors. Across studies, 82% of the research was conducted in the eastern Pacific (Oregon and Washington, USA and British Columbia, Canada) showing a limited geographical scope. Using a semiquantitative approach to summarize the literature, including a weight-of-evidence metric, we found a range of results from low to moderate-high confidence in the consequences of the stressors. For example, we found moderate-high confidence in the negative impacts of pollutants and sea lice and moderate confidence in negative impacts from connectivity loss and changes in flow. Our results suggest that overall, multiple anthropogenic activities cause negative impacts across ecological scales. However, our results also reveal knowledge gaps resulting from minimal research on particular species (e.g. sockeye salmon), regions (e.g. Atlantic) or stressors (e.g. entrainment) that would be expedient areas for future research. With estuaries acting as a nexus of biological and societal importance and hotspots of ongoing development, the insights gained here can contribute to informed decision-making.

KEYWORDS

environmental impact assessment, estuary impacts, salmon, smolt, stressors

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1 | INTRODUCTION

Estuaries are hotspots of ecological importance for a multitude of species (Nagelkerken, Sheaves, Baker, & Connolly, 2015; Peterson, Comyns, Hendon, Bond, & Duff, 2000) while also being areas of high human use (Cloern et al., 2016; Elliott & Whitfield, 2011). As regions of high productivity, estuaries serve as nursery habitats for a diversity of fish species including salmon (Beck et al., 2001; Peterson et al., 2000). However, because of their unique geography, they have been areas of human development for millennia (Limburg, 1999; Lotze, 2010), providing important ecosystem services (Costanza et al., 1997). Currently, 40% of the world's population lives in coastal regions (Barragán & de Andrés, 2015). In some estuaries, over 90% of important species have been depleted to biomass below 50% of historical abundance, where exploitation and habitat loss are substantial drivers of this change (Lotze et al., 2006). These impacts have accelerated in the last 150–300 years (Lotze et al., 2006) and occur at very high rates in some cases (Cloern et al., 2016). For example, across 55 estuaries on the US West Coast, there has been an estimated 85% loss of the vegetated tidal wetlands since European settlement (Brophy et al., 2019). Thus, to chart a course forward for estuary management, information is needed to inform decisions towards balancing these competing, and sometimes conflicting, uses.

In particular, we need to understand how multiple estuary stressors affect species of importance (Nobre, 2011). Many estuaries are

undergoing environmental changes (Figure 1), where each activity in isolation has potential biological consequences, and in combination likely build in their effects. For many years, estuaries were not a common area of research, but this has changed in the last half-century (Elliott & Whitfield, 2011). There is now a substantial body of work on the biological impacts of changing estuaries (e.g. Cloern et al., 2016; Toft, Cordell, Simenstad, & Stamatiou, 2018). To make informed decisions on the management of a variety of estuary types, from those that have been impacted for hundreds to thousands of years, to those that may be closer to 'pristine', there is a need to synthesize the body of knowledge. Specifically, information on the relative risks from different estuary activities could inform ongoing and future environmental decision-making.

One tool used in decision-making is risk assessment, and this relies on determining confidence in how an activity may impact a valued ecosystem component (Holsman et al., 2017; ISO, 2009; NRC, 1983). Uncertainty is a foundational component of risk, as '[r]isk refers to uncertainty about and severity of the consequences (or outcomes) of an activity with respect to something that humans value' (Aven & Renn, 2009, p. 2). For example, this can be interpreted as indicating that low severity with high uncertainty does not necessarily mean low risk as it demonstrates a lack of confidence in the consequence of the activity. One qualitative approach to uncertainty/certainty determination used by the Intergovernmental Panel on Climate Change (IPCC) applies the weight of evidence (Mastrandrea et al., 2010). This method assesses qualitative confidence with two

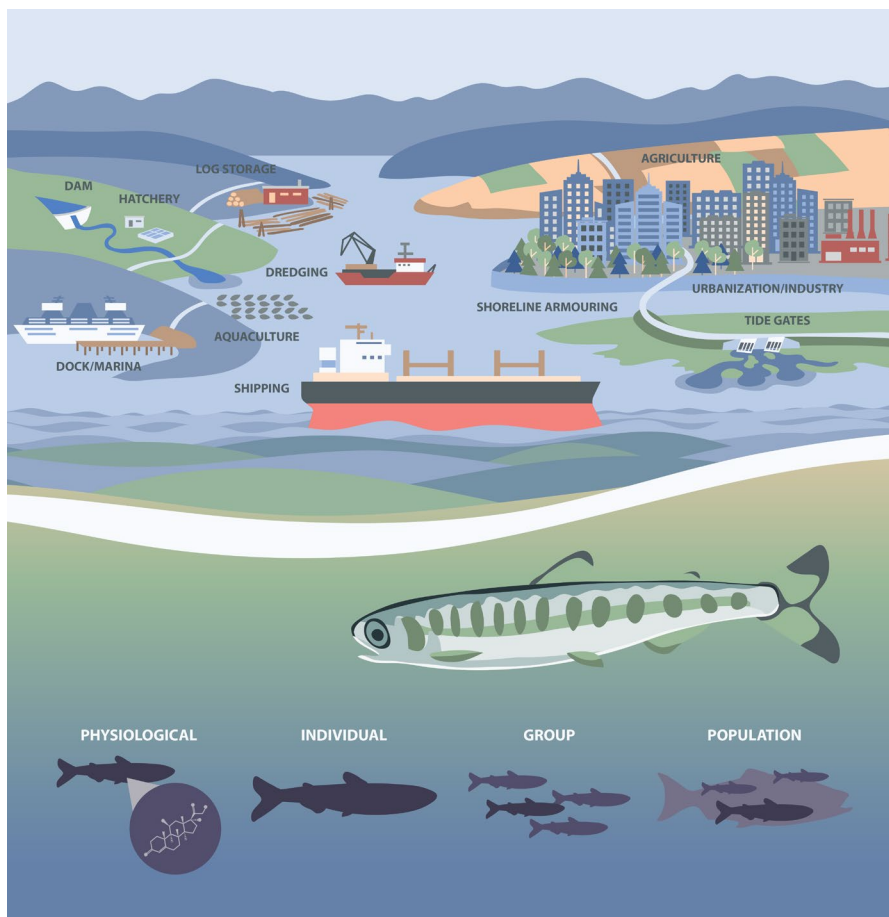


FIGURE 1 Infographic showing multiple activities that occur in estuaries and the biological scales at which impacts are measured for salmon (created by Fuse Consulting)

axes, evidence (amount, quality, consistency) and agreement among the studies (Mastrandrea et al., 2010). Accordingly, activities or circumstances could have high confidence of low severity (potentially low risks), high confidence of high severity (potentially high risks) or low confidence overall (high uncertainty and thus potential risk from the unknown) (Figure S1). A full risk assessment would link this uncertainty and direction of impact assessment with an assessment of the magnitude of impact. Thus, effective synthesis of the state of knowledge of how human activities impact species of interest necessitates quantifying the direction of impacts and the confidence level (Astles et al., 2006; Barnthouse, 1992).

There is an opportunity to determine the state of knowledge regarding estuary impacts on migratory Pacific salmon (*Oncorhynchus* spp.) and Atlantic salmon (*Salmo salar*). Salmon are a highly valued species and more heavily studied than most. Because of their importance to humans (Augerot et al., 2005; Colombi, 2009) and ecosystems (Naiman, Bilby, Schindler, & Helfield, 2002), salmon can be a pivotal, and sometimes controversial, part of decision-making (Moore et al., 2015; Ruckelshaus, Levin, Johnson, & Kareiva, 2002). Salmon use estuaries for growth (Healey, 1982; Thorpe, 1994), as a physiological transition zone to prepare for migration from freshwater to the sea (Quinn, 2018; Taylor, 1922) and are hypothesized to use estuaries as a refuge from predation (Munsch, Cordell, & Toft, 2016; Quinn, 2018; Thorpe, 1994). Researchers have shown that there is a relationship between the size of salmon smolts and their marine survival (Beamish, Mahnken, & Neville, 2004; Duffy & Beauchamp, 2011; Moss et al., 2005); thus, taking advantage of the opportunity for growth in estuaries may be highly important in some cases. While there is substantial variation in estuary use across and within salmon species (Weitkamp, Goulette, Hawkes, O'Malley, & Lipsky, 2014), there is a common recognition that estuaries are, at minimum, an important transition habitat for juvenile salmon (Levings, 2016; Quinn, 2018). Research into the consequences of estuary development on juvenile salmon has documented impacts from individual stressors, for example, log boom storage (Levy, Northcote, & Barr, 1982) and sea wall development (Munsch, Cordell, Toft, & Morgan, 2014; Toft et al., 2007), as well as large-scale habitat loss (Magnusson & Hilborn, 2003). Yet, to date there has been no comprehensive synthesis on how the broad diversity of estuary stressors impacts juvenile salmon.

Here we summarize findings from a systematic literature review conducted to assess how different types of estuary change impact juvenile salmon across species and systems. We asked the questions: what has been studied, where are the major knowledge gaps and how do stressors affect salmon? We present findings in a semiquantitative manner as a full meta-analysis was not possible; we use the common framework from cumulative effects assessment, such that we link development activities to their associated stressors, and resulting biological responses (Foley et al., 2017). To assess confidence in the impacts of particular stressors, and elucidate major uncertainties, we employed the IPCC weight-of-evidence approach (Mastrandrea et al., 2010). This systematic knowledge synthesis reveals how different estuary activities and their associated stressors pose negative

impacts to salmon; such information can inform estuary management processes such as conservation planning and environmental risk assessments.

2 | METHODS

We conducted a systematic review of the effects of anthropogenic activities on juvenile salmon in estuarine and nearshore coastal habitats. We limited the scope of the review using the following criterion: we included only studies of salmon inhabiting estuaries (the zone between the limits of freshwater influence and the tidal extent in a region where a river meets the sea) and coastal areas (within ~1 km of the coast) and excluded studies where the experiment was solely laboratory based. We included all articles on Pacific salmon (*Oncorhynchus* spp.) including sockeye (*O. nerka*), Chinook (*O. tshawytscha*), chum (*O. keta*), coho (*O. kisutch*) and pink (*O. gorbuscha*) salmon, but excluded steelhead trout (*O. mykiss*). We also included Atlantic salmon (*Salmo salar*) but excluded other members of the *Salmo* genus. We explicitly excluded sources examining the effect of habitat restoration and mitigation. While these are both relevant topics for salmon management, they were beyond our scope. However, for mitigation or restoration studies that included positive and negative controls, we included the positive (disturbed sites) and negative controls (natural sites) but not the treatment (restored) groups. We did not exhaustively search the habitat mitigation/restoration literature for these cases.

We conducted the literature search in several stages, first by searching online databases, followed by forward and backward scanning to create a comprehensive list of potential studies from white and grey literature sources. We used five databases: the Canadian Federal Sciences Library, the American National Oceanic and Atmospheric Administration's Central Library, Google Scholar (GS), ISI Web of Science, and the University of Washington ResearchWorks Archives. All searches were conducted prior to 1 September 2018. We used two sets of search terms for searching databases. These terms were chosen based on activities and stressors that had the potential to affect juvenile salmon (Levings, 2016) and those that, in our experience with juvenile salmon research, were relevant to salmon in estuaries. For the federal databases and the University of Washington ResearchWork Archives, because they had fewer articles than academic databases, we used broad terms (*salmon OR salmonid OR salmo OR oncorhynchus*) AND (*estuary OR estuarine OR estuaries OR nearshore OR tidal OR coastal*). For Google Scholar and ISI Web of Science, we used the broad terms followed by specific search terms (Table S1), to narrow the search. We used a scraping software Publish or Perish (<https://harzing.com/resources/publish-or-perish>), to collect the first 500 GS search results for each specific search term plus the broad terms (thus we completed 29 searches), whereas we completed the ISI Web of Science search with broad terms and all specific terms simultaneously. To minimize redundancy, we eliminated duplicate

sources. This initial literature scan identified ~9,000 sources that examined anthropogenic impacts on estuaries and their effects on juvenile salmon.

We used our search criteria, outlined in the first paragraph of the Methods, to identify field studies on impacts of anthropogenic disturbance on salmon in estuaries and nearshore areas. We first excluded or included studies by scanning titles and abstracts of sources to see whether they met our criteria. In several cases, the abstract and title did not provide enough detail, in which case, we read the source. For GS searches, we scored the first 100 studies from each search and stopped once we had rejected 50 successive articles. In this way, we scanned at least 100 articles associated with each GS search term but did not always review all 500. The

main exception for this was for some search terms, after duplicates were removed, there were fewer than 100 sources to search through for GS results.

Once we identified articles of interest from this list, we searched the referenced sources (backward scanning) and articles that had cited the initial study since it was published (forward scanning) to identify more potential articles. In some cases, old government documents were not possible to track online with citation tools. In this case, we did the backwards search, but not the forward search. We iteratively completed forward and backward scanning on articles of interest, until we found minimal additional articles of interest (two rounds of forward and backwards scanning). In several cases, we could not locate articles to match references. Efforts were taken

TABLE 1 Elements recorded from each source retained in the database. Here we provide a definition and example for each metric; for a full list of elements that fall into each of these metrics, see Table S2

Metric	Definition	Example(s)
Study region	The location (estuary, state/province and country) where the study was conducted.	Puget Sound, Washington, USA
Species	Study species, grouped by common groupings used in the studies found.	Chinook/coho; chum/pink; sockeye; Atlantic ^a
Activity	Anthropogenic changes in estuaries that result in potential stressors; these are specific forms of developments.	Log boom storage; mining
Stressor category	The potential biological stressor(s) associated with each activity, retained at broad scale groupings.	Habitat quality; biological interaction; physical habitat alteration
Stressor sub-category	Detailed potential biological stressor(s) related to each activity, each falls within a stressor category.	Temperature; light; sea lice; habitat modification ^b
Response category	Biological response scale at which the study was conducted; these were broken down into four overarching categories.	Physiological; individual; group; population
Response sub-category	Detailed biological response measured, falling into an overarching response category, but tracked at higher resolution.	Abundance (in the category 'group'); survival (in the category 'population')
Effect category	The type of effect that was measured. As not all studies involved clear control and impacted site comparisons, or biological responses that could be assigned a direction, we retained studies that documented different effects.	Direction measured (further broken down into 'positive', 'negative' or 'null'); diet measured; presence of stressor measured (e.g. a contaminant); impact versus impact ^c comparison (i.e. no control, rather impacts of different stressors compared)
Robustness	Whether the statistical analysis was carried out and reported in a robust manner.	Robust = authors use model selection methods (AIC or BIC) or where significance ^d was tested. Non-robust = authors did not perform a statistical test or used very small sample sizes ^e .

^aWe grouped together Chinook and coho salmon, as often studies did not differentiate between these two; they are hard to identify separately. We also grouped across pink and chum salmon because they exhibit similar life histories and enter the ocean at similar times and sizes (Groot & Margolis, 1991).

^bHabitat modification was a stressor which in most cases was linked to developments that would alter habitat, but cases where the authors did not specify a more concrete stressor linked to a particular activity, for example, the development of a pier may be linked to numerous stressors including light, barrier to migration, loss of habitat, however if this link was not made, it was assigned the stressor 'habitat modification'.

^cStudies comparing impact versus impact sites were not sought out, thus there may be other literature on these comparisons not included in our review, but if there were tests like this in the studies, we documented them.

^dWe used a p value of .07, as .05 is an arbitrary cut-off and some reported what we called a 'trend' ($p < .07$) and although not significant at the level $p < .05$, we deemed these robust and directional.

^eThe sample sizes categorized as non-robust were for the most part $n = 2-3$. For pollutant studies, these were non-robust when composites consisted of a small number of individual fish (though most composites were between 10 and 60 individuals). We did categorize composite samples as robust even if the total number of composites compared were small ($n = 2-3$). We discuss this further in the section on Pollutants.

to locate these sources, through contacting the authors or relevant agency (federal, provincial, state or consulting firm) and with the help of federal, state and university librarians. If the source could not be located, then we had to exclude it.

Overall, we scored over ~13,000 studies and identified 167 studies that examined the effect of anthropogenic disturbance on juvenile salmon in estuaries or nearshore areas. We acknowledge that our a priori process of identifying activities or stressors might have missed some activities or stressors; however, given the extensive nature of our search with over 13,000 reports and papers, we expect that many of these would have been captured. As well, as with any review, there are possible biases imbedded in the publication process that could influence our findings, the main concern being a tendency to only publish 'significant' results (Greco, Zangrillo, Biondi-Zoccai, & Landoni, 2013). However, given our focus on both published literature and government reports and our documenting studies finding no impact, we believe biases have been minimized here.

Of the 167 articles identified as relevant, we mined each for details including: (a) study region, (b) species, (c) activity category, (d) stressor category (overarching category, referred to as 'stressor category' throughout) and sub-category (specific stressor studied, referred to as only 'stressor' throughout), (e) biological response category and sub-category (i.e. across biological scales of physiology, individuals, groups and populations), (f) type of effect and (g) robustness (see Table 1 for variable descriptions and examples). With few studies reporting response metrics in a table form and the units measured being highly variable across studies, a meta-analysis was impossible. Instead, we summarized studies semiquantitatively. We present responses based on activities, stressors, response types and the direction of response, reporting the total number of studies by topic (e.g. by activity) or the total number of tests, as some studies conducted multiple tests.

To assess confidence in the direction of biological response (qualitatively), we used the IPCC framework for evaluation of confidence in findings (Mastrandrea et al., 2010). Because we could not calculate the severity of impact from different stressors, we did not assign risk; however, we could identify the confidence in the direction of impact as one step towards risk determination, as risk in this case is made up of severity of consequence when exposed to a stressor and confidence in that finding (Aven & Renn, 2009). To determine our rankings of evidence and agreement (the two components of confidence; Figure S1), we developed a set of criteria. For both axes, we used the number of tests conducted in robust comparisons only (see Table 1 for definition of robust). Evidence rankings were categorized as: low = 1–10 tests on the impacts of a stressor, medium = 11–20 and high = 21+. Agreement was determined based on the proportion of tests showing the dominant directional response. That is, if the ratio of positive to negative tests was <1 , we calculated the proportion of all tests with a negative response, whereas if the ratio was >1 we calculated the proportion of all tests with a positive response. Thus, we determined the amount of agreement among tests showing the dominant directional response. Qualitative categories for

agreement were assigned as: low $\leq 1/3$ proportion of tests in a particular direction, $1/3 < \text{medium} < 2/3$ and high $\geq 2/3$. This approach enabled us to determine our confidence in a *directional* response (Figure S1), not our confidence in whether there was or was not a response. It is important to note, however, that the agreement metric in this case assumes that there are linear responses to stressors. This is likely not the case for some of the stressors we document (e.g. temperature) and as such, we discuss this limitation below. Regardless, this framing is useful in providing a means to categorize different stressors.

3 | RESULTS AND DISCUSSION

Across the 167 sources in our final database and the 2,383 individual tests (Table 2), it is evident that juvenile salmon in estuaries are impacted by diverse pathways of effects (Figures 1 and 2). We identified connections between at least 24 different human activities (e.g. dredging, log boom storage, shipping and shoreline development), to 13 stressors (e.g. temperature, habitat modification and noise) and 11 types of biological responses (i.e. across biological scales of physiology, individuals, groups and populations; Figure 2). A 14th stressor, light, did not make it onto the pathways plot as no studies measured directional impacts of light (only studies comparing different types of impacts with no reference site). Some stressors formed many different pathways of connection between activities and responses. For example, pollution resulted from upwards of eight activities that fed into over 10 biological responses. Overall, these connections are conservative, as the diagram only summarizes links that were tested in the studies collated. There are likely additional pathways leading to consequences for juvenile salmon that have yet to be studied.

While cumulative responses to multiple stressors were not the focus of the articles summarized, this diverse set of connections demonstrates that while each activity was only associated with one or two stressors, there is clear potential for interactions between activities (Clarke Murray, Mach, & Martone, 2014). For example, if multiple activities result in different types of pollutants in the estuary, there is a potential for an accumulation within fish. There are evidently a multitude of pathways linking salmon responses to different activities in estuaries (Figure 2).

3.1 | What has been studied and where are the major knowledge gaps?

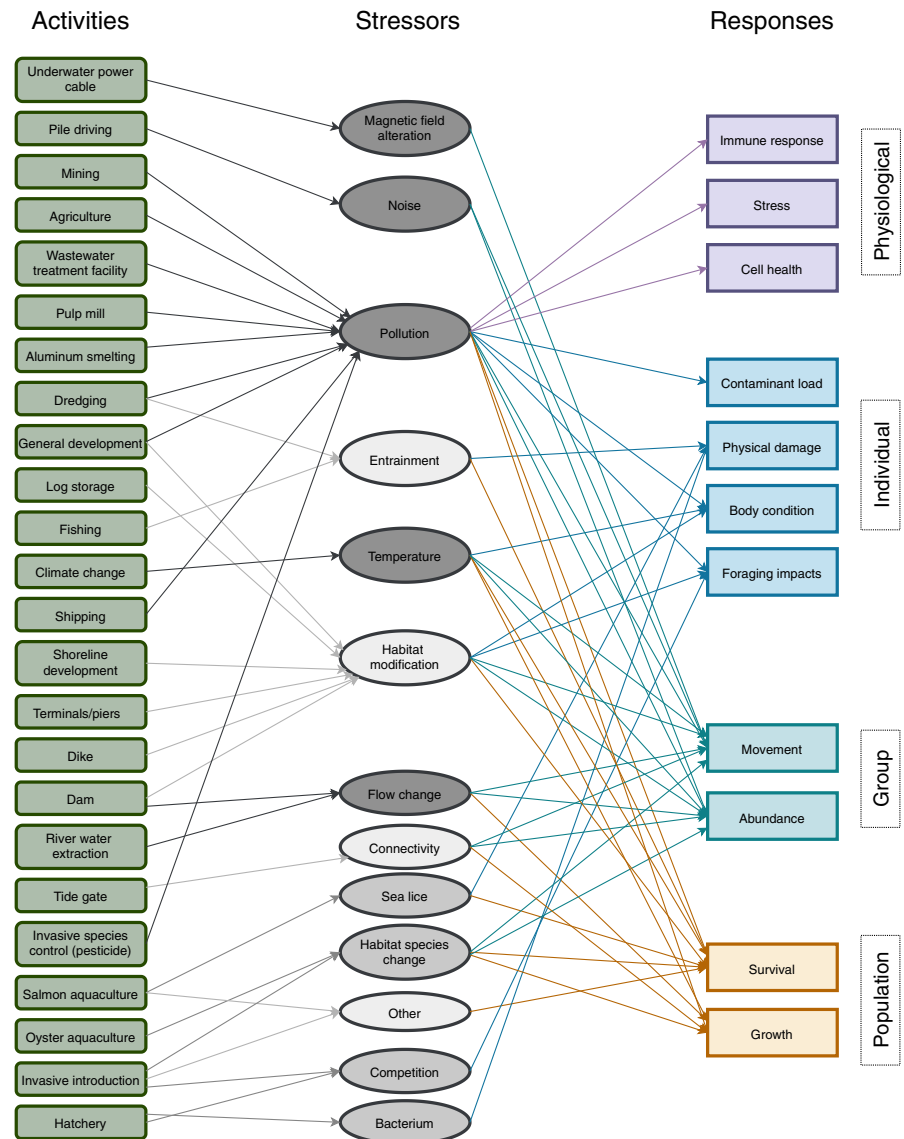
A substantial body of research has investigated the different biological consequences for juvenile salmon from a suite of activities. From the 167 sources in our final database, there were 2,383 individual tests documented, where 1,369 of those tests compared reference to impacted treatments, such that they reported an impact as positive, negative or null for impacts on physiological-, individual-, group- or

TABLE 2 Metrics from literature review on numbers of studies and tests by stressor

Sub stressor	# studies	# tests	# tests				Species (by # tests)				Response scale				Direction (# non-robust in brackets)			
			# tests				ck/co	ch/pk	sk	at	ph	i	g	p	-	/	+	
			- / +	D	P	lvl												
Habitat species change	5	20	16	4	0	0	18	2	0	0	0	8	5	7	2 (3)	8 (2)	1 (0)	
Pollutants	50	1,541	749	234	176	382	1,056	455	1	6	126	1,171	168	76	346 (43)	318 (14)	19 (9)	
Habitat modification	37	321	198	47	0	76	141	115	2	0	0	110	204	7	10 (38)	88 (13)	22 (25)	
Temperature	18	129	125	2	2	0	112	9	1	6	0	82	28	19	38 (3)	53 (3)	27 (1)	
Sea lice	31	191	157	0	9	25	4	137	11	38	1	166	0	24	53 (49)	47 (4)	2 (2)	
Entrainment	7	62	34	0	28	0	18	15	10	1	0	18	0	44	0 (18)	0 (15)	0 (1)	
Flow	7	18	18	0	0	0	17	1	0	0	0	0	16	2	9 (2)	7 (0)	0 (0)	
Bacterium	1	2	2	0	0	0	2	0	0	0	0	2	0	0	2 (0)	0 (0)	0 (0)	
Connectivity	10	57	43	0	1	13	50	7	0	0	0	0	55	2	6 (27)	4 (3)	1 (2)	
Noise	2	10	10	0	0	0	1	9	0	0	0	0	10	0	5 (0)	4 (1)	0 (0)	
Competition	4	15	8	0	7	0	14	0	0	1	0	14	1	0	0 (1)	2 (5)	0 (0)	
Other	4	4	3	1	0	0	1	0	0	3	0	1	0	3	0 (0)	0 (2)	1 (0)	
Light	2	6	0	0	0	6	0	6	0	0	0	0	6	0	0 (0)	0 (0)	0 (0)	
Magnetic field alteration	2	7	6	0	1	0	7	0	0	0	0	0	6	1	2 (0)	3 (0)	1 (0)	

Abbreviations: at, Atlantic; ck/co, chinook and coho; ch/pk, chum and pink; D, diet measured; g, group-level response; i, individual response; lv, impact versus impact (i.e. comparisons between types of impact such as a dock and riprap); P, presence of impact measured; p = population response; ph, physiological response; sk, sockeye; -, negative impact; /, null, +, positive impact; -/+, directional studies.

FIGURE 2 Pathways of effects between activities, stressors and biological responses (biological responses are grouped by scale). Stressors are coloured according to stressor categories: habitat alteration (light grey), habitat quality (dark grey) and species interactions (medium grey). Arrows are only included for connections made by studies in the database that tested for a directional response (positive, negative or null)



population-level responses (Table 2). The rest of the tests documented impacts on diet, presence of the stressor (e.g. contaminants in a tissue) or comparisons between the types of impact (Tables 1 and 2). These tests are included in our summarizing figures (Figures 3 and 4), but not in detailed stressor summaries, as no clear direction of impact was feasible to determine. Across studies, the bulk of the research came from the eastern Pacific (Figure 3; Figure S2) and focused on Chinook, coho, pink and chum salmon (Table 2; Figure 4). Although this body of research has been identified, it also points out substantial gaps in our knowledge on specific species, regions and stressors.

There is a dearth of evidence on sockeye and Atlantic salmon ($n = 7$ and 15 studies, respectively; Figure 3). It is perhaps not surprising that the Chinook/coho and pink/chum salmon groups have received the most attention (Figure 3), as some Chinook and chum salmon populations may use estuaries more than other species (Quinn, 2018; Weitkamp et al., 2014). Yet, even if many sockeye salmon smolts migrate through estuaries rapidly and thus may have less exposure to stressors than other species on average, some populations of sockeye salmon have been found

to reside in estuaries for 7–18 days (Moore et al., 2016), or even up to months (Simmons, Quinn, Seeb, Schindler, & Hilborn, 2013), meaning that in some regions they might be more susceptible to changes in habitat quality or quantity. As sockeye salmon are an incredibly important fishery resource, the lack of research into sockeye salmon smolt responses to changes in estuaries and near-shore coastal areas means very low confidence in any estimates of potential impact, and therefore potentially high risk. By summarizing information for species of a particular importance, like sockeye salmon, this synthesis highlights potential key gaps to prioritize for decision-making.

There are clear geographical foci and corresponding geographical gaps in the body of research on stressors and salmon in estuaries. Regions beyond a restricted area in the eastern Pacific have had very minimal research (Figure 3). Only 16 studies documented findings from Europe, Japan and eastern North America, where 152 were conducted in western North America. Even along the Canadian–US coastline, most of the research was conducted within eight degrees of latitude between southern Oregon and the northern tip of

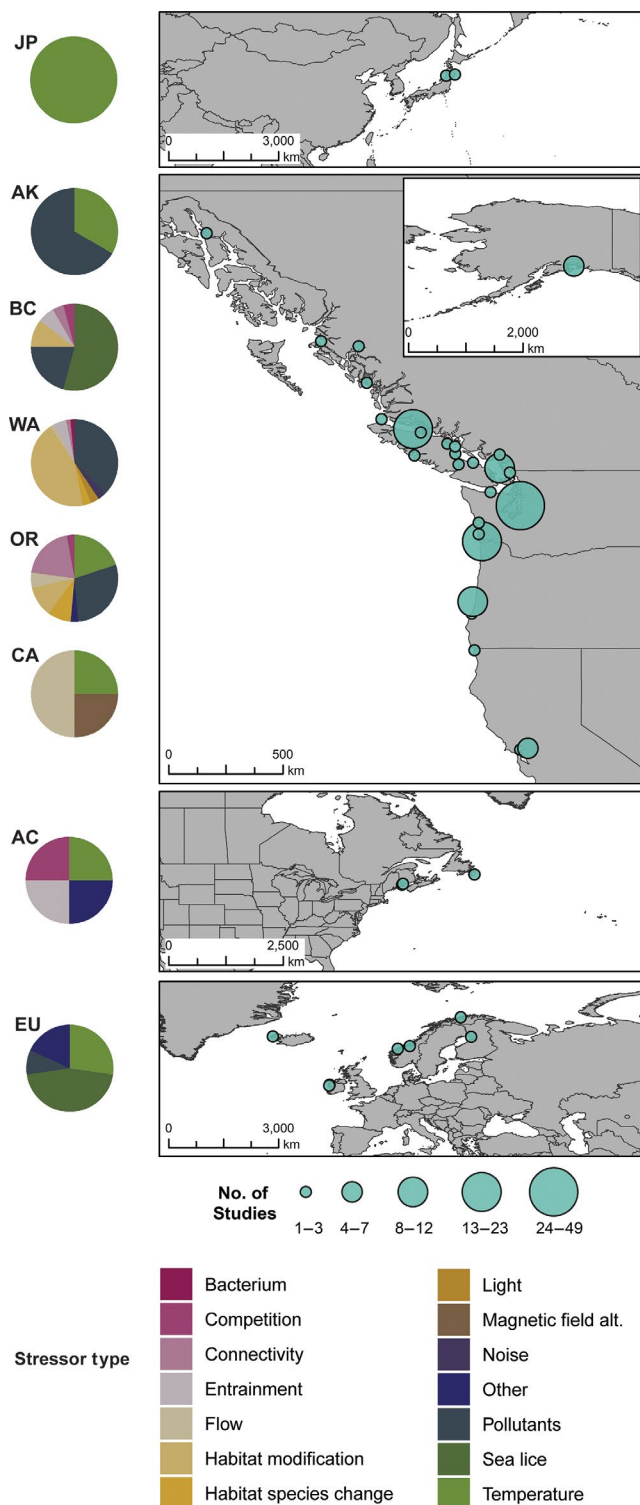


FIGURE 3 Studies by region, showing relative numbers across the Atlantic and Pacific oceans, broken down into proportions focused on the 14 stressors

Vancouver Island, B.C. ($n = 135$ between 43° and 51°N). Some of these geographical differences may be due to our focus on English-language studies, in particular the lack of studies from Russia and Japan. While some information could have been missed from other

languages, we were thorough within the English-language research. Regional differences in the activities studied are also evident, for example, while the stressor *pollution* tended to be a focus across multiple regions, the type of pollutants focused on were specific to the geographical region of study. For example, all pollutants research in Alaska was focused solely on the impacts of oil spills. This limits our region-specific understanding of how other pollutants or stressors may impact Alaskan salmon, as these populations may vary in their population-specific sensitivities to particular stressors compared to populations in other areas or the contaminants may behave differently in different environmental conditions (e.g. temperatures). As a result, this limited focus on particular stressors within individual regions can contribute to uncertainty when applying findings across systems.

Studies of different stressors tended to focus on particular biological response type(s), which raises challenges for scaling information up to a population-level understanding. Overall, the bulk of the research focused on biological responses at the individual (66%) or group level (21%; Table 2; Figure 4). For example, research into the consequences of both physical habitat alteration and species interactions each presented a substantial focus on a single primary response sub-category (e.g. abundance), providing a strong suite of evidence for the respective sub-categories, but limited studies at other biological scales. Physical habitat alteration studies often measured changes in abundance (group level; $n = 33$ of 69), where species interactions focused on physical damage (individual level; $n = 23$ of 49). Physical damage in the latter case was driven by work on sea lice, which has documented increased numbers of lice on individuals closer to salmon farms (e.g. Price, Morton, & Reynolds, 2010), where the attachment of lice on salmon causes damage. For each of these two stressor categories, there was almost no research at the physiological level and limited work on population metrics. Changes in habitat quality (encompassing stressors like temperature, pollution and light), in contrast, were the most spread out across response scales with the bulk of the work focused on individual contaminant loads (individual level; $n = 30$ of 109) followed by abundance (group level; $n = 21$) and survival (population level; $n = 19$). The scale at which each investigation was conducted was likely a result of the feasibility of measuring particular types of stressor–response pairs, as within each stressor category the research was largely driven by one or two specific stressors (Figure S3).

Identifying substantial knowledge gaps helps highlight areas for future research but also illuminates key uncertainties in decision-making processes. As a component of any risk determination accounts for confidence in findings, areas where there has been minimal research leads to the potential for high risk. This highlights that risk can result from both our known knowns and known unknowns (stressors where there is not sufficient evidence to either support or rule out an impact). Here, such stressors include, for example, entrainment and light which had no robust studies (Table 2), where more of these stressors are discussed in the following sections. There are also substantial knowledge gaps with regard to different salmon

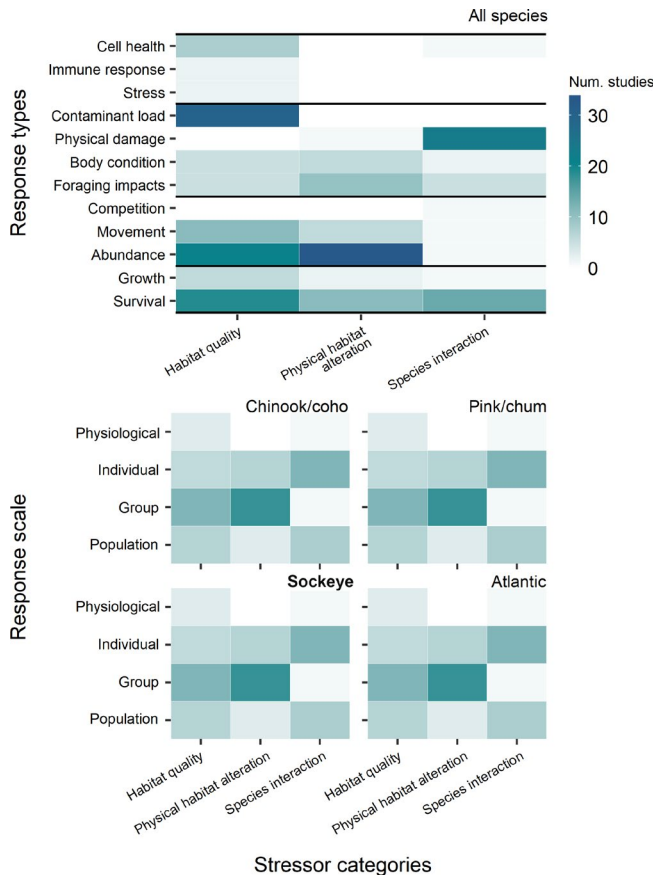


FIGURE 4 Number of studies broken down by response scale (and type in top panel) according to each stressor category, for all species (top) and broken down into Chinook/coho, Pink/chum, Sockeye and Atlantic in bottom four panels

species. With complex life histories, it is quite likely that species-, population- and individual-level characteristics may render salmon more or less sensitive to estuary stressors. For example, there is a lack of information on how juveniles of some of the most important salmon species will respond to estuary change: Atlantic and sockeye salmon (Figure 4). These gaps contribute to assessment of potential risks to different salmon species from future activities, as lower confidence in findings contributes to risk (Aven & Renn, 2009). As we move forward, there is a need to integrate understanding of salmon biology with exposure to stressors to provide a more comprehensive picture of risk.

3.2 | How do stressors affect salmon?

We found that there was a range in the amount of evidence and agreement in the direction of response across the different stressors, revealing diverse levels in confidence (Figure 5; Figure S1). Where most stressors had medium or medium-low agreement in the direction of impact, there was a fairly even spread across the evidence axis, with approximately a third of the stressors having

low, medium and high evidence (Figure 5). This latter result highlights differences in the extent to which individual stressors have been a research focus. As the qualitative categorization of confidence is a product of both the amount of evidence and the agreement in the direction of impact (Figure S1), stressors ranged from low up to moderate-high confidence in direction of impacts, with no stressor being characterized as having a high level of confidence (Figure 5).

This approach allowed us to report on the weight of evidence of directional responses, but it is a simplifying construct and warrants caution. For example, it is possible that some stressors such as temperature may have non-linear impacts on salmon, which could lead to medium or low levels of agreement. Furthermore, there were a fair number of tests showing a null response which could be driven by different processes. It is possible that null responses represent cases where salmon are robust to some activities. Alternatively, null responses could be the result of a lack of statistical power, which would be a particular challenge for studies trying to detect biological signals in dynamic estuary ecosystems. Thus, we suggest exercising caution in interpreting null results as having no impact and recommend that those interested in particular activities or stressors should investigate the detailed circumstances and characteristics of the studies with null results.

We now discuss example stressors to elucidate trends from each of the three zones: moderate-high and moderate confidence, low-moderate confidence and low confidence.

3.2.1 | Moderate to moderate-high confidence

Four stressors were found to have moderate or moderate-high confidence (Figure 5; Figure S1): sea lice, pollutants, connectivity and flow. Stressors with negative trends for which we had the highest confidence included sea lice and pollutants (both with high evidence and medium agreement), where connectivity and flow showed moderate confidence (medium evidence and medium agreement). In the case of the first two, there were a very small number of positive results ($n = 2$ of 201 (2.0%) and $n = 19$ of 518 (3.3%), respectively), providing evidence that these stressors generally have overall negative impacts when there is a directional response. In the cases of connectivity and flow, both showed moderate confidence that these stressors cause negative impacts; where connectivity had one test showing a positive response (of 11 total) and flow had none. Flow consistently showed negative responses, where studies found that with decreased flows (from dams and water extractions), there were measures of lower survival, lower abundance and longer transit times through the estuaries. We explore pollutants and connectivity in detail to provide examples of studies for which we have more research but also different limiting factors.

Pollutants

Driven by studies ranging from the impacts of mining and aluminium smelting, to shipping, dredging and general development, pollutants

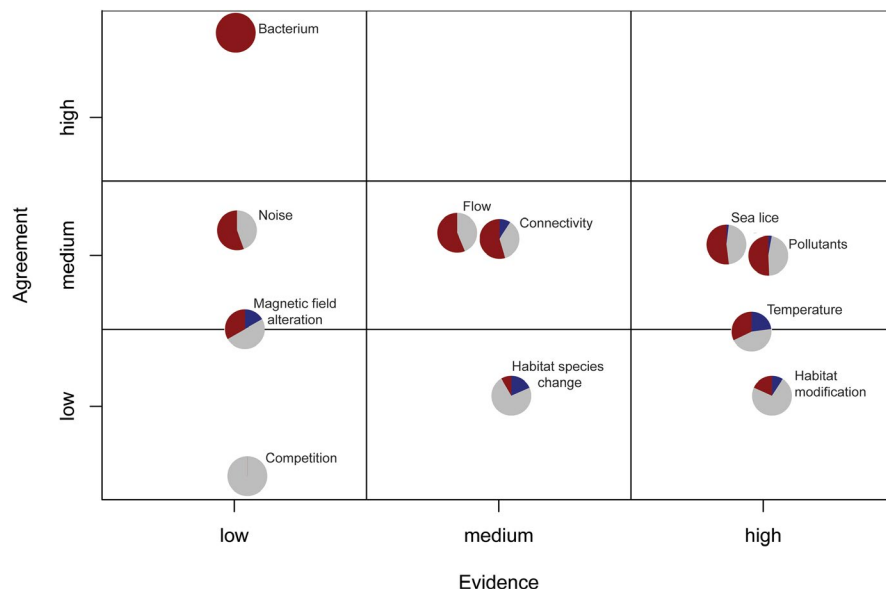


FIGURE 5 Confidence plot showing agreement and evidence for 12 stressors with robust studies, where level of confidence ranges between low to high based on IPCC methodology (Figure S1). Each stressor is represented by a pie chart with the proportion of tests showing positive (blue/dark grey), negative (red/medium grey) or null (light grey) results. Placement along the Agreement axis is in line with percent agreement; placement along the Evidence axis was binned into low, medium or high and subsequently jittered to avoid overlap of pie charts. Both stressors light and entrainment are not shown here, as there were no robust studies for either of these stressors

in estuaries have received considerable focus. Accordingly, pollutants are stressors that cause a wide variety of impacts on salmon; they both result from many activities (nine) and result in many types of biological response (ten; Figure 2). Studies on pollutants found negative responses in approximately half of all cases (50.7% of tests), compared to only 2.8% of tests showing a positive response. These positive responses resulted when fish from a reference estuary with less anthropogenic change than an impacted estuary had higher contaminant levels (O'Neill et al., 2015) or in some studies in Alaska comparing oiled to non-oiled sites, for example, higher weight and longer fork length fish found in oiled sites (Sturdevant, 1996). However, there were few cases like this. Within pollutant research, one of the clear advantages is the incredible diversity in the types of pollutants that have been investigated including PAHs, PCBs and metals (Appendix Table S3), and across geographical regions and biological scales of organization. However, one disadvantage is that many pollutant studies, in particular those comparing between impacted and non-impacted estuaries, did use a small number of composite samples for their analyses ($n = 2-3$ in some cases). Though individual composites included anywhere from 10 to 60 fish, the small number of true replicates does diminish the strength of these findings. For more robust work into the future, authors would do well to ensure a higher number of composite samples.

When a directional response was found, pollutants caused consistently negative impacts across biological scales: physiological to population (Figure S4). At the individual level, these findings linked higher contaminant loads in fish or their tissues in contaminated sites as compared to either control estuaries or hatchery fish prior to estuary entrance (e.g. Johnson et al., 2007; Stein, Hom, Collier, Brown, & Varanasi, 1995; Varanasi et al., 1993). Although for some of these studies it was not always clear whether the point source of pollution was in the estuary or in upstream waters, the overall trend showed that fish in contaminated waters tended to have higher in-tissue contaminant concentrations than those from less contaminated systems. In some cases, these were linked to

thresholds known to cause adverse effects on growth or survival (Johnson et al., 2013) but these links were often not made. Future work would benefit from consistently identifying when thresholds are crossed, where these thresholds have been identified. While some studies found no difference at the individual level, this is likely due to the diversity of pollutant types (sometimes over 100) that were tested within each study. These data suggest that different pollutants accumulate to varying degrees in juvenile salmon tissues, something common across fishes (van der Oost, Beyer, & Vermeulen, 2003).

At the population level, a scale often more easily translated into natural resource management, there was stronger support for negative ($n = 7$ tests) than positive ($n = 4$ tests) impacts of pollutants on juvenile salmon. Again, one of those mixed cases came from a single paper that found lower adult returns for Chinook salmon smolts that had migrated through contaminated estuaries, but somewhat higher returns for coho salmon smolts (Meador, 2013). The coho salmon results were not significant for most statistical comparisons, and the one significant result for coho salmon was driven predominantly by one outlier hatchery. This study highlights the nuance within a single stressor, of the multiple factors that interact and result in particular findings. Furthermore, the contaminated estuaries also had a multitude of other co-occurring stressors and activities, suggesting caution in inferring causality. Nevertheless, across studies, there is strong evidence that within more developed estuaries, juvenile salmon have higher contaminant loads with potential population-level impacts (e.g. lower survival).

Connectivity

Connectivity is a stressor linked to a single activity (tide gates) that was found to have moderate confidence. This confidence ranking was largely driven by agreement among studies, which is comparatively higher than other stressors; however, the amount of evidence was limited, in part because a bulk of the research (74.4% of tests) were categorized as non-robust. Tide gates are generally used for water

management within estuary environments, such as flood protection of lands behind dikes. However, tide gates isolate parts of estuaries from each other, potentially making some habitats inaccessible to salmon. Within a total of nine studies investigating connectivity and reporting control versus impact type experiments, we found the vast majority of tests were non-robust (33 of 57). There were, however, primarily negative responses within the robust tests that measured a directional response ($n = 6$ of 11), where studies suggest that there are negative effects resulting in fewer salmon upstream of tide gates than downstream or in reference streams. Scott (2014) reported on a robust paired design, while controlling for other land use changes and found 2.5 times greater juvenile salmon abundance in reference sites compared to sites with tide gates. However, there were few studies that examined metrics other than abundance. The scarcity of similar tide gates and limited availability of reference streams to pair for comparisons make the impacts of tide gates challenging to quantify, yet from what is available they have negative effects. Broadly, connectivity is a good example metric showing that when a large proportion of research has been conducted in a non-robust manner, such as using low sample sizes, it introduces uncertainty and lack of ability to identify a clear direction of response.

3.2.2 | Low-moderate confidence

Three stressors fell into the low-moderate confidence ranking: temperature, habitat modification and bacterium, though for different reasons. Both temperature and habitat modification have been heavily studied with many tests (125 and 198 directional tests, respectively), whereas bacterium had only two tests. Because of the limited studies on bacterium, with full agreement among two tests, overall findings were low-moderate support but from a very limited suite of evidence. In comparison, while there was a large amount of evidence, the lower agreement among temperature and habitat modification findings resulted in both cases having mixed results among positive, negative and null outcomes, where temperature was slightly more dominant in the negative finding (32.2% negative, 22.4% positive) and directional responses for habitat modification were more frequently 'positive' (18.3% positive, 8.3% negative). We explore the mixed results for habitat modification and temperature below.

Habitat modification

Habitat modification was linked to many different activities in our database with quite variable results regarding the direction of impact across activities and biological scales; however, the interpretation of many of these findings poses challenges. Habitat modification had a fairly high proportion of studies finding positive directional responses at 18.3% of tests (8.3% negative) and a high percentage of null results (73.3%). This stressor included a diversity of study types: those when the stressor was clear but also when it was not explicitly stated. For example, some of the studies measured definitive habitat loss, such as building of dikes,

but other studies were less definitive, and habitat modification was inferred (such as building a ferry terminal or shoreline armouring). Importantly, it was uncertain whether a 'positive' impact of habitat modification on abundance was associated with benefit or harm to salmon. Almost all positive responses were driven by shoreline development (armouring and riprap) and terminals/piers (Figure S5) at the group scale ($n = 19$ positive tests, 4 negative and 58 null) with increasing abundances often exhibited in impacted habitats. Previous studies have found that salmon may avoid going under or around such structures, which can result in barriers to movement and fish aggregating in adjacent areas leading to observations of high numbers of fish (Munsch et al., 2014; Toft et al., 2007). Moreover, when salmon do go under structures such as piers, they rarely feed, such that aggregating in these areas potentially results in extended periods in suboptimal habitats with possible exposure to increased predation (Munsch et al., 2014; Toft et al., 2007). In contrast, neither general development nor log storage resulted in any positive responses, with some negative tests, and a substantial number of tests with a null response (Figure S5). Thus, studies that use abundance as a response variable should take care to consider what processes are contributing to the pattern.

There were somewhat clearer trends in negative impacts of habitat modification at the individual response level; however, these were still not substantial and suggest responses are context-dependent. Studies at the individual level showed $n = 4$ negative tests but $n = 3$ positive with $n = 26$ null. These individual response studies were entirely focused on impacts on foraging or body condition (Figure S3) where comparisons between sites with null findings showed no consistent trend in foraging success between impacted and non-impacted sites. Many responses where null interactions have been found to occur may not clearly represent the potential impacts if the study does not compare sites with increasing levels of impact or across a range of conditions (i.e. hidden thresholds of impact). For example, David et al. (2016) found that only once over half of former wetlands were lost was a signal of density-dependent competition for food resources observed. There is a need for continued rigorous research on how different types of habitat modifications impact salmon across levels of biological organization and contexts.

Temperature

Temperature is a stressor that can have connections to both global and local processes with resulting consequences across a number of biological scales (Figure 2). Although some industrial developments do discharge water with elevated temperatures (e.g. water cooling systems in liquified natural gas terminals), most studies provided no clear indication of the activity that would be associated with that stressor. Thus, we use these as a suite of papers indicating the consequences from rising temperatures with climate change. The biological responses to increasing temperatures that were measured included body condition, movement, survival and growth, thus covering individual through to population metrics. However, the non-linear relationship between temperature and salmon performance (Brett, 1967, 1971) posed challenges to the certainty metric, in particular along

the agreement axis. For example, across studies and tests, to ensure consistency, we assigned a directional response to temperature that coincided with whether there was a negative relationship with increasing temperature. However, salmon performance is optimized at intermediate temperatures (Brett, 1971); thus, increasing temperatures in locations with cold temperatures could benefit salmon, while an increase in temperature in locations with pre-existing warm temperatures would harm salmon. To address this, we completed a post-hoc review of the temperature studies. In this analysis, we allowed for the non-linear relationship by assigning a negative impact to temperature changes when they moved from within the optimal range (defined as 11–17°C), to outside of it, in either the increasing or decreasing direction. Using this, the agreement in the temperature metric exhibited a small shift as did the overall trend towards more negative results from changes in temperature (Figure S6). Thus, for the most part studies found negative consequences from temperatures shifting outside of the optimal range.

3.2.3 | Low confidence

Four stressors were found to have low or very low confidence (noise, magnetic field alteration, habitat species change and competition) (Figure 5) with an additional three not even on the plot because of a lack of robust, directional studies (for light and entrainment) and because agreement would not be expected with mixed stressors (for the stressor other). These highlight stressors for which we have a limited amount of information, yet also opportunities for further research. Moreover, they highlight issues with studies that are non-robust in their design. Approximately a fifth (21.0%) of the directional tests we documented were categorized as non-robust (with an additional 42.5% of tests overall not even testing a directional response from an impacted to reference site). While in some cases non-robust investigations were pilot studies, and may have been connected to fuller investigations later, there remain important gaps in our understanding of particular stressors because of the research approaches that were used. For example, although the activity of dredging is linked to pollution, and pollution is well studied, of the eight sources specifically focused on dredging (a common activity), only one documented a robust test (Smith, Prinslow, Salo, Campbell, & Snyder, 1979). This creates a considerable challenge when documenting the consequences of particular stressors or activities, as non-robust tests are not readily usable for making concrete recommendations. Here we explore further the stressors noise and light, as examples of stressors for which there is limited work but a fair amount of agreement among findings (in the case of noise) and stressors that are not easily studied in isolation of other stressors (light).

Noise

Only one study was found that tested the impacts of noise, pile driving specifically, on juvenile salmon in a robust manner (Feist et al., 1992). In this case, the authors looked at behavioural responses of

both movement and abundance of pink and chum salmon across a few sites in Puget Sound, Washington, USA. They found that in most cases there were fewer fish in the area of pile driving, observed as either a decrease in the total number of fish or a smaller size of schools on days when pile driving occurred. In addition, they did not find a substantial change in the rate of movement of fish nor in fish vertical distributions. Overall, the limited evidence suggests that juvenile salmon tend to avoid substantial noise, but opportunity to expand on this information is extensive.

Light

Light poses an interesting stressor in that there were no studies that only studied the direct impacts of light. Of the two studies that discussed the consequences from light (Bax, Salo, Snyder, Simenstad, & Kinney, 1980; Prinslow et al., 1980), both acknowledged that it could not be separated out from the development of a wharf. For example, Prinslow et al. (1980) found no difference in the catch per unit effort of salmon around the lit compared to unlit wharf, suggesting salmon did not avoid the lit wharf, but it is not possible to separate this out from the influence of the presence of the wharf. Teasing out the influences of one versus another stressor is important for management decisions but challenged by the reality of a world of co-occurring stressors.

4 | TOWARDS INFORMING ESTUARY MANAGEMENT FOR SALMON

Our synthesis of the state of knowledge of estuary activities and salmon has three key implications for the management of these complex socio-ecological systems. First, there is a need for more robust science on how estuary activities and stressors impact salmon. While some activities and stressors had strong bodies of research, there were limited or no robust studies for other common stressors. These knowledge gaps are surprising given the cultural importance of salmon, the extensive development of estuaries and the frequent requirement of monitoring in project approval or regulatory processes (Noble & Birk, 2011). From these monitoring programmes, there are likely highly useful data that are often not disclosed to the public (Hodgson, Halpern, & Essington, 2019). We employed a rigorous methodology to obtain peer-reviewed studies as well as 'grey' literature, yet unpublished reports and reports not made publicly available by consultants were not included in the study. In some circumstances report titles from consulting agencies were in the lists of results from search engines, but there was no publicly available PDF and when we contacted organizations reports were still not shared. Moving forward, there is an urgent need for consistent, ongoing and publicly reported monitoring that allows for large scale, statistically robust analyses that contribute to the study of ongoing estuary development.

Second, with the diversity of ongoing changes in estuaries, there is a clear need to both study the cumulative impacts of multiple pathways of impact on salmon and ensure study endpoints

are useful to managers. We found evidence that 24 activities and their 14 stressors impact juvenile salmon in estuaries. While studies of single factors are an important first step, we need to move beyond this limited scope to investigate cumulative and carryover effects; this is a growing area of research (Hodgson et al., 2019) and a topic of considerable management and decision-making interest (e.g. Impact Assessment Act, 2019). With a complex life cycle, salmon will potentially experience stressors at multiple life stages (Healey, 2011), and impacts on juveniles could potentially carry-over to increased vulnerability at later stages. For example, impacts of salmon farming on ocean survival of wild sockeye salmon were magnified (synergistic) in years when juveniles also were at sea during years of high pink salmon abundance (Connors et al., 2012). Integration of cumulative effects from human activities and development scenarios into holistic considerations of salmon in estuaries is a challenging but important next step for informing decision-making processes. Furthermore, it has been noted previously that impact assessments in the literature are often carried out without careful design of study endpoints, such that they are not designed to fit into decision-making (Kienast, Wildi, & Brzeziecki, 1998). Future studies would benefit from careful endpoint design, to ensure results are tangible and clearly link into pathways of effects frameworks (Mach, Martone, & Chan, 2015), or direct metrics for management such as threshold determination.

Third, estuary activities pose both known risks and risks of the unknown to salmon. The body of scientific evidence found in our review illustrates that there are some stressors, such as pollution, where there is strong evidence that they pose negative impacts to salmon. Other stressors had little evidence and/or agreement, indicating that they pose risks due to low confidence. Given the role that confidence plays in determination of risk, there is no stressor for which it can be asserted with high confidence that there is no risk to salmon. Environmental impact assessments, including those that underpin regulatory processes, consistently assert that proposed projects do not cross the significance threshold (where 'significance' rather than 'risk' is the critical term in many impact assessments; Singh et al., 2018; Murray et al., 2018) and, in fact, Murray et al. (2018) found that in some cases model uncertainty was used as a justification for finding non-significance. This is contradictory to the consideration that uncertainty contributes to levels of threat (Aven & Renn, 2009).

There is a need to align scientific evidence with the environmental laws and policies that regulate development of salmon estuaries (Moore et al., 2018). Specifically, our study, which represents the most comprehensive synthesis to date, indicates that the continued development of estuaries poses risks to salmon which is a factor to consider in decision-making processes. In the last three decades, populations of many species of salmon have plummeted leading many species to be listed as at risk (Gustafson et al., 2007; Huntington, Nehlsen, & Bowers, 1996). Estuary habitats have been decimated by human activities, such as the 85% loss of vegetated tidal wetlands along the US west coast (Brophy et al., 2019). Given that major estuaries are also often major ports

and heavily developed, many of the populations of greatest concern are those that pass through highly anthropogenically affected coastal environments. Importantly, without a more robust body of scientific research and its effective incorporation into environmental decision-making, trying to achieve dual objectives of estuary development and estuary function for salmon will continue to pose risks to these important and often-imperiled species (Gustafson et al., 2007).

ACKNOWLEDGEMENTS

We are grateful to the graduate students and research technicians that contributed to developing the database of studies: Michael Arbeider, Kirsten Bradford, Ciara Sharpe and Jordan Stewart. We also appreciate the work of Kate Broadley from Fuse Consulting, who designed the infographic in Figure 1. We appreciate insights shared by Colin Levings, the Marine Plan Partnership, the Environmental Stewardship Initiative and biologists at the Province of British Columbia, most notably Rebecca Martone. Thank you to the anonymous reviewer and editor. Funding support for Emma Hodgson came from the Liber Ero Postdoctoral Research Fellowship and for Samantha Wilson from Vanier Canadian Graduate Scholarship, American Fisheries Society: Michael Stevenson Scholarship and American Fisheries Society: Steven Berkeley Marine Conservation Fellowship. Jonathan Moore is supported by the Liber Ero Research Chair in Coastal Science and Management.

CONFLICT OF INTEREST

The authors have no conflict of interest related to this research.

DATA AVAILABILITY STATEMENT

A pared down version of the database, including all papers included in the review will be published with the manuscript. Please email the authors for access to the full database including all details from sources.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

How to cite this article: Hodgson EE, Wilson SM, Moore JW. Changing estuaries and impacts on juvenile salmon: A systematic review. *Glob Change Biol*. 2020;00:1–16. <https://doi.org/10.1111/gcb.14997>