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Review

Emerging trends in science and news of climate change threats to and adaptation of aquaculture

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ABSTRACT

Food production is one of the main contributors to climate change, but is also vulnerable to the resulting stressors, which is well documented for agriculture and fisheries. Attention is now turning to the rapidly growing aquaculture sector and its vulnerability to a changing climate. Here we explore the extent to which climate stressors and aquaculture, and concomitant adaptation strategies, are studied in science and addressed in public media (news) to assess focus and attribution of climate change. We reviewed 553 scientific publications and 228 news media articles on climate stressors, impacts, and adaptation approaches with respect to aquaculture. Results indicate that coverage in the scientific community of climate stressors on aquaculture have not kept pace with growth of production in the sector, especially compared to agriculture and fisheries. Temperature, sea level rise, and ocean acidification were most often the focus in science (44%) and news (42%), suggesting some alignment. Combined coverage tended to revolve around Asia, Europe, and North/Central America (70%) and at least 10 countries' science and news linked current impacts on aquaculture to climate change. The majority of scientific articles addressing adaptation were regional rather than global, and emphasized governance and institutional strategies over technological solutions. In all, this research highlights the comparatively nascent focus of climate change implications for aquaculture, narrow emphasis of stressors, but fairly representative coverage of regions with more aquaculture. Our work highlights the need for more research and public awareness of the social and ecological climate change threats and impacts on, and adaptive strategies for aquaculture.

1. Introduction

The threat of climate change due to anthropogenic greenhouse gas emissions to the global food system is well recognized and a major concern for food security, sustainability, and resilience of the systems on which humans rely (Blanchard et al., 2017; Thiault et al., 2019). However, the level of knowledge and risks vary among systems, locations, and time. In agriculture, there is evidence of crops already being impacted due to warming temperatures and shifts in precipitation (Ray et al., 2019), with yields predicted to decline, particularly for nations in lower latitudes (Myers et al., 2014; Rosenzweig et al., 2014; Thiault et al., 2019). In wild fisheries, reduction in productivity (Free et al., 2019b) and distributional shifts of some stocks (Pinsky et al., 2020) have been reported and are expected to continue in the absence of fisheries management and climate change mitigation (Free et al., 2019a; Gaines et al., 2018). Small island and developing nations in the tropics are anticipated to be particularly hard hit (Blanchard et al., 2017; Blasiak et al., 2017; Cinner et al., 2018; Thiault et al., 2019). Yet, with aquaculture (i.e., aquatic farming), the current versus future threats are comparatively less resolved (FAO, 2018; Froehlich et al., 2018), leaving a critical gap in knowledge and awareness given its continued increasing importance in the seafood sector (FAO, 2020a).

Like any food system, aquaculture will be affected by climate change, effects that will differ depending on the taxa being cultivated (e.g.,

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finfish, shellfish, seaweed), the farming environment (freshwater, brackish, marine), practices (e.g., open vs. closed systems), and country of origin (FAO, 2018; Reid et al., 2019). In general, average warming conditions could increase growth for some species, which, if food is not limited, could result in greater productivity (Klinger et al., 2017). However, temperature extremes, not average conditions, can challenge such positive growth due to thermal stress (Reid et al., 2015). In addition, many stressors co-occur, likely making conditions more challenging (Froehlich et al., 2016; Reid et al., 2015). Species cultivated in different aquatic environments have to contend with an array of other anthropogenic climate-change related stressors, including ocean acidification, harmful algal blooms, hypoxia, sea level rise, as well as changes to average rates of precipitation (FAO, 2018; Handisyde et al., 2017). In addition, threats of disease and invasive species (e.g., invasive tunicates; Goldstien et al., 2010), induced by direct climate change effects, also impact aquaculture (FAO, 2018; Handisyde et al., 2017; Reid et al., 2015). Disease outbreaks are presently one of the largest threats to aquaculture (Lafferty et al., 2015; Stentiford et al., 2017) and are likely to be exacerbated by climate change, but by how much and when remains challenging to predict (Lafferty and Holt, 2003; Reid et al., 2019). While all of these aspects can impact aquaculture, the relative importance and occurrence of stressors to specific regions is still being uncovered.

Scientific and public awareness of the potential climate change threats appear to be increasing, but we lack a more comprehensive understanding of which stressors are already being linked to climate change and aquaculture. The extent to which the news covers climate change impacts on, or threats to, aquaculture – and whether that coverage matches scientific results – has important implications for how society recognizes the issue and the attention necessary to address the problem, particularly from a governance perspective (Bolsen and Shapiro, 2018). Indeed, news is the primary mechanism by which information on climate change is conveyed to larger, public audiences (Bolsen and Shapiro, 2018), and climate change in the media is divisive, especially on social media platforms (Williams et al., 2015).

Several papers have reviewed global and regional climate change risks to different forms of aquaculture—generally through the lens of qualitative or risk-assessment frameworks (Callaway et al., 2012; Collins et al., 2020; De Silva and Soto, 2009; FAO, 2018; Hall, 2015; Handisyde et al., 2006; Islam et al., 2019; Reid et al., 2019; Stewart-Sinclair et al., 2020). Of note, Asia has been identified as a region of very high risk because of the skewed nature of production (ca. 90% of all aquaculture) (FAO, 2020a; 2018; Handisyde et al., 2017), i.e. the region has much more to potentially lose. More quantitative approaches have been constrained to calculating the broader *potential* stressors on production due to lack of finer spatial understanding of aquaculture distribution (Falconer et al., 2019; Froehlich et al., 2018; Handisyde et al., 2017; Klinger et al., 2017) – which generally align (directionally) with the more qualitative reports – and meta-analyses, based mainly on limited experimental data for species (Catalán et al., 2019). While these approaches provide significant advancement in our understanding of anticipated climate change consequences for aquaculture, the current stressors and research therein has not been synthesized.

Adaptation is also a key consideration when it comes to climate change and aquaculture (Galappaththi et al., 2020; Reid et al., 2019). How individuals and regions are responding provides critical information on the gaps in and need for resilience planning across the sector. In particular, preparedness of governments to aid in mitigating and reducing risk rests on understanding climate change related stressors at local and national scales (FAO, 2018), and arguably global scales as well due to the level of trade associated with the seafood market (Gephart and Pace, 2015). It is essential for scientists and policy makers to identify current and overlooked threats, aquaculture's adaptive capacity, and overall vulnerability to future challenges for both existing aquaculture and future development to be sustainable.

Here we provide a comparative snapshot of scientific literature and news addressing aquaculture and climate change. We explore the current evidence and reports of climate stressors around the globe, highlighting the variability and discrepancies of the studies (e.g., region vs global) and news coverage. We specifically report on the major stressors and evidence of aquaculture already feeling the impacts of climate change, as well as the adaptive measures being proposed most frequently.

2. Materials and methods

To compare the general trends of annual food production (FAO, 2013, 2020a) and scientific inquiry of the three major food systems, we searched Web of Science (WOS) using separate food system search terms *fisher**, *agriculture*, or *aquaculture*, AND *climate change* for all papers between 1900 and 2018 (search date: September 18–19, 2018; $N_{total} =$ 13,880). We compared production scale (tonnes and growth rate) to scientific publications as a coarse indicator of whether climate science tracks the relative importance of the respective food systems, particularly aquaculture. While a small fraction of the most recent papers will not be captured in this corpus, finding and adding those few additional papers likely would not alter the broader trends due to the large sample size. We compared the number of English language individual publications per year and the relative cumulative proportion of each topic. For aquaculture, we also compiled papers using *aquaculture*, *climate change* AND *adapt** ($N = 180$), in order to capture and compare the adaptation versus stressor-centric literature. Papers were included from all searches based on the food system topic and mention of climate change in the title, abstract, and/or key terms. Although a few relevant papers may have been missed because they did not use 'climate change' in these search areas, we expect this number to be minute. Duplicated references were removed.

From the WOS search results for aquaculture only ($N = 680$), we manually extracted several key pieces of information from each paper and excluded papers which only mentioned, but did not focus on, aquaculture and climate change. For example, aquaculture may be mentioned as a threat to a wild population or species (e.g., sea birds) in conjunction with climate change, but the primary context is not aquaculture. Of the papers that remained ($N = 553$), we documented the countries or region being studied – including papers focused on a *global* context – obvious taxonomic group(s) of interest, each paper's stressor topic(s) of interest, and if 'impact' was mentioned in the title as an indicator of clearer attribution. Some articles did not explicitly identify the stressors, or mentioned more broadly several stressors. In these cases, a categorization of *all* or *multiple* was assigned and individual stressors were added to the totals across clearly defined stressors, thus contributing to the absolute values, but not proportional contribution, of any given stressor topic. Most data were extracted from the title, keywords, and abstracts of papers; if the data could not be garnered from these paper components, we would read the methods and results of the article for the required information. Papers which described aquaculture as a stressor alongside climate change effects were not included in the analysis (e.g., mangrove loss; $n = 39$) as we were interested in aquaculture being stressed by climate change, not aquaculture as a stressor. The one exception was 'invasives,' which can have an impact on or be exacerbated by climate change and aquaculture (Hellmann et al., 2008). For the adaptation papers, we similarly noted geographic information and the kind of adaptation described in each article (e.g., policy, technology, diversification). Once the information was manually compiled, we identified and grouped the stressors and adaptations into 10 and 15 categories (Supplementary Material Table 1), respectively, guided by terminology in the review literature (FAO, 2018; Reid et al., 2019).

In addition to capturing the snapshot of science on aquaculture and climate change, we also wanted to identify which stressors were being highlighted in the news and if those patterns matched the focus in the scientific literature. To do so, we collected English language Google News articles per year (2000–2018) using the same aquaculture search terms and categories as were used with WOS ($N = 228$). The shortened search time window reflects the 1998 establishment of Google. We extracted data from the title and relevant quotes highlighted by the Google News search platform, linked to the article. Similar to the WOS search, if the specifics of aquaculture and climate change for a given story were not clear, the news article was read for the relevant information. Given news articles can highlight science and events, we differentiated between stressors and impacts ‘now’ versus concern for the ‘future’ to further explore environmental stressors on aquaculture being linked to climate change and recognition of current impacts. We also noted any adaptation language mentioned in the news articles, but focused on stressors for this portion of the analysis. Lastly, for all WOS and news articles we documented when aquaculture was mentioned as an adaptive solution for fisheries or agriculture at the regional and global level.

We report and compare totals and regional proportions of taxa, stressors, and adaptive approaches from WOS and news articles. We also descriptively compare the global versus regional stressor trends to identify discrepancies between the focus of such studies. All analyses and figure creation was performed in R*v4.0.2* (R Core Team, 2020). Consolidated data of the publications and news articles are publicly available at https://github.com/Froehlich-Lab/aqua_climate_sci-news.git.

3. Results

3.1. Food system trends

As of 2016, total aquaculture (seafood and seaweed) production (110 million tonnes) was already greater than the level of wild fisheries (92 million tonnes) and grew more rapidly and consistently (mean annual growth ± SD = 6.0 ± 1.5%) over the last decade than wild capture (−0.1 ± 2.2%) and agriculture (1.7 ± 3.9%) (Fig. 1a), but the scientific understanding of aquaculture and climate change has not kept pace with the comparative need (Fig. 1b). The independent WOS searches for publications on climate change and agriculture, fisheries, and aquaculture yielded increasing numbers of annual publications, but with far fewer studies on aquaculture (5% of total) relative to agriculture (74% of total) and fisheries (21% of total) (Fig. 1b). Beginning in 1989, publications on agriculture and climate change totaled over 10,000, with nearly 1500 published in 2017 alone. Fisheries and climate change publications started in 1990, with a total of just under 3000 publications, with nearly 400 articles in 2017. Finally, aquaculture and climate change had one publication in 1995, but was not continuously published on until 2000—relatively mirroring the global rise of aquaculture production (Fig. 1a). Yet, there were less than 700 publications in total, resulting from just ca. 50 yearly articles since 2007, with no region necessarily publishing proportionally more on aquaculture compared to the other food systems (Fig. 1b). Over half the articles were published between 2015 and 2018.

3.2. Stressors to aquaculture reported in scientific literature

Of the nearly 700 papers on aquaculture and climate change, we found 553 were actually aquaculture *and* climate change focused, and half ($n = 359$) were clearly focused on *stressors*. Most common and categorized stressors included *temperature*, *sea level* or *floods*, *ocean acidification* (OA), *storms* or *extreme events* (e.g., heatwave), *precipitation*, *drought*, *disease*, *harmful algal blooms* (HAB), *hypoxia*, and *invasives*. Literature on non-regionally specific stressors – papers focused on global or species-specific research (e.g., Atlantic salmon) – accounted for 130 of the 359 stressor-specific studies. Notably, stressor-oriented aquaculture research only began in 2004. Of the stressor papers, 53 were clearly on *impacts* (i.e., featured in the title), and only one reported lack of evidence of climate change affecting aquaculture to date, in the UK and Ireland (Callaway et al., 2012). The impact papers identified here began in 2008, with the first one documenting sea level rise in Taiwan.

The focus of aquaculture papers was skewed towards regions with more aquaculture production, as well as on highly produced animal taxa. The vast majority of all articles concentrated on countries in Asia and Europe for both stressor and impact studies (Fig. 2a)—the most studied being Vietnam ($n = 38$) and Bangladesh ($n = 27$). The Middle East had the least scientific coverage. Of the articles which identified a species or taxa ($n = 239$), finfish and mollusc were the main focus, though impacts on invertebrates collectively were more numerous (Fig. 2b). Interestingly, of the WOS publications, farmed aquatic plants (i.e., seaweeds) were not overtly mentioned through a climate change lens until 2014, even though they account for a third of cultured production (wet weight) and are the fastest growing (7.6 ± 4% per year) segment of the industry (Fig. 1a).

Of the *stressor* papers, collectively, nearly a quarter of the studies ($n = 160$) identified temperature as a stressor to aquaculture, followed by sea level or flooding ($n = 97$), and OA ($n = 75$) (Fig. 2c); these were also the top three reported impacts within the 53 *impact* papers. Hypoxia had

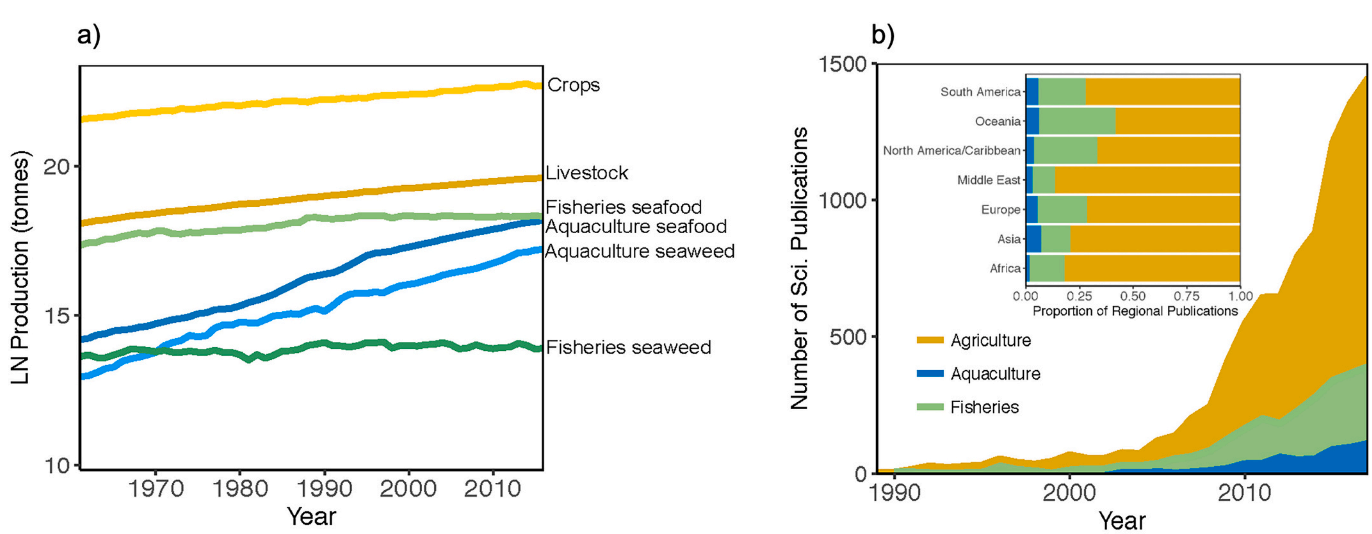

Fig. 1. Temporal trends of **(a)** production (natural-log transformed) and **(b)** annual and regional proportions of scientific publications per year on climate change and agriculture (*yellows*), fisheries (*greens*), and aquaculture (*blues*). The terms in panel (b) combine literature on crops and livestock in agriculture, as well as seaweed and seafood in aquaculture or fisheries.

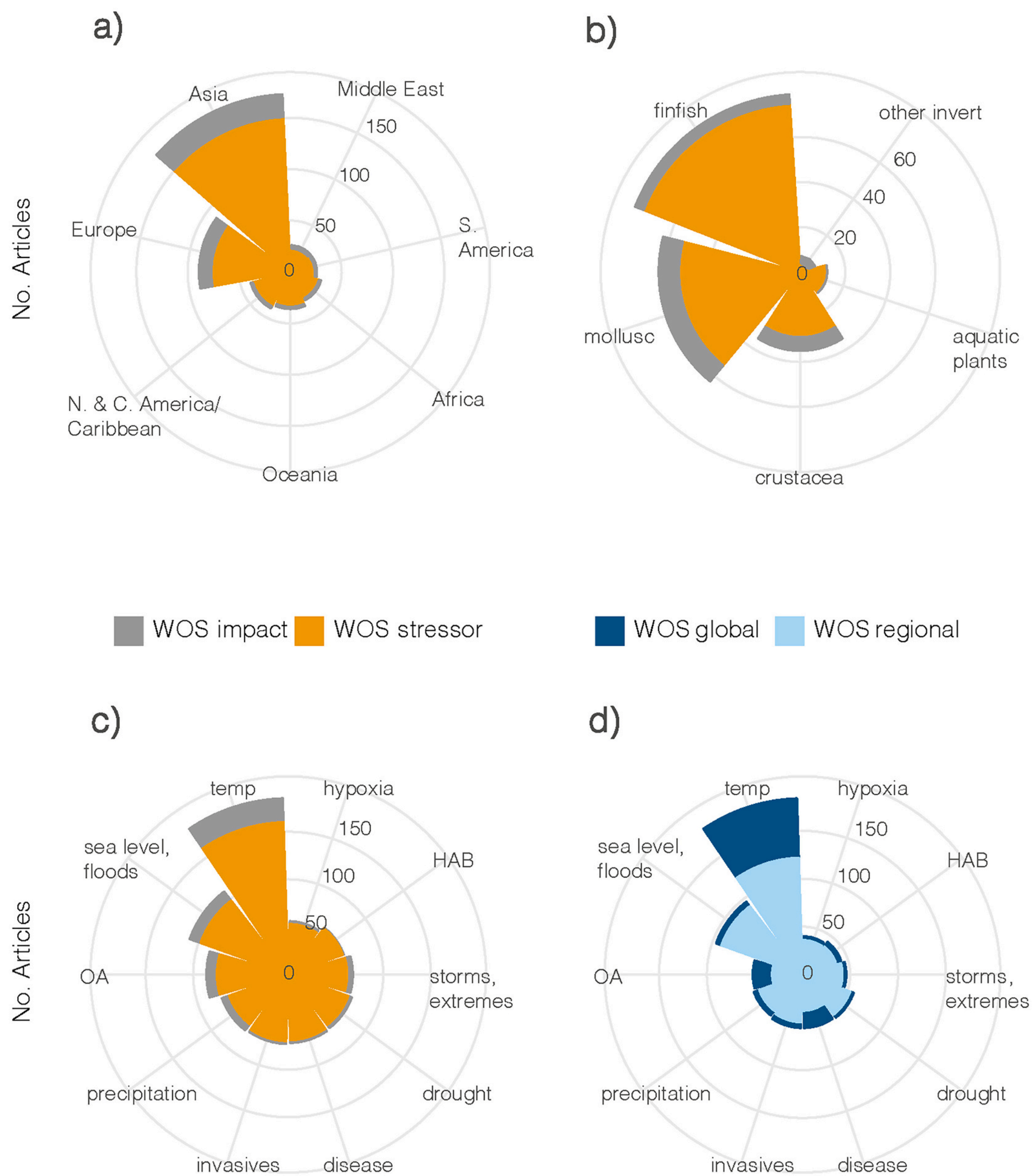

Fig. 2. Total coverage (number of articles) of WOS stressors (*yellow*) and impacts (*gray*) articles at the **(a)** region, **(b)** taxonomic, **(c)** stressor-specific level (experiments included), as well as the same articles at **(d)** global (*dark blue*) versus regional scale. The counts capture mentions, where multiple regions, taxa, and/or stressors or impacts can be studied in a single paper. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the least number of *stressor* mentions ($n = 53$) and HAB had the fewest *impact* related mentions ($n = 1$). Precipitation and drought fell out in the middle of the *stressor* and *impact* literature coverage (Fig. 2c and d). When comparing the global and regional papers, we found general alignment in the stressor trends, but global papers had a greater skew towards temperature and OA (Fig. 2d). Importantly, few global studies emphasized sea level and flooding, the second most important of the regional papers. In fact, of the impact papers, only six were global and four were on OA.

Regionally, temperature was the most studied stressor, except in Asia (Fig. 3a). Countries in Asia reported sea level and flooding stressors more often ($n = 63$), while it was the second most documented in Africa ($n = 6$) and the Middle East ($n = 2$). Interestingly, only in North & Central America/Caribbean did OA and invasives garner as much attention as temperature, while OA was the only stressor not identified in the research of Asian countries (Fig. 3a). Precipitation and drought had some coverage in largely developing regions (Fig. 3a) and disease did not rank highly among the other stressors/impacts in any one region. Notably, many studies were not country specific, but Vietnam ($n = 24$), Australia ($n = 21$), and Bangladesh ($n = 20$) had the highest country-level science coverage of climate stressors (Fig. 3b).

3.3. Stressors in the news

We found 228 articles from Google News on aquaculture and climate change spanning 2001 to 2018. Similar to the scientific publication trends, the majority (67%) of news articles were published since 2015. Of those articles, we found 135 reports of negative stressors/impacts. The earliest article in 2001 came from the Intergovernmental Panel on Climate Change (IPPC) on warming waters potentially slowing marine aquaculture growth in the future.

Collectively, when comparing news reported in English to scientific

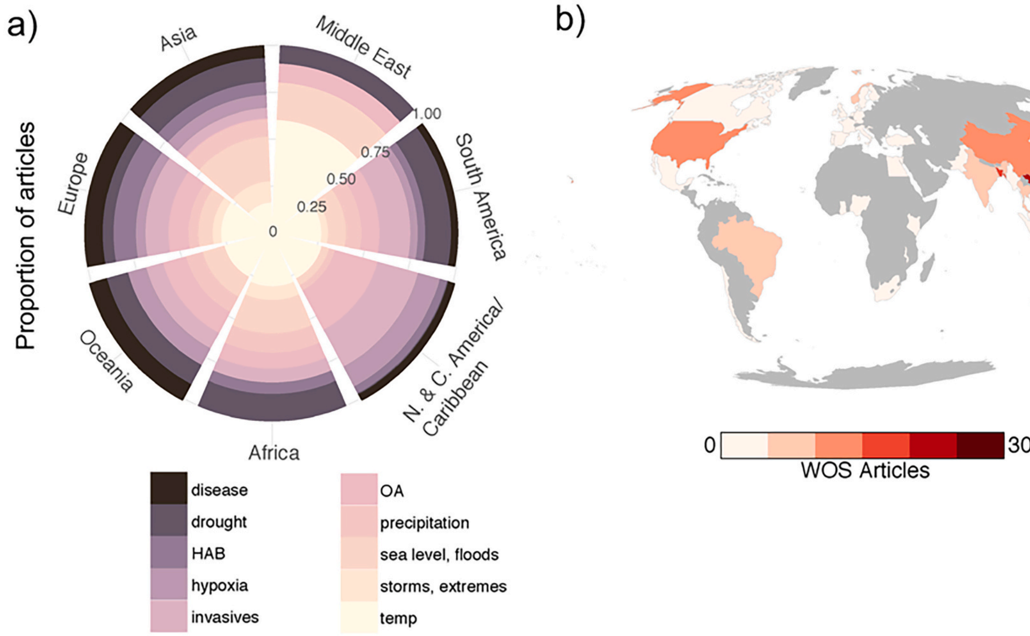

Fig. 3. Mapping scientific publications on aquaculture and climate change. **(a)** The 10 climate change linked stressors (*pink scale*) reported in WOS publications depicted as regional proportions (count of stressors in articles: Africa = 50, Asia = 318, Europe = 133, Middle East =14, N. & C. America/Caribbean = 65, South America = 86, Oceania = 24) and **(b)** the associated number of articles per country (*reds*). Note, some papers were only at the regional level, and thus not reflected in the country level map. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

coverage, we found fairly close proportional alignment in regional or topical coverage, particularly in Asia. Within a given region, however, news tended to focus on fewer stressors than scientific articles (Fig. 4). The greatest discrepancy was the news covering North & Central America/Caribbean and OA proportionally more than the scientific community, and less coverage on invasives (Fig. 4). News sources did not have the same emphasis on temperature as the scientific articles. Nonetheless, the top three reported aquaculture stressors were the same: OA ($n = 78$), temperature ($n = 76$), and sea level or flooding ($n = 60$).

We found near equal numbers of news articles on current ($n = 64$) and future ($n = 71$) climate change concerns, including 17 countries which reported news on stressors linked to climate change already *impacting* the aquatic farming industry now (Fig. 4a & b). Of the 17 countries, 14 also had *stressor* scientific articles ($n = 130$) and 10 with *impact* specific literature ($n = 26$) (Fig. 4b). The majority of the current impact news focused on the United States ($n = 19$), Australia ($n = 6$), and Vietnam ($n = 4$), largely pertaining to OA, temperature, and sea level/flooding, respectively. However, only five of the seven regions had future-based news articles (Fig. 4a). Concerns in the news for aquaculture under climate change reported only in a future, long-term context were OA in Asia, HAB and disease in Europe, and hypoxia in North & Central America/Caribbean.

3.4. Adaptation

The WOS adaptation search yielded 153 scientific articles and 139 had some clear mention of one or more adaptive approaches. From these studies, the 15 adaptive categories ranged from general to specific, tactical to strategic, and farm to global level (SM Table 1). Of the total, 35 papers (25%) were global in nature.

Across all adaptive aquaculture literature, the trends followed the stressor literature, with Asia ($n = 54$) and Europe ($n = 16$) comparatively well represented, but focus differed depending on scale (global vs regional) (Fig. 5a-b). Among adaptive categories, genetics/breeding ($n = 25$) was the most cited way for aquaculture to address climate change impacts, followed by management ($n = 23$), governance/policy ($n = 21$), integrated systems ($n = 20$) and technology ($n = 19$). In comparison, insurance ($n = 1$), incentives ($n = 3$), infrastructure ($n = 4$), and education ($n = 5$) had the fewest number of mentions (Fig. 5c). Global papers in particular focused mostly on genetics/breeding and technology as solutions, while the focus of regional papers included a broader range of adaptive strategies, favoring management, governance/policy, and integrated systems alongside genetics/breeding (Fig. 5c). Regional papers had more emphasis on education and infrastructure than global papers, but less on incentives. Social equity/license was only mentioned in nine articles, but again the majority (89%) from regional studies. Similar to the *stressor* literature, Vietnam ($n = 18$), Bangladesh ($n = 14$), and Australia ($n = 9$) had the greatest country-level adaptation coverage (Fig. 5b). While many of the categories are linked and overlap, the point of this exercise was to highlight the relative role or importance of differing adaptive measures being conveyed in the literature.

From both WOS and news searches of stressors and adaptations, we found a shift towards mentioning aquaculture production as a potential solution for agriculture and/or fisheries impacted by climate change, including making wild species more resilient through recovery and breeding programs, such as those for corals and lobster. Total mentions connecting aquaculture with fisheries outnumbered those for agricultural 3:1. The news and scientific literature had the same number of articles ($n = 35$), though proportionally more in the news (15% of articles) than science (5%), and regional patterns differed greatly (Fig. 6). In particular, Europe and South America had little to no reference to such claims, while news concerning African and North & Central America/Caribbean countries were the most numerous. Global scientific papers mentioned aquaculture solutions for fisheries under climate change the most (Fig. 6). Of note, two WOS studies were more cautious about the true potential aquaculture could offer (Aguilar Ibarra et al., 2013; Foale et al., 2013).

4. Discussion

Across scientific literature and news media, we found a common emphasis of specific stressors, while adaptive approaches were a smaller focus and convergent. Although aquaculture continues to increase its

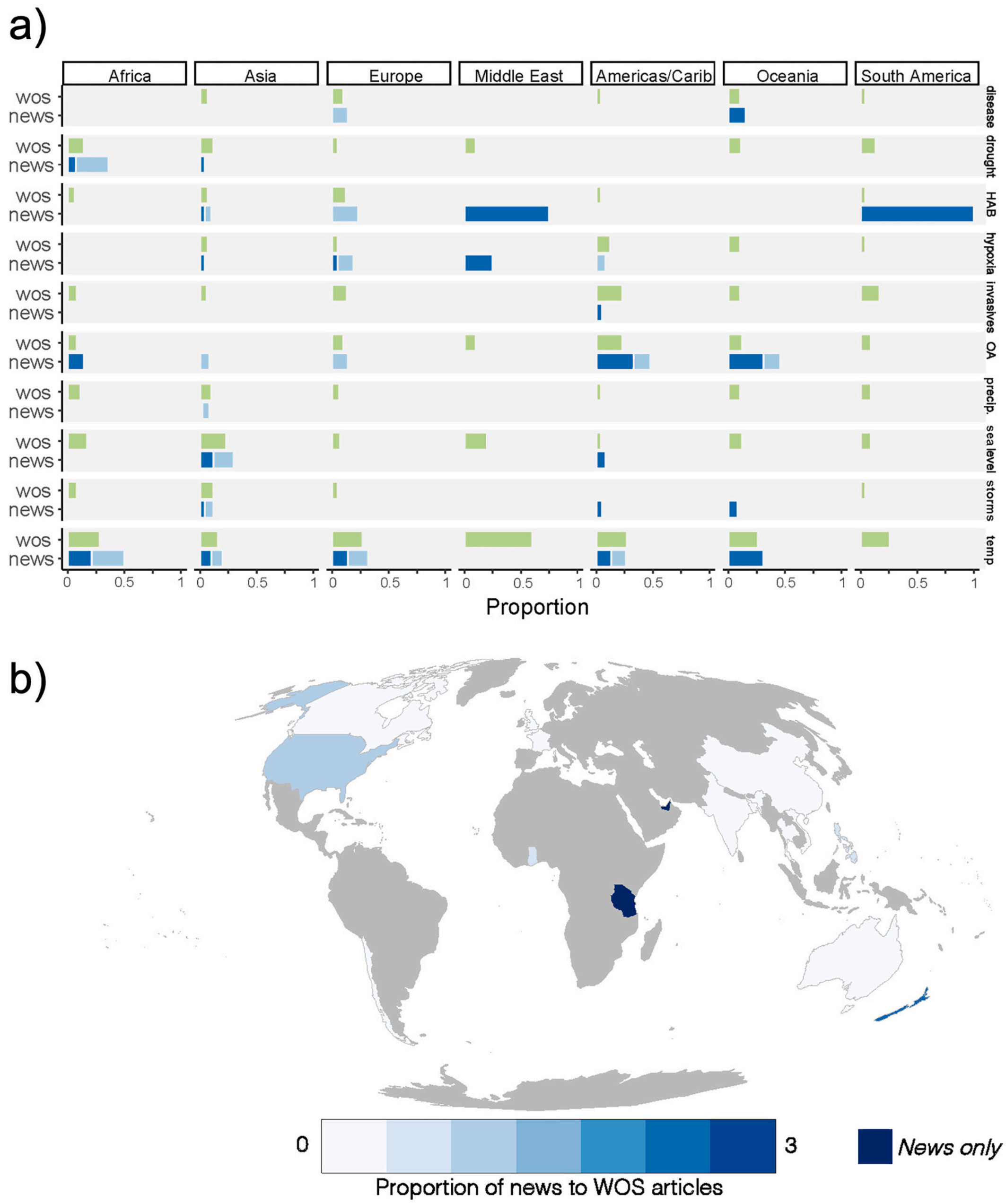

Fig. 4. **(a)** Comparative proportional coverage of news on climate-change linked stressors *now* (*dark blue*) and in the *future* (*light blue*), as well as those from WOS articles (*green*) for each region and stressor and **(b)** proportion of news articles reporting impacts *now* ($n = 17$) relative to the WOS articles on countries reporting stressors on their aquaculture industry in those associated countries (*blue gradient*). Three countries only had news articles, shown in *dark blue*. The proportions capture mentions, where multiple regions, taxa, and/or stressors can be studied in a single article. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

share of global seafood production, there has not been concomitant increases in publications and news coverage on climate change consequences for the sector. That said, news has covered temperature, sea level rise, and ocean acidification—all of which were well represented in scientific literature. This suggests some alignment between science and news coverage, despite some regional and country-level variation between stressors. We also found a diversity of adaptive approaches, with varying levels of specificity and some inconsistency between regional versus global emphasis on the importance of management and governance versus technological solutions, respectively. In all, these results offer a clear evaluation of climate change concerns, impacts, uncertainty, and future research and policy needs for aquaculture.

Temperature is the most studied and reported climate change stressor, but sea level rise and floods take center stage in Asia, where 90% of aquaculture production occurs (FAO, 2020a). Temperature can impact aquaculture (freshwater and marine) through direct and indirect effects on growth, reproduction and survival across the life-stages of a given species (Reid et al., 2019). For example, temperatures in Southern Australia are rapidly changing, including more frequent and intensified heatwaves impacting salmon growth and oyster disease (Lehman, 2017), which likely increases the economic threat (Oliver et al., 2018; Schrobback et al., 2018; Van Putten et al., 2014). Markedly, temperature can exacerbate the other stressors, such as hypoxia, but studies on the negative additive or synergistic effects on farmed species beyond two stressors remain sparse, and thus the magnitude of consequences is uncertain for aquaculture (Catalán et al., 2019). As important as

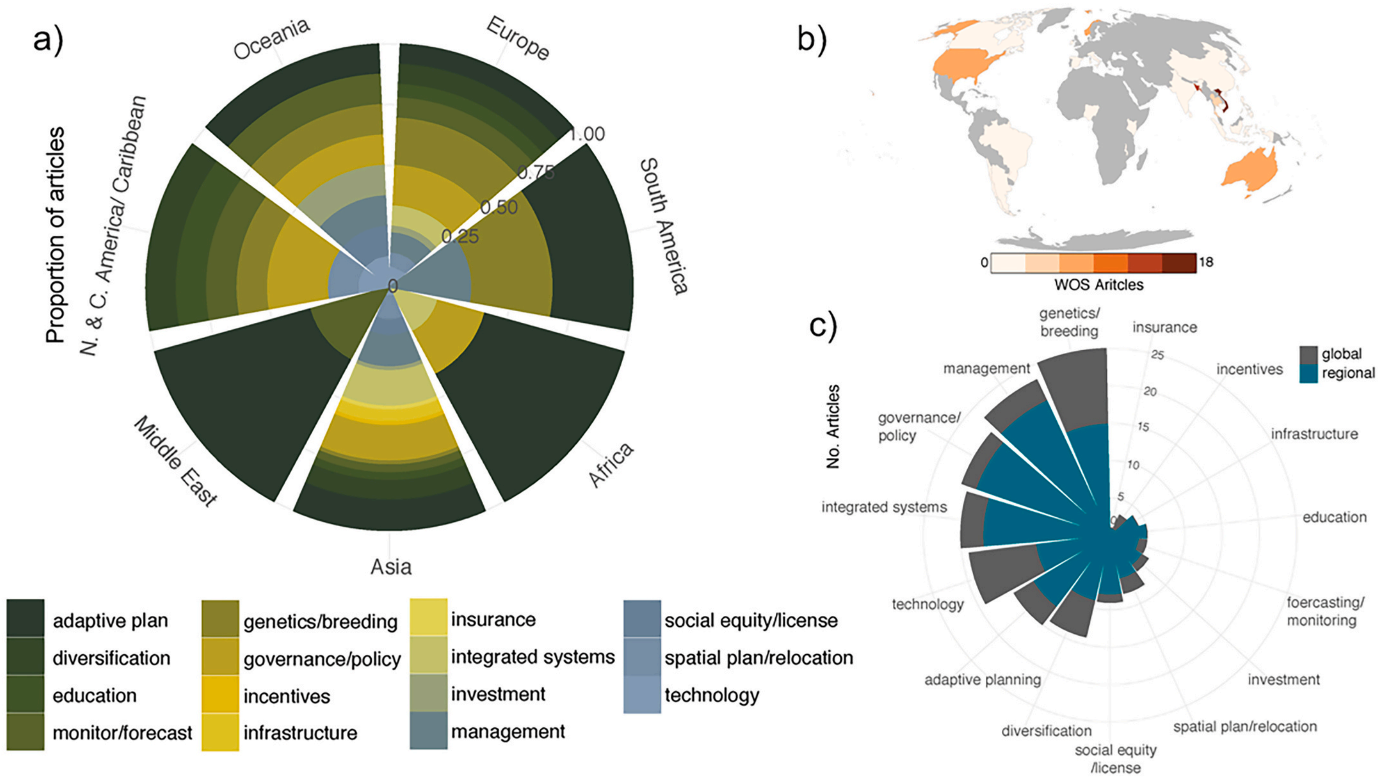

Fig. 5. **(a)** Proportion of WOS publications on a given region pertaining to adaptation of aquaculture through the 15 categories (*green to blue gray* colour ramp), with the **(b)** country defined number of articles (*oranges*) and **(c)** comparative focus from region-specific (*aqua*) versus global papers (*dark gray*). Note, some papers were only at the regional level, and thus not reflected in the country level map. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

increasing temperature is to aquaculture – a conclusion supported by the emphasis of the regional and global coverage in science and the news – the prominence of sea level/floods in countries, such as Vietnam, Bangladesh, and China, is critical to acknowledge. For example, with an increase in 0.1 m in sea level there is a 3-fold increase in flood frequency (Church et al., 2006; Zhai et al., 2015), creating infrastructure and husbandry problems for most land-based and marine aquaculture, which tend to be located at or near low-lying coasts (Reid et al., 2019). These are also aquaculture regions where sea level rise manifested most to date (Fasullo and Nerem, 2018; Nerem et al., 2018).

We found evidence across research and news coverage of at least 10 countries, one in almost every region, already feeling the effects of climate change related stressors on aquaculture. As mentioned, Vietnam, Bangladesh, and China are reporting on environmental impacts linked to climate change, largely related to sea level and flooding. Indeed, we identified a few of the WOS ($n = 12$) and news ($n = 6$) articles describing the *impacts* of sea level rise, floods, and/or salinity intrusion currently affecting the industry in these countries. Note, this is probably a conservative representation given the limitations of our sampling methods (e.g., English language, ‘impact’ in WOS title) and the fact that not all impacts are documented. Regarding the former limitation, given the majority of aquaculture is produced in Asia (FAO, 2020a), a more targeted assessment of the scientific and news literature in that region – especially articles in the languages of the respective countries – would improve the conclusions of this study. That said, even with the English-language constraint, there was consistent focus, linkage, and impact-based language highlighting the current and future threat of climate change in Asia, particularly the aforementioned countries, which have been identified as most vulnerable by risk-assessment modeling (Handisyde et al., 2017). Similarly, other countries also reporting effects of climate change consistently across science and news, included Australia, Canada, Chile, UK, India, Thailand, and the USA. Many of these countries are already global contributors to aquaculture production (e.g., China) or are interested in expanding (e.g., USA) (FAO, 2020a; Froehlich et al., 2021), have capital to invest, and have relatively stable governance warranting more clear and strategic planning for the future, both domestically and around trade (Davies et al., 2019; Froehlich et al., 2020).

Disease, which includes pathogens and parasites in our categorization, received comparatively little attention across science and news, even though climate change stressors can affect farmed species susceptibility to disease and has been argued as the most pressing issue in aquaculture (Jennings et al., 2016; Lafferty, 2020; Reid et al., 2019; Stentiford et al., 2017). In fact, mitigating, treating and recovering from diseases costs the global aquaculture industry an estimated $6 billion (USD) dollars a year (Stentiford et al., 2017). Yet, linking and predicting climate change and disease impacts is challenging due to the suite of other factors, such as stocking density, water quality, feed (e.g., dry vs. wet), therapeutic treatments or vaccines, and interactions with wild stocks, which carry numerous infectious agents (Lafferty et al., 2015), which perhaps explains some of the disconnect. When considering adaptation, even though forecasting/monitoring were not as prominently mentioned in the climate change adaptive literature, they are critical features to effectively address disease as part of good management practice—especially alongside genetic and technological improvements (Jennings et al., 2016; Lafferty et al., 2015; Reid et al., 2019; Stentiford et al., 2017).

Compared to the other stressors, precipitation and drought had only moderate coverage in science and news, mostly in more developing regions, such as Africa, Asia, and South America. The lack of emphasis is somewhat surprising given the majority of aquaculture is of freshwater origin (60%) (FAO, 2020a) and water security is of growing concern, especially in relation to agriculture (e.g., ‘water wars’) (Busby, 2017; Wake, 2021). Drought is already a major constraint to inland

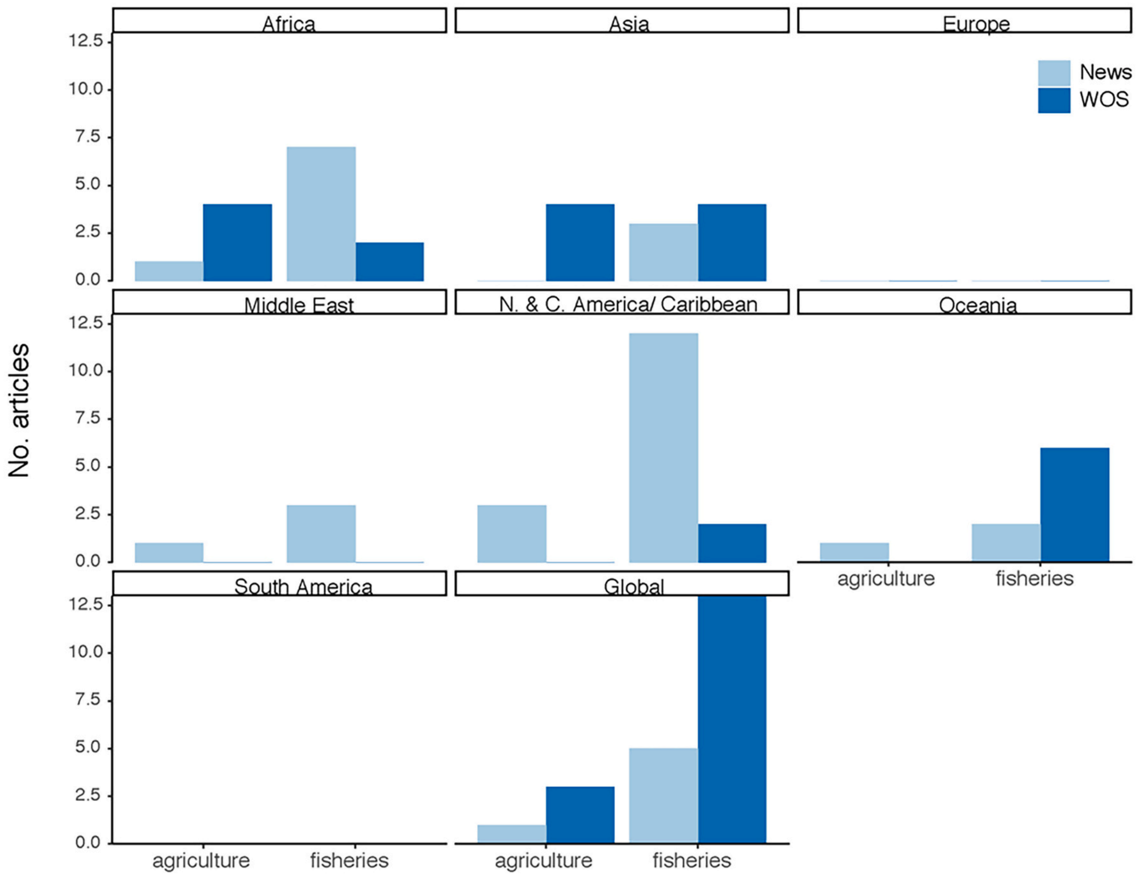

Fig. 6. Number of WOS and news articles mentioning aquaculture potentially buffering the impacts of climate change on agriculture or fisheries around the world.

aquaculture (Ahmed et al., 2018a, 2018b; Ahmed and Diana, 2016), which is only expected to become more pervasive under climate change, with some estimates of ca. 25% of land to be affected by severe drought by mid-century (Park et al., 2018). Reduction in precipitation and groundwater due to climate change, alongside irrigation of agriculture, shortens or eliminates freshwater aquaculture growing seasons; impacts already reported in countries like China, Thailand, and Bangladesh (Ahmed et al., 2018b; Gephart et al., 2017). Yet, despite this present and future threat of changing water access due to climate change and conflicting uses, the quantifiable impacts on freshwater aquaculture production and people into the future are not well understood, especially compared to fisheries and agriculture.

Adaptive measures were diverse, where regional instead of global studies in the scientific literature highlighted the importance of governance and management over technological solutions. Certainly, genetics/selective breeding and technology are part of the adaptive response for aquaculture (FAO, 2019; Houston et al., 2020; Kumar et al., 2018), as emphasized by global coverage. However, we caution too much emphasis on tech-based solutions, which may be constrained in lower income regions most vulnerable to climate change (Kumar et al., 2018), limited by standing policies or practices supporting native and genetic protections – especially capture-based production systems (FAO, 2020b) – and/or create a false sense of security in actually addressing climate change and impact. There were several adaptive approaches which were not as prominently featured. Spatial planning or zoning is crucial for site selection to reduce exposure and/or increase relocation flexibility as conditions change (FAO, 2018). Similarly, less emphasis on adapting infrastructure in aquaculture suggests that the literature may not fully consider how climate stressors can affect coastal farms, harbors, or processing plants (e.g., increasing temperatures disrupting the cold chain in processing plants) (James and James, 2010). Mentions of insurance markets as an adaptation strategy were also less apparent. It is predicted that increasing effects of climate change on agriculture will lead to higher demand for crop insurance (Falco et al., 2014). As it stands now, most aquaculture insurance is ill defined and those in the industry may be unaware of existing options – which arguably is part of education, another underrepresented adaptive component – creating a critical disconnect in adaptation aquaculture options (van Anrooy et al., 2006; Theodorou and Tzovenis, 2014). We should also note, more detailed articulation of adaptive approaches are even more sparce in the literature than the broader representation captured in this study (Galappaththi et al., 2020). In all, there appears to be a need for clarity and support for solutions with less emphasis on technology in this space.

Regional-level science and news coverage also accounted for a broader range of climate stressors than at the global level. These results are intuitive since climate change consequences and local responses are quite context dependent (Popova et al., 2016). Regional science and news appear to perceive, and potentially prioritize, covering specific climate stressors impacting production sectors important to that region. For example, we found OA was repeatedly identified as a key issue for shellfish aquaculture in the Americas, perhaps reflecting a strong history of research support for OA studies, but not so for countries in Asia, where sea level rise and flooding have already had more prominent impacts on the aquaculture sector. Better understanding of local level climate change implications is critical for aquaculture to plan and adapt, especially as it grows (Falconer et al., 2019; Froehlich et al., 2020), but global analyses do provide a wider lens to identify growing interregional inequities and needs, especially with wealthiest nations responsible for the vast majority of carbon emissions (FAO, 2018; Füssel, 2010; Kenner, 2019).

5. Conclusion

Climate change already affects aquaculture and the impacts are likely to increase, especially in the absence of proactive interventions. Despite the important role aquaculture now plays in the global food system – accounting for approximately half of all seafood (FAO, 2020a) – the recognition of this vulnerability of aquaculture in the scientific literature and news is fairly recent and is underrepresented compared to other food sectors. In order to improve policy and management that is science-based and publicly supported, we need to rapidly increase research and media attention to the social and ecological impacts of climate change on aquaculture. Technological solutions may have widespread appeal but are often costly and have longer time spans between development and implementation. There is an immediate need for understanding climate impacts on aquaculture and practical adaptation measures to address regionally specific impacts. A greater emphasis on the effectiveness and feasibility of adaptation solutions for aquaculture could help evaluate the relative social and economic benefit of technological solutions as compared to equitable policy solutions, win-win governance measures, and emergency response and insurance aimed at alleviating farm level impacts. And while not directly assessed in this study, emerging aquaculture research is also exploring mitigation potential of some forms of aquaculture, such as seaweeds (e.g., carbon sequestration, local buffering of ocean acidification and hypoxia), one of the least studied farmed taxonomic groups in this study, which warrants further investigation (Froehlich et al., 2019; Theuerkauf Jr et al., 2019). In all, dissemination of climate change and aquaculture research findings through communication plans and media coverage could help bolster understanding of impacts and solutions, as well as garner support for future research in this increasingly critical food sector.

Declaration of Competing Interest

HEF sits on the scientific Technical Advisory Group for the Aquaculture Stewardship council.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.aquaculture.2021.737812.

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