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Climate change adaptation in aquaculture

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Abstract: This study conducts the first systematic literature review of climate change adaptation in aquaculture. We address three specific questions: a) What is aquaculture adapting to? b) How is aquaculture adapting? and c) What research gaps need to be addressed? We identify, characterise, and examine case studies published between 1990 and 2018 that lie at the intersection of the domains of climate change, adaptation, and aquaculture. The main areas of documented climate change impacts relate to extreme events and the general impacts of climate change on the aquaculture sector. Three categories of adaptation to climate change are identified: coping mechanisms at the local level (e.g., water quality management techniques), multi-level adaptive strategies (e.g., changing culture practices), and management approaches (e.g., adaptation planning, community-based adaptation). We identify four potential areas for future research: research on in-land aquaculture adaptation; studies at the household level; whether different groups of aquaculture farmers (e.g., Indigenous people) face and adapt differently to climate change; and the use of GIS and remote sensing as cost-effective tools for developing adaptation strategies and responses. The study brings essential practical and theoretical insights to the aquaculture industry as well as to climate change adaptation research across the globe.

Keywords: Aquaculture, adaptation, climate change, research directions, systematic literature review

1. Introduction

Aquaculture is the fastest-growing food-producing sector, accounting for over 50% of global fish production (FAO, 2017, FAO, 2018), and is often promoted as a solution for meeting the growing food demands of this century (Béné et al., 2015, Béné et al., 2016). Currently, about 424 aquatic species are farmed globally, supporting millions of people through the provision of nutrition, food security, and livelihoods, as well as through the alleviation of poverty (Pauly and Zeller, 2017, Barange et al., 2018, FAO, 2018, FAO, 2019). In 2016, about 59.6 million people were engaged in the primary sector of capture fisheries and aquaculture; of this total, 32% were engaged in aquaculture (Bhari and Visvanathan, 2018, FAO, 2018). According to the Global Aquaculture Alliance, 62% of food fish will come from aquaculture by 2030 (GAA, 2019). Most of the world aquaculture production comes from small-scale producers in the global south, with the top five producers being China, India, Indonesia, Vietnam, and Bangladesh. Collectively, these five countries contributed 82.2% of the world production by quantity in 2016 (FAO, 2016, FAO, 2018). From this perspective, aquaculture gains significant scholarly attention, including the recent IPCC 1.5°C report (IPCC, 2018) and the IPCC land report (IPCC, 2019), which identifies aquaculture as one of the key sectors that requires attention on global food security and the upgrading of adaptation policy.

The impacts of climate change increase the complexity and uncertainty of aquaculture systems, which can result in various unfavourable conditions (e.g., disease) (FAO, 2015, Seggel and De Young, 2016, Galappaththi et al., 2019). In research involving adaptation to climate change, it is well-documented that some aquaculture systems are better able to adapt to changing conditions (Adger et al., 2009, De Silva and Davy, 2010, Berrang-Ford et al., 2011, Rodima-Taylor et al., 2012). Yet, there has been limited advancement in the understanding of what adaptations are occurring/needed/viable in the social and social-ecological systems of aquaculture (Berkes et al., 1998, Berkes et al., 2003). Aquaculture systems (the social-ecological systems associated with aquaculture operation) that are undergoing rapid change should be able to respond innovatively to adapt more quickly and thoroughly to mitigate challenges and harness opportunities, similar to other widely studied resources systems in the climate adaptation research (Scheffran et al., 2012, Kabisch et al., 2016, Siders, 2019). While an increasing amount of research is producing knowledge in the area of climate change adaptation (Berrang-Ford et al., 2011, Berrang-Ford et al., 2015, Sherman et al., 2016, Biesbroek et al., 2018, Siders, 2019), limited research assesses and characterises adaptations specific to the aquaculture industry (with exceptions been FAO report chapters: (De Silva and Soto, 2009, Barange et al., 2018, Dabbadie et al., 2018, Soto et al., 2018)). To the best of our knowledge, no global systematic literature reviews are available that are aimed at the area of the human dimension of aquaculture and climate change adaptation. Against this backdrop, an examination of global aquaculture systems is needed to advance the understanding of ways in which they experience the shocks and stressors and how such systems adapt to climate change impacts. Furthermore, certain aquaculture systems can benefit from the scaling up of the community adaptive responses of the studied aquaculture systems that have already adapted. This will advance the future research needs of the overlapping areas of aquaculture and climate change adaptation.

In this article, we identify and assess case studies across the globe, published between 1990 and 2018, that lie at the intersection of climate change, adaptation, and aquaculture so as to understand the emergence and nature of research on the human dimensions of climate change adaptation in a global aquaculture context (IPCC, 2014). Climate change adaptation in the aquaculture context is a growing research field that has received limited attention. We sought to fill this gap by addressing three primary questions related to global aquaculture: i) What is aquaculture adapting to? ii) How is aquaculture adapting? and iii) What research gaps need to be addressed? Moreover, our primary research questions can bring novel insights to the field of aquaculture and climate change adaptation in general, such as: How is aquaculture affected by climate change impacts?; What conceptual approaches are used to study climate adaptation in aquaculture?; What specific types of aquaculture have, to date, been the most-studied with respect to climate adaptation?; What are the adaptive responses and strategies?; What are the commonly used management approaches in aquaculture for adapting to climate change?; and What are the policy contributions from aquaculture studies aimed at climate adaptation? The next section will explain the systematic literature review process (i.e., the methodology). This will be followed by the results section, which will include descriptive results and answers to specific questions identified in the global aquaculture assessment. There is a growing interest in systematically assessing adaptation as part of adaptation tracking research (Ford et al., 2015, Lesnikowski et al., 2016) and growing sectoral coverage of this work (e.g., cities, tourism, certain regions such as the Arctic and small-island developing states, health, the national level), though none of these works focuses more broadly on aquaculture or even fisheries.

2. Methods

To examine the existing literature of adaptation to climate change in the context of aquaculture, we used the systematic literature review approach. A systematic literature review is characterised by an explicit and rigorous methodology which differs from traditional reviews in its use of transparent, objective criteria (Berrang-Ford et al., 2011, Berrang-Ford et al., 2015, Siders, 2019). Increasingly, climate change adaptation literature has explicitly used this approach as a means of synthesising results and identifying gaps for future work (Ford and Pearce, 2010, Berrang-Ford et al., 2015, Sherman et al., 2016, Biesbroek et al., 2018). Following Berrang-Ford et al. (2015), we first outline the data source and document the selection process, including a description of the literature source, search process, and inclusion and exclusion criteria for literature. Second, we describe the methods used for analysis and critical appraisal of the information quality of this study.

To meet the aim of the research, this paper reviews the literature at the intersection of climate change, adaptation, and aquaculture across disciplines. Thus, we did not limit the search for publications to any specific academic field and we included publications in peer-reviewed academic journals and book chapters. We searched only for publications in the English language. Using the search engine Web of Science (WOS), we used the search terms "climat* chang*", "fish* farm*" or "aquaculture", AND "adapt*" in the TOPIC category in the time frame 1990-2018 (Appendix A: table S1). We conducted the search in January 2019 to capture all publications from 1990-2018. Two searches were conducted to return publications referencing "aquaculture" and those referencing "fish* farm*" separately. Each search string returned publications that included ALL of the word(s) fragments in the search string as part of the publications' TOPIC. The Digital Object Identifier (DOI) number was used to identify and remove duplicates from the comprehensive search.

After we removed duplications, we had an initial dataset of 129 publications. We extracted the initial dataset to Microsoft Excel. For the first round of screening, we read the title and abstracts of these publications (and the full text in cases in which the classification was doubtful) to determine whether we would keep or discard the publication in the final dataset. The first three authors then characterised the 129 publications for a second round of screening. The principal criterion for inclusion or exclusion was whether the publication contained a distinct link between climate change adaptation and aquaculture (see Table 1 for all the inclusion criteria). For example, to create a clear boundary for our study, we exclude studies that use vulnerability as a primary approach to examining human response, as vulnerability and adaptation are distinct approaches in climate change adaptation research. The authors met weekly throughout the screening and data collection process to ensure consistency in characterisation and to discuss any issues that arose. On an Excel sheet, we made notes about the reasons for our elimination of each excluded study. The final set of publications explicitly recognised the impacts of climate change and the different ways in which people adapt in the context of aquaculture. By contrast, excluded publications did not belong to the intersection of adaptation, climate change, and aquaculture or belonged to only one or two of those domains. Forty-four articles met the inclusion criteria and were retained for final review. We collected specific data, including publication year, first author affiliation, key funding sources, research location, target people, type of aquaculture, nature of climate change impacts, key theories used, adaptation responses studied, and policy implications (Table 2). Finally, before data analysis, one author reviewed the complete dataset for consistency in characterisation.

Forty-four articles focused on both individual and multiple case studies, though we use the term 'paper' as a unit of analysis to capture the scale of the studies (community to global). The term 'case studies', used in the remainder of the text, refers to the number of papers reviewed and not to the specific case studies of focus within the paper. Data analysis was based on qualitative content analysis, which is often used to analyse selected text (Yow, 2014, Hancock and Algozzine, 2015, Berg, 2016, Clifford et al., 2016). The key techniques used were 'manifest' and 'latent' content analysis (Krippendorff, 2018) supplemented with 'critical discourse' analysis (Wodak and Meyer, 2015) to develop themes and linkages related to the case studies of adaptations to climate change in the aquaculture context. To express the original point of view of respondents, direct quotations are also used. Most of the descriptive statistics were formulated using the advanced features of Microsoft Excel 2013, and percentages refer to the total sample size (n=44). Percentages in the text refer to the number of respondents from the immediately mentioned sub-sample who made that particular statement.

3. Results

3.1 Descriptive results

Our study shows that a limited number of case studies is available through which to understand adaptations to climate change in the aquaculture context, despite an increasing trend in overall publications on the topic. Figure 1 shows the recent increase in publications at the intersection of climate change, adaptation, and aquaculture as well as the journals in which they were published. Interestingly, the first case study was published in 2010 in the journal *Climate Research*; the paper focused on the effects of global change on bivalve rearing activities and its adaptive management (Canu et al., 2010).

The majority (57%) of the case studies are published in journals such as *Marine Policy* (18%), *Regional Environmental Change* (11%), *Ocean and Coastal Management* (7%), and *Environmental Development & Sustainability* (7%) (Figure 1). In addition, the majority (50%) of studies use a mixed approach of qualitative and qualitative research designs, while the rest of the studies use only a qualitative approach (27%) or only a quantitative approach (23%). Furthermore, the majority (59%) of the studies are based on primary data such as those collected through participant observation, face-to-face interviews, and/or surveys. In terms of geographic scale, 57% of the studies are at the regional level and covered a few communities to large geographical regions within a country. The rest of the studies are at other geographic scales: community (23%), national (11%), and international (9%). None of the studies are done at the household level. We found that IDRC (International Development Research Centre), ADB (Asian Development Bank), and CCCEP (Centre for Climate Change Economics and Policy) are the top three funding agencies in the area of climate change adaptation in an aquaculture setting.

Studies on climate change adaptation in the context of aquaculture are written by authors of both global south and global north countries, while the studies are conducted primarily in the global south except for Australia (Figures 2). Most of the studies (57%) are initiated by five countries: USA (8), Australia (5), Thailand (5), Vietnam (4), and UK (4) (Appendix A: table S2). Interestingly, 30% of the studies are produced by four institutions: Chiang Mai University (Thailand), University of Arkansas at Pine Bluff (USA), CSIRO-The Commonwealth Scientific and Industrial Research Organisation (Australia), and University of Leeds (UK). As seen in Figure

2, the country where the highest number of case studies was carried is Vietnam (11). Interestingly, four of those case studies are done by authors from Vietnam. Following that is Bangladesh, with seven case studies, of which three are written by authors from the USA and Thailand, with five case studies written entirely by authors from Thailand. Small and vulnerable Pacific islands have also been the subject of studies. A total of six case studies have been done in Vanuatu, Fiji, and the Solomon Islands.

3.2 Climate change has mixed impacts on aquaculture

Most case studies (52%) in the dataset attempt to identify climate change as a key driver of changes in multiple aspects of aquaculture systems (e.g., economic impacts, risk and uncertainty, and management implications). The main documented areas of climate change impacts are extreme events such as floods/droughts and cyclones, which cause damage to aquaculture systems (25%) (Hossain et al., 2018, Lebel et al., 2018b, Limuwa et al., 2018); climate impacts in general (18%) (van Putten et al., 2014, Rodríguez-Rodríguez and Ramudo, 2017, Tran et al., 2017); and changes in aquaculture-related systems such as mangroves, livelihoods and landscape, and supply chains (16%) (Paprocki and Cons, 2014, Orchard et al., 2015, Orchard et al., 2016) (Figure 3). The majority of cases (64%) illustrate the intertwined nature of multiple impacts of climate change. For instance, multiple climate change impacts in southwest Bangladesh (floods, droughts, sea-level rise, and sea surface temperature change) contribute to changes in prawn-fish-rice ecosystems in a combined way, resulting in social, economic, and ecological changes associated with aquaculture production (Ahmed et al., 2014). Further, tropical storms in coastal Vietnam have varied impacts on shrimp aquaculture through sea-level rise, floods and the progression of the low water line, and coastal erosion (Nguyen et al., 2017).

3.3 Theoretical approach towards studying climate adaptations in aquaculture

Many studies (over 50%) have adapted integrated approaches that combine various conceptual approaches (e.g., combining an economic approach with marine protected areas) to study adaptation in an aquaculture setting (Dey et al., 2016a) (Appendix A: table S3). The most common (27%) conceptual approach used to study aquaculture is the ‘systems approach’ (Berkes et al., 2003), supplemented with the scholarship areas of social-ecological systems (Berkes et al., 1998), resilience (Folke, 2016), ecosystem-based management (Long et al., 2015), knowledge systems (Berkes, 2012), and integrated farming systems (Bosma et al., 2012). Only two studies use the vulnerability approach to study adaptations in an aquaculture setting (Arimi, 2014, Orchard et al., 2016). Developed countries (United Kingdom, Sweden, Canada, and Spain) lead the majority of such studies to assess aquaculture systems in Asian countries such as Vietnam and Bangladesh (Galaz et al., 2012, Orchard et al., 2015, Khan et al., 2018). Publications from the United States incorporate a number of national-level studies aimed at Pacific islands (Fiji, the Solomon Islands, Timor-Leste, and Vanuatu), looking at the economic impacts of climate change in aquaculture (Dey et al., 2016a, Dey et al., 2016b, Rosegrant et al., 2016). Sustainability and livelihood is another approach often employed to study aquaculture in the development context (e.g., Malawi, Bangladesh, and Vietnam) (Nguyen et al., 2017, Hossain et al., 2018, Limuwa et al., 2018). Most of the studies that assessed local aquaculture by using adaptive capacity, resource management approaches (e.g., co-management and adaptive management), risk and uncertainty, and human perceptions of climate change adaptation are led by the same country (Arimi, 2014, van Putten et al., 2014, Frisch et al., 2015, Lim-Camacho et al., 2015, Spillman et al., 2015, Ho et al., 2016, Bunting et al., 2017, Nguyen et al., 2017, Hossain et al., 2018, Lebel and Lebel, 2018, Lebel et al., 2018a, Lebel et al., 2018b).

3.4 Types of targeted aquaculture

Aquaculture operations in marine and coastal areas are the most commonly studied in this analysis. The economic impacts of marine and coastal aquaculture are a major topic among studies aimed at national-level adaptation strategies (Dey et al., 2016a, Dey et al., 2016b, Rosegrant et al., 2016). Inland aquaculture is the second targeted area of aquaculture and all the study areas are limited to global south nations (Bosma et al., 2012, Jayanthi et al., 2018, Lebel and Lebel, 2018, Lebel et al., 2018a, Lebel et al., 2018b, Limuwa et al., 2018). Almost all studies focusing on inland aquaculture have a regional focus (two or more communities or regions within the country). Another significant portion of studies targets a specific species or group of species rather than having a geographic focus (Boonstra and Hanh, 2015, Spillman et al., 2015, Fleming et al., 2017). The most commonly studied species are shrimps in the flood-prone areas of Vietnam, Bangladesh, and Australia (Boonstra and Hanh, 2015, Spillman et al., 2015, Bunting et al., 2017).

3.5 Coping mechanisms in aquaculture

The adaptation responses used by most of the aquaculture farmers are coping mechanisms and are reliant on several factors, such as knowledge of adaptation strategies, farmers' access to early-warning information, access to credit facilities, and participation in workshops as well as conferences organised by extension consultants (Arimi, 2014) (table 3) (Appendix A: table S4). In the regions of Bangladesh, Vietnam, Thailand, Fiji, India, and the United States, common sets of adaptive responses in small-scale aquaculture are specifically applied (Schmitt et al., 2013, Frisch et al., 2015, Lebel et al., 2015, Bunting et al., 2017). The most commonly documented responses to flooding are building higher pond-dikes, netting and fencing around the low elevated ponds, community-based flood protection, and changing stocking dates (Boonstra and Hanh, 2015, Ahmed and Diana, 2016, Oviedo et al., 2016). Pumping out groundwater, changing fish culture accordingly, and rain water harvesting are some of the common responses documented for drought conditions (Oviedo et al., 2016, Lebel et al., 2018b, Limuwa et al., 2018). However, adaptive responses across studies vary based on geographical region and the scale of the operation.

3.6 Adaptive strategies in aquaculture

Thirty-seven percent of studies were clearly aimed at analysing and documenting adaptive strategies of aquaculture systems at various scales (community, regional, and national). Interestingly, all the studies aimed at adaptive strategies in the aquaculture context focus on countries in the global south (Dey et al., 2016a, Dey et al., 2016b, Ho et al., 2016, Li et al., 2016, Oviedo and Bursztyn, 2016, Tran et al., 2017, Nguyen et al., 2018) and half of these studies were initiated by countries in the global north. Such southern countries are adapting by using various strategies, implemented from the local level to the national level; those strategies can be categorised as future-benefit, easier early, and up-front (Lebel et al., 2018a) (table 3) (Appendix A: table S4). Many strategies developed in selected case studies are specific to the region or country, which also considers the complexity and uncertainty of multiple climate change impacts embedded in aquaculture systems (Oviedo and Bursztyn, 2016, Lebel et al., 2018a). At the national level, in the marine policy sector, aquaculture itself is considered a strategy for adapting to climate change impacts; for instance, the Solomon Islands, Vanuatu, Timor-Leste, Fiji, and Vietnam included aquaculture as a national adaptation strategy within the natural resource sector plans (Dey et al., 2016a, Dey et al., 2016b, Dey et al., 2016c, Rosegrant et al., 2016). The majority (81%) of adaptive strategy studies focus on the regional scale to the national scale, with only about 19% focusing on the community scale (Arimi, 2014, Lebel et al., 2015). Economic impacts, food security, and adaptive capacity are three highlighted conceptual areas used to study the adaptive strategies of aquaculture (Arimi, 2014, Dey et al., 2016a, Dey et al., 2016b, Rosegrant et al., 2016). Furthermore, 75% of such adaptive strategies studies are conducted using mixed research methods (qualitative and quantitative) using both primary and secondary data; only 25% of studies based on primary data are driven by a qualitative design.

3.7 Management approaches in aquaculture

Apart from adaptive strategies, studies identified four key management approaches for climate impacts adopted in aquaculture resource management and in other areas such as adaptation planning, community-based management, adaptive management, and government support (Appendix A: table S5). The first approach is regional-level 'adaptation planning' related to aspects of aquaculture resource management (mostly shrimp aquaculture) studied in Vietnam, Bangladesh, Australia, and Thailand (Bosma et al., 2012, Lim-Camacho et al., 2015, Lebel et al., 2016, Bunting et al., 2017). The second key management approach is regional 'community-based adaptation' (or community-based management), employed in particular against climate change impacts such as ocean acidification in coastal aquaculture (Frisch et al., 2015), more frequent intense precipitation in shrimp aquaculture (Bunting et al., 2017), and floods, droughts, sea-level rise, and sea surface temperature changes (Ahmed et al., 2014). Third, 'adaptive management' is documented as an approach for adapting to the implications of climate uncertainties in the context of inland and coastal aquaculture systems in Italy, Vietnam, and Malawi (Canu et al., 2010, Pham, 2017, Limuwa et al., 2018). Fourth, we identified 'government support' and attention at the community and regional levels as an approach for dealing with the impacts of climate change (Paprocki and Cons, 2014, Spillman et al., 2015, Rodríguez-Rodríguez and Ramudo, 2017).

Moreover, aquaculture management uses various aspects of adaptation to climate change, such as adaptive options, responses, processes, measures, and pathways. For example, adaptation measures were studied in an inland aquaculture setting on the southeast coast of India so as to adapt to the impacts of coastal erosion and potential sea-level rise (Jayanthi et al., 2018). Other unique methods of managing climate change impact are to use GIS and remote sensing to select new aquaculture sites (Liu et al., 2014). Another innovative solution used in Australia is to monitor progress towards sustainable goals in salmon aquaculture (Miller, 2000, van Putten et al., 2014, Fleming et al., 2017).

3.8 Policy contributions

Over 70% of the studies address specific aspects of policy implications related to adaptation to climate change in aquaculture. Forty-eight percent of these studies are initiated by the same country (i.e., the research location and first author affiliation are the same) (Arimi, 2014, Lim-Camacho et al., 2015, Bunting et al., 2017). These 31 studies were published in 16 journals, including multiple publications in *Marine Policy* and *Regional Environmental Change*. Among the studies that do not directly address such policy implications (about 30%, n=13), 69% of them are initiated by the same country; these studies are published in 13 journals. Some of the most highlighted policy implications are recorded from Asian Pacific Island countries (Dey et al., 2016a, Dey et al., 2016b, Rosegrant et al., 2016). For example, adaptation policy implications in Fiji include various natural resource management practices, including marine protected areas and locally managed marine areas, the ridge-to-reef concept, alternative livelihood developments, inshore low-cost fish aggregating devices, improve the coherence of government fisheries regulations, finance literacy, aquaculture, improvement of post-harvest quality, and waste reduction (Dey et al., 2016a). The Solomon Islands is implementing natural resource management approaches in its adaptation policy, including upstream watershed management, marine protected areas and locally managed marine areas, and the conservation and restoration of mangroves. The integration of aquaculture into policy, such as Taiwan's policy, can have implications for food security by mitigating uncertainty and enhancing resilience to climate change in the fisheries and aquaculture sectors (Ho et al., 2016).

4. Discussion

Asian countries such as China, Indonesia, India, Vietnam, and Bangladesh lead world aquaculture production (FAO, 2018). Climate change can bring unexpected impacts to these countries' labour-intensive aquaculture systems with their respective livelihoods and local economies (FAO, 2018). Most of the studies focus on aquaculture production systems in Asia, where most aquaculture production takes place (FAO, 2018, Cai et al., 2019). However, based on the first author affiliation, the top three publishers on climate change adaptation in the context of aquaculture are the US, Thailand, and Australia (Figure 2). Some global north countries almost exclusively initiate studies in the south. We did find that an increasing number of studies are initiated by the same country (e.g., Vietnamese authors studying Vietnam). This finding is important because of the place-specific nature of climate change impacts and the study of aquaculture systems from a local perspective. This is one of the primary goals of successful climate adaptation research which can be more effective with respect to sustainable aquaculture (Adger et al., 2005, Osbahr et al., 2010, Piggott-McKellar et al., 2019).

The implications of the impacts of climate change on aquaculture reflect the high level of complexity embedded in aquaculture social-ecological systems. We identified diverse ways in which climate change impacts aquaculture (Figure 3). These identified climate vulnerabilities support previous global assessments of aquaculture (FAO, 2015, Seggel and De Young, 2016, FAO, 2017) and reflect the unidentified climate impacts within the scope of the study. We identified three categories of climate change impacts based on the documented ways in which people experience such changes: simultaneous multiple impacts (e.g., heat waves and extreme weather events); mixed and interrelated impacts (e.g., disease outbreaks and economic impacts to supply chains); and geographically-specific impacts (e.g., storms) (Canu et al., 2010, Ahmed et al., 2014, Bunting et al., 2017, Tran et al., 2017, Hoque et al., 2018, Galappaththi et al., 2019). About 18% of the studies are aimed at climate change in general (no specific hazard identified) without capturing specific climate impacts, which may limit our ability to better track global impacts in aquaculture.

We identified three categories of responding to the implications of climate change impacts on the global aquaculture setting: 1) coping mechanisms, 2) adaptive strategies, and 3) management approaches for adaptation. First, coping responses are widely practiced by aquaculture farmers across the world to deal with the diverse range of climate impacts at the farm (or local) level (e.g., minimising fish stress through biosecurity measures). These responses are applied in a broad range of regions (e.g., Bangladesh, Vietnam, Thailand, Fiji, India, and the United States) and are characterised by a) a short-term nature, b) a technical nature, c) low/no-regret-type responses, and d) a response to specific climate impacts (Schmitt et al., 2013, Ahmed et al., 2014, Lebel et al., 2015, Lebel et al., 2016, Bunting et al., 2017, Lebel et al., 2018a). In FAO (2017) reports, coping mechanisms are identified as adaptation measures, while in general aquaculture literature, such responses are documented as pond water management techniques (Lucas et al., 2019). As suggested by the recent IPCC 1.5°C report, community-level coping mechanisms and collective responses can be enhanced by local governments influencing mitigation and adaptation (Araos et al., 2017, IPCC, 2018).

Second, we identified diverse multi-level adaptive strategies in aquaculture to deal with climate change impacts (FAO, 2017). Changing cultural practices (e.g., species, production systems) can be an effective climate adaptation strategy, as suggested by several cross-sectoral researchers including the IPCC (Altieri and Nicholls, 2017, Handisyde et al., 2017, IPCC, 2018). In our review, all recorded studies were limited to the global south and the identified strategies are mostly specific to a country, region, or community. However, most of the recorded adaptive strategies focus on the regional and national levels. We identified three characteristics of adaptive strategies: i) applied in a multi-level context (mostly top to bottom), ii) of a long-term nature (bring future benefits), and iii) responds to a broad range of climate impacts and sectors (e.g., to adapt to mixed implications in the areas of aquaculture and agriculture). For example, protecting and restoring the ecosystems of Amazon flood plains in Brazil is a specific adaptive response to climate impacts affected by the local people in Amazon communities (Oviedo et al., 2016). Furthermore, we identified more geographically generalisable adaptive strategies such as community-based watershed management, the installation of rainwater harvesting tanks, the use of rainwater for fish culture and pond-dike cropping (Ahmed and Diana, 2016), and the development of new export markets and the strengthening of existing markets for farmed fish products to achieve higher farm prices (Dey et al., 2016a, Dey et al., 2016c), which can be used with appropriate changes. In the national-level climate change adaptation policy context, "aquaculture" is identified as an adaptation strategy for food security and economic development (e.g., Fiji, the Solomon Islands). Beyond the scope of our study, we identified useful adaptive strategies including the use of a zonal crop calendar system to manage shrimp aquaculture disease conditions aggravated by climate change impacts (Galappaththi et al., 2019).

Third, we identified four management approaches: i) adaptation planning (Preston et al., 2011, Pearce et al., 2012), ii) community-based management/adaptation (Ford et al., 2018, Piggott-McKellar et al., 2019), iii) adaptive management (Beymer-Farris et al., 2012, Fidelman et al., 2017), and iv) government support (co-management-like arrangements) (Armitage et al., 2007, Plummer et al., 2012, d'Armengol et al., 2018). These management approaches could create or support local-level coping mechanisms and multi-level adaptive strategies that are widely documented in several other sectors and the climate change adaptation literature in general (d'Armengol et al., 2018, IPCC, 2018, Rahman and Hickey, 2019). Adaptation planning is about addressing broader climate adaptation concerns that are initiated at the government level (e.g., National Adaptation Plans) (Rahman and Hickey, 2019) and mostly overlaps with the policy development that leads to adaptive strategies and actions (e.g., the Solomon Islands, Taiwan). Community-based management is implemented primarily at the local level and mostly supports (but is not limited to) short-term local adaptive responses (Hung et al., 2018, Piggott-McKellar et al., 2019). Adaptive management can happen at a broader multi-level from national to community (d'Armengol et al., 2018). Government support of community-based adaptation could lead to adaptive co-management efforts to address climate change impacts. These approaches are not limited to aquaculture and are more commonly documented in small-scale fisheries aimed at highly natural-resource-dependent populations such as Indigenous populations (Berkes and Armitage, 2010, Armitage et al., 2011, Galappaththi and Berkes, 2015, Galappaththi et al., 2019). As suggested by the recent IPCC 1.5°C report, enhancing multi-level governance, institutional capacities, lifestyle and behavioural changes, and technological innovations, as well as strengthening policy, are key means of supporting these global adaptation responses to climate change impacts (IPCC, 2018).

Adaptation to climate change in aquaculture is a growing area of study but we found that limited research has been published in peer-reviewed journals. Certainly, we recognized the documented knowledge about climate change in aquaculture, which could not be captured in our methodology (e.g., De Silva and Soto, 2009, Phillips and Pérez-Ramírez, 2017, Dabbadie et al., 2018, Johnson et al., 2019). Yet, the aquaculture sector can benefit from specific studies aimed at climate adaptation, which enable a deeper understanding of climate change impacts and adaptive responses related to aquaculture. For instance, most commonly cultured species groups in world aquaculture (e.g., freshwater fin fish, macro algae) (Cai et al., 2019) are not adequately represented in the current adaptation literature. In some regions, it is difficult to distinguish between various aquaculture systems because of the complexity of such human-environment systems. Subsistence aquaculture for personal use is quite different from, but related to, small-scale aquaculture and then to commercial aquaculture (e.g., the co-existence of subsistence and commercial aquaculture systems) (Galappaththi et al., 2019, Galappaththi et al., in review). Further, limited conceptual and methodological consistency with respect to examining adaptation has made our analysis across case studies more obscure as regards climate adaptation policy development. However, this study helps us better understand possible ways forward with respect to climate adaptation research in aquaculture.

5.0 Directions for future research

An important component of systematic reviews like that completed here is to identify directions for future research based on an understanding of the current state of knowledge. In our study, research on climate change adaptation in aquaculture systems is recent, beginning in 2010 (Figure 1), and flagged only 44 publications. However, using broader search criteria (searching terms of aquaculture and climate change), Dabbadie et al. (2018) show a higher number of publications related to climate change in aquaculture (Appendix A: figure S1). Thus, the research area of climate adaptation in aquaculture has significant potential for further development (FAO, 2017). For example, our study found that, currently, the peer-reviewed literature contains no documented evidence regarding how climate change affects inland aquaculture in global north countries. While it is important to focus on aquaculture communities in the developing world (including Asia), to advance the field of research it is also important to study aquaculture systems in non-Asian countries that are equally vulnerable to climate change (e.g., Haiti, Nigeria) and/or that are reliant on aquaculture for livelihoods.

Scale is an important focal area in adaptation research (Adger et al., 2005, Handisyde et al., 2017). In this study, no studies were conducted at the household level and very few studies were conducted on a global scale, for any type of aquaculture. Studies at the household level are needed so as to create an understanding of the adaptation realities of bottom-level aquaculture-dependent vulnerable families. Studies at the international level are needed to uncover broader pictures of adaptation and to help answer key questions such as: Are we adapting?; How are we adapting?; and What are the research gaps that need to be addressed? (Berrang-Ford et al., 2011). For example, a broad understanding of effective ways to govern adaptation and specific barriers to adaptation across scale, as well as assessing community adaptation to scale-up in the aquaculture context, are potential research areas that warrant scholarly attention.

Similarly, some types of aquaculture—such as inland aquaculture at the community level and at the national level—remain seldom studied; most studies on climate change adaptation in inland aquaculture are at the regional scale. Inland aquaculture has many potential benefits to locals in terms of nutrition, livelihoods, and food security, as only 40% of the world's population lives in coastal areas (Katiha et al., 2005, Seggel and De Young, 2016). Specifically, inland aquaculture provides direct food security to some of the world's poorest populations in developing African and Asian countries—including those that are at a high risk of climate impacts related to water quality and availability (Johnson et al., 2019). However, the focus on coastal aquaculture can be explained by the fact that coastal aquaculture is more climate-dependent—coastal farmers can face greater risks and more tangible impacts, such as sea-level rise, ocean acidification, and unexpected extreme weather events. For example, ocean acidification and an increasing sea surface temperature could further complicate the lucrative black pearl industry in Polynesia; such increasing temperatures could affect pearl quality by disturbing the nacre deposition rate and increasing the susceptibility of pearl oysters (*Pinctada margaritifera*) to disease (Marie et al., 2012).

While most studies investigate small-scale aquaculture farmers (Galaz et al., 2012, Fleming et al., 2017), they do not explore differences among farmers. It would be of interest for further research to study whether certain groups of aquaculture farmers are more affected by climate change, more willing to adapt than other groups, or less able to adapt than other groups. For example, from the selected papers, it remains unknown whether Indigenous farmers are unequally impacted or unequally able to adapt to climate change. Based on first-hand experience, we know that Indigenous people in aquaculture face uniquely different vulnerabilities as compared to other aquaculture communities and that these systems have seldom been studied (e.g., reservoir aquaculture of the Coastal-Vedda people in eastern Sri Lanka). A comparison of case studies will help create a broader understanding of climate adaptations in aquaculture.

The conceptual approaches used vary among selected publications; particularly, we can see that the type of approach used varies by continent. Most publications combine several theoretical approaches to produce a novel conceptual approach. This is explained by the fact that research in social aspects of climate change adaptation in aquaculture is interdisciplinary by nature and that, to understand the complexity of adaptation responses in the social dimension, multiple approaches must be employed (e.g., social-ecological systems resilience, ecosystem management) (Kelly et al., 2019). The lack of studies using the vulnerability and political ecology approaches may indicate a limited focus on power and dispossession in studies (Veuthey and Gerber, 2012). Currently, authors from developed countries employ the systems approach the most, mainly to study Asian and Pacific aquaculture, whereas authors from developing countries mostly study themselves and use the sustainability and livelihoods approach to uncover how livelihood (mostly of the poor) and the environment are interlinked. Consistency and/or comparisons between methods could be taken into consideration in future research.

GIS and remotely sensed data are used extensively in modelled/predictive studies in aquaculture (Saitoh et al., 2011, Meaden and Aguilar-Manjarrez, 2013). Although only two case studies use GIS and remote sensing, they could bring more value, as they could be a cost-effective management tool revealing broader insights (Smith et al., 2013, Liu et al., 2014). Both case studies conduct spatial analysis over a large temporal and spatial scale. In both cases, the authors used GIS and remote sensing to understand the impacts of complex physical processes, e.g., ocean circulation. These kinds of data could be related to, and combined with, traditional and local knowledge of local farmers to better understand and project the effects of climate impacts and the use of adaptation from their perspective (Folke et al., 2003, Galappaththi et al., 2019). This brings forth the question: Could the use of GIS and remote sensing improve climate change adaptation research and aquaculture management in the future? Such tools are cost-effective and help visualise changes and impacts on a broader temporal scale, at all spatial levels. They could provide needed information for adaptation planning and informed decision-making towards sustainable aquaculture.

Much attention and many resources are likely needed to help the aquaculture sector develop strategies and tools to adapt to current and future climate change. Our study highlights the ways in which climate change impacts can affect aquaculture systems and adaptation responses that can affect global aquaculture production. A decrease in aquaculture production has impacts for farmers as well as for a growing world population, as it is interlinked with food security (Béné et al., 2015, Béné et al., 2016, FAO, 2016). It is pivotal for climate change adaptation research to continue studying and improving adaptation in aquaculture settings. If climate change adaptation research in aquaculture redirects itself towards more national and regional adaptation strategy and policy development, while scaling-up community adaptations, it could not only increase production but also help alleviate poverty and improve food security for a vast number of populations.

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Appendix A. Supplementary material

Table S1: Definitions of terms used for search engine Web of Knowledge.

Climat* Chang*: This term refers to climate or climatic change related to aquaculture production systems and the associated geographical region.
Fish* Farm*: This term refers to the fish farm or farming production system that carried out aquatic species production.
Aquaculture: This term refers to the culturing or production of aquatic species under controlled aquatic environments.
Adapt*: This term refers to human adaptation or adaptive management to climate-associated changes related to aquaculture systems.

Search terms in the TOPIC field

1. "climat* chang*", "fish* farm*" AND "adapt*"
2. "climat* chang*", "aquaculture", AND "adapt*"

Search in the TOPIC field searches for terms in the following portions of publications:

- Title
- Abstract
- Author Keywords

"climate change"- terms searched within quotations marks "" will return only results with both words exactly as they appear between the quotes.
"Climate Change" AND "adapt" finds records containing the words "climate change" and "adapt". The two strings may appear in the same Topic field or they may appear in different fields.
farm* finds records containing the words farm, farming, farmer, and so on as long as the string of letters before the * is present.

Table S2: List of countries with authors who produced the most publications, and the research location of those authors.

Author's country	Location studied	Number of cases	Total cases
USA	Bangladesh	3	10
	Vanuatu	2	
	Timor-Leste	2	
	Solomon Ilds	1	
	Fiji	8	
	USA	1	
Australia	Australia	4	5
	Vietnam	1	
Thailand	Thailand	5	5
Vietnam	Vietnam	4	4
UK	Vietnam	2	4
	Bangladesh	2	
Canada	India	1	2
	Vietnam	1	
Netherlands	Vietnam	2	2
Sweden	Global	1	2
	Vietnam	1	
Bangladesh	Bangladesh	2	2

Brazil	Brazil	1	1
China	China	1	1
India	India	1	1
Italy	Italy	1	1
Japan	Japan	1	1
Malaysia	Indonesia	1	1
Nigeria	Nigeria	1	1
Norway	Malawi	1	1
Taiwan	Taiwan	1	1

Note: The total number of case studies does not equal the total number of publications because a publication can include more than one case study.

Table S3: Conceptual approaches to studying climate change adaptation in aquaculture.

Conceptual approach	Description	References
Social-ecological systems	SES explicitly links the social and ecological sub-systems for the evaluations of the integrated system. This approach emphasizes neither purely ecosystems nor societies; rather, the SES is the unit of study.	Berkes et al., 1998
Resilience	The resilience concept provides a means of measuring thresholds, uncertainty, and surprise inherent in the coupled human and natural systems.	Folke, 2016
Ecosystem-based management	A holistic approach that manages human impact on ecosystems and takes these effects into account in decision making.	Long et al., 2015
Knowledge systems	The co-evolving cumulative body of knowledge (including observations, experience, lessons, and skills) belonging to a specific human-environment system (or place) and handed down through generations by cultural transmission; reflects local and/or Indigenous people's cultural identity.	Berkes, 2012
Integrated farming systems	The co-culture of organisms to produce additional valuable crops and remove nutrients and materials wasted from intensive feeding.	Bosma et al. 2012
Vulnerability Approach	An evaluation of the exposure of groups, individuals, or ecological systems to a climate change, their sensitivity to the disturbance, and capacity to absorb change.	Arimi, 2014, Orchard et al., 2016
Economic Impacts	An assessment of the economic impacts of climate change on aquaculture.	Dey et al., 2016a, Dey et al., 2016b, Rosegrant et al., 2016
Sustainability/Livelihoods	Comprehensive approach to assessing the environmental and economic resources needed for individual or community well-being.	Nguyen et al., 2017, Hossain et al., 2018, Limuwa et al., 2018
Adaptive Capacity	Capacity of systems to adjust to potential change.	Arimi, 2014, Lim-Camacho et al., 2015.
Resource Management	Managing the ways in which people and natural landscape interact, particularly in the context of climate change (e.g., co-management and adaptive management).	Bunting et al., 2017, Nguyen et al., 2017, Hossain et al., 2018, van Putten et al., 2014,
Risk and Uncertainty	Risk assessment, risk management through the identification of the nature and estimate the magnitude of risk associated with climate change.	Spillman et al., 2015, Ho et al., 2016, Lebel and Lebel, 2018, Lebel et al.,

		2018a, Lebel et al., 2018b
Human Perceptions	An assessment of public understanding and awareness of adaptation and mitigation.	Frisch et al., 2015

Table S4: Definitions of types of coping mechanisms and adaptive strategies (building on Lebel et al., 2018).

Type of coping mechanism	
No-regret	Short-term (or immediate) actions could be taken to cope with climate variability that brings no harm (and no risk) to the aquaculture system.
Low-regret	Short-term (or immediate) actions could be taken to cope with climate variability that could bring minimal harm to the aquaculture system.
Type of adaptive strategy	
Future-benefit	Implementation of a series of actions/plans over the long-term that allows the aquaculture system to adapt to climate impacts with benefits in the future.
Easier-early	Implementation of a series of actions/plans over a relatively short period with relatively less effort/fewer resources that allow the aquaculture system to adapt to climate impacts with relatively immediate benefits.
Up-front	Implementation of a series of actions/plans over the short-term that allows the aquaculture system to adapt to climate impacts with immediate benefits after application.

Note: This table provides essential definitions for table 3. The terms ‘short-term’ and ‘long-term’ are difficult to specify, as they rely on the context of the aquaculture system and the adaptive response. Cost-benefit analysis is an integral part of all types of coping mechanisms and adaptive strategies.

Table S5. Management approaches taken in aquaculture.

Management approach	Description	References
Adaptation planning	A process to analyse, select, and prioritize possible responses to address a range of climate change impacts and scenarios.	Bosma et al., 2012, Lim-Camacho et al., 2015, Lebel et al., 2016, Bunting et al., 2017
Community-based adaptation	A bottom-up process that involves active participation and engagement of community members to adapt to a range of climate change impacts and scenarios.	Frisch et al., 2015, Bunting et al., 2017, Ahmed et al., 2014
Adaptive management	An iterative process in which best practices are adjusted given changing conditions and knowledge gained from previous efforts.	Canu et al., 2010, Pham, 2017, Limuwa et al., 2018
Government support	A top-down process that involves active governmental provisioning of resources, such as technical trainings or financial subsidies for individuals or communities.	Paprocki and Cons, 2014, Spillman et al. 2015, Rodriguez-Rodriguez and Ramudo, 2017

Table S6: List of 44 publications including details about the author(s), journal, and year of publication.

Title	Authors	Source Title	Year
Adaptation to climate change as social-ecological trap: a case study of fishing and aquaculture in the Tam Giang Lagoon, Vietnam	Boonstra, Wiebren J.; Tong Thi Hai Hanh	Environment Development And Sustainability	2015

Analysis of the economic impact of climate change and climate change adaptation strategies for fisheries sector in Pacific coral triangle countries: Model, estimation strategy, and baseline results	Dey, Madan Mohan; Rosegrant, Mark W.; Gosh, Kamal; Chen, Oai Li; Valmonte-Santos, Rowena	Marine Policy	2016
Combining participatory approaches and an agent-based model for better planning shrimp aquaculture	Joffre, Olivier M.; Bosma, Roe H.; Ligtenberg, Arend; Van Pham Dang Tri; Tran Thi Phung Ha; Bregt, Arnold K.	Agricultural Systems	2015
Community- based climate change adaptation strategies for integrated prawn-fish- rice farming in Bangladesh to promote social- ecological resilience	Ahmed, Nesar; Bunting, Stuart W.; Rahman, Sanzidur; Garforth, Christopher J.	Reviews In Aquaculture	2014
Cumulative Pressures on Sustainable Livelihoods: Coastal Adaptation in the Mekong Delta	Smith, Timothy F.; Thomsen, Dana C.; Gould, Steve; Schmitt, Klaus; Schlegel, Bianca	Sustainability	2013
Determinants of climate change adaptation strategies used by fish farmers in Epe Local Government Area of Lagos State, Nigeria	Arimi, Kayode S.	Journal Of The Science Of Food And Agriculture	2014
Does climate change matter for freshwater aquaculture in Bangladesh?	Ahmed, Nesar; Diana, James Stephen	Regional Environmental Change	2016
Economic impact of climate change and climate change adaptation strategies for fisheries sector in Fiji	Dey, Madan Mohan; Gosh, Kamal; Valmonte-Santos, Rowena; Rosegrant, Mark W.; Chen, Oai Li	Marine Policy	2016
Economic impact of climate change and climate change adaptation strategies for fisheries sector in Solomon Islands: Implication for food security	Dey, Madan Mohan; Gosh, Kamal; Valmonte-Santos, Rowena; Rosegrant, Mark W.; Chen, Oai Li	Marine Policy	2016
Economic impacts of climate change and climate change adaptation strategies in Vanuatu and Timor-Leste	Rosegrant, Mark W.; Dey, Madan Mohan; Valmonte-Santos, Rowena; Chen, Oai Li	Marine Policy	2016
Economic impacts of climate change: profitability of freshwater aquaculture in China	Li, Sheng; Yang, Zhengyong; Nadolnyak, Denis; Zhang, Yaoqi; Luo, Yuxi	Aquaculture Research	2016
Effect of global change on bivalve rearing activity and the need for adaptive management	Canu, Donata Melaku; Solidoro, Cosimo; Cossarini, Gianpiero; Giorgi, Filippo	Climate Research	2010
Evaluating the contribution of diversified shrimp-rice agroecosystems in Bangladesh and West Bengal, India to social-ecological resilience	Bunting, Stuart W.; Kundu, Nitai; Ahmed, Nesar	Ocean & Coastal Management	2017

Facing the wave of change: stakeholder perspectives on climate adaptation for Australian seafood supply chains	Lim-Camacho, Lilly; Hobday, Alistair J.; Bustamante, Rodrigo H.; Farmery, Anna; Fleming, Aysha; Frusher, Stewart; Green, Bridget S.; Norman-Lopez, Ana; Pecl, Gretta T.; Plaganyi, Eva E.; Schrobback, Peggy; Thebaud, Olivier; Thomas, Linda; van Putten, Ingrid	Regional Environmental Change	2015
Factors affecting farmers' adoption of integrated rice-fish farming systems in the Mekong delta, Vietnam	Bosma, Roel H.; Nhan, Dang K.; Udo, Henk M. J.; Kaymak, Uzay	Reviews In Aquaculture	2012
Fishing for the impacts of climate change in the marine sector: a case study	van Putten, Ingrid; Metcalf, Sarah; Frusher, Stewart; Marshall, Nadine; Tull, Malcolm	International Journal Of Climate Change Strategies And Management	2014
Gauging perceptions of ocean acidification in Alaska	Frisch, L. C.; Mathis, J. T.; Kettle, N. P.; Trainor, S. F.	Marine Policy	2015
Human ecological effects of tropical storms in the coastal area of Ky Anh (Ha Tinh, Vietnam)	Thinh An Nguyen; Dung Anh Vu; Phai Van Vu; Thanh Ngoc Nguyen; Tam Minh Pham; Hang Thi Thuy Nguyen; Hai Trinh Le; Thanh Viet Nguyen; Lich Khac Hoang; Thanh Duc Vu; Tung Song Nguyen; Tuyen Thi Luong; Ngoc Phuong Trinh; Hens, Luc	Environment Development And Sustainability	2017
Impacts of aquaculture on social networks in the mangrove systems of northern Vietnam	Orchard, Steven E.; Stringer, Lindsay C.; Quinn, Claire H.	Ocean & Coastal Management	2015
Impacts of climate change on agro-ecological landscapes in the coastal area of the Thai Binh province (Vietnam) using the Delphi technique	Le Trinh Hai; Nguyen An Thinh; Tran Anh Tuan; Dao Dinh Cham; Luu The Anh; Hoang Luu Thu Thuy; Nguyen Manh Ha; Tran Quoc Bao; Le Van Huong; Uong Dinh Khanh; Bui Thi Mai; Tong Phuc Tuan; Hoang Hai; Quang Hai Truong	International Journal Of Climate Change Strategies And Management	2015
Impacts, Perceptions and Management of Climate-Related Risks to Cage Aquaculture in the Reservoirs of Northern Thailand	Lebel, Louis; Lebel, Phimphakan; Lebel, Boripat	Environmental Management	2016

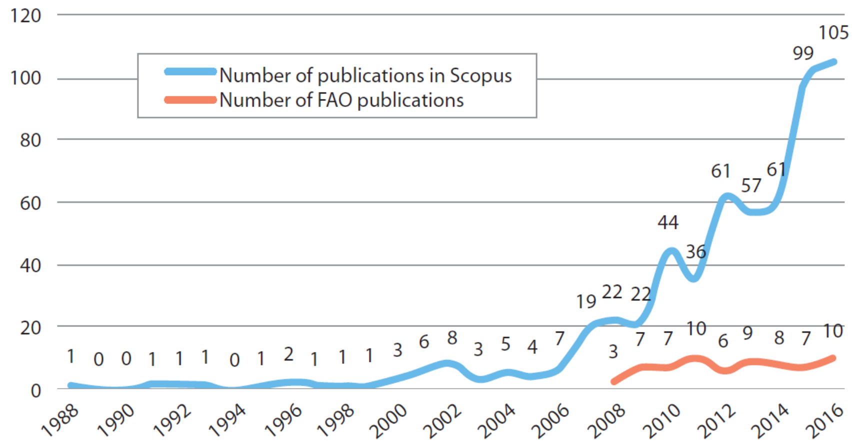
Implementing climate variability adaptation at the community level in the Amazon floodplain	Oviedo, Antonio F. P.; Mitraud, Sylvia; McGrath, David G.; Bursztyn, Marcel	Environmental Science & Policy	2016
Indonesian aquaculture futures: An analysis of fish supply and demand in Indonesia to 2030 and role of aquaculture using the AsiaFish model	Nhuong Tran; Rodriguez, U. -Primo; Chan, Chin Yee; Phillips, Michael John; Mohan, Chadag Vishnumurthy; Henriksson, Patrik John Gustav; Koeshendrajana, Sonny; Suri, Sharon; Hall, Stephen	Marine Policy	2017
Life in a shrimp zone: aqua- and other cultures of Bangladesh's coastal landscape	Paprocki, Kasia; Cons, Jason	Journal Of Peasant Studies	2014
Mangrove system dynamics in Southeast Asia: linking livelihoods and ecosystem services in Vietnam	Orchard, Steven Emmerson; Stringer, Lindsay Carman; Quinn, Claire Helen	Regional Environmental Change	2016
Market driven management of climate change impacts in the Spanish mussel sector	Rodriguez-Rodriguez, Gonzalo; Bande Ramudo, Robetto	Marine Policy	2017
Mitigating uncertainty and enhancing resilience to climate change in the fisheries sector in Taiwan: Policy implications for food security	Ho, Ching-Hsien; Chen, Jyun-Long; Nobuyuki, Yagi; Lur, Huu-Sheng; Lu, Hsueh-Jung	Ocean & Coastal Management	2016
Perceptions of climate-related risks and awareness of climate change of fish cage farmers in northern Thailand	Lebel, Phimphakan; Whangchai, Niwooti; Chitmanat, Chanagun; Promya, Jongkon; Lebel, Louis	Risk Management-Journal Of Risk Crisis And Disaster	2015
Polycentric systems and interacting planetary boundaries - Emerging governance of climate change-ocean acidification-marine biodiversity	Galaz, Victor; Crona, Beatrice; Osterblom, Henrik; Olsson, Per; Folke, Carl	Ecological Economics	2012
Predicting environmental drivers for prawn aquaculture production to aid improved farm management	Spillman, C. M.; Hartog, J. R.; Hobday, A. J.; Hudson, D.	Aquaculture	2015
Site-specific and integrated adaptation to climate change in the coastal mangrove zone of Soc Trang Province, Viet Nam	Schmitt, K.; Albers, T.; Pham, T. T.; Dinh, S. C.	Journal Of Coastal Conservation	2013
The regional impacts of climate change on coastal environments and the aquaculture of Japanese scallops in northeast Asia: case studies from Dalian, China, and Funka Bay, Japan	Liu, Yang; Saitoh, Sei-Ichi; Igarashi, Hiromichi; Hirawake, Toru	International Journal Of Remote Sensing	2014

The sustainable development goals: A case study	Fleming, Aysha; Wise, Russell M.; Hansen, Heidi; Sams, Linda	Marine Policy	2017
Understanding social-ecological change and transformation through community perceptions of system identity	Andrachuk, Mark; Armitage, Derek	Ecology And Society	2015
Emotions, attitudes, and appraisal in the management of climate-related risks by fish farmers in Northern Thailand	Lebel, Louis; Lebel, Phimphakan	Journal Of Risk Research	2018
Managing the risks from the water-related impacts of extreme weather and uncertain climate change on inland aquaculture in Northern Thailand	Lebel, Louis; Lebel, Phimphakan; Chitmanat, Chanagun; Uppanunchai, Anuwat; Apirumanekul, Chusit	Water International	2018
The effects of tactical message inserts on risk communication with fish farmers in Northern Thailand	Lebel, Louis; Lebel, Phimphakan; Lebel, Boripat; Uppanunchai, Anuwat; Duangsuwan, Chatta	Regional Environmental Change	2018
Is Fish Farming an Illusion for Lake Malawi Riparian Communities under Environmental Changes?	Limuwa, Moses Majid; Singin, Wales; Storebakken, Trond	Sustainability	2018
How do local communities adapt to climate changes along heavily damaged coasts? A Stakeholder Delphi study in Ky Anh (Central Vietnam)	An Thinh Nguyen; Anh Dung Vu; Dang, Giang T. H.; Anh Huy Hoang; Hens, Luc	Environment Development And Sustainability	2018
Impacts and responses to environmental change in coastal livelihoods of south-west Bangladesh	Hossain, Mostafa A. R.; Ahmed, Munir; Ojea, Elena; Fernandes, Jose A.	Science Of The Total Environment	2018
Coastal climate change, soil salinity and human migration in Bangladesh	Chen, J.; Mueller, V.	Nature Climate Change	2018
Women's perspectives of small-scale fisheries and environmental change in Chilika lagoon, India	Khan, Fatima Noor; Collins, Andrea M.; Nayak, Prateep Kumar; Armitage, Derek	Maritime Studies	2018
Differential livelihood adaptation to social-ecological change in coastal Bangladesh	Hoque, Sonia Ferdous; Quinn, Claire; Sallu, Susannah	Regional Environmental Change	2018
Shoreline change and potential sea level rise impacts in a climate hazardous location in southeast coast of India	Jayanthi, Marappan; Thirumurthy, Selvasekar; Samynathan, Muthusamy; Duraisamy, Muthusamy; Muralidhar, Moturi; Ashokkumar, Jangam; Vijayan, Koyadan Kizhakkedath	Environmental Monitoring And Assessment	2018

Figure S1: Figure 20.1 from the FAO assessment report (Dabbadie et al., 2018).

FIGURE 20.1

Numbers of published scientific papers per year dealing with aquaculture and climate change in Scopus and FAO databases, as a proxy of interest in the issue



The terms aquaculture and climate change were searched for in the title and/or abstract. The Scopus database includes peer-reviewed papers published in scientific journals, books and conference proceedings. The FAO database includes all publications released by the organization.

Tables

Table 1: Inclusion and exclusion criteria for document selection.

Particulars	Inclusion	Exclusion	No. of studies excluded
Language	English	Non-English	2
Publication type	Research articles, case studies	Synthesis, abstracts, editorials, reviews, meetings/workshops, insights, frameworks	23
Who adapts?	People/social adaptation	Natural systems, fish, plants (for example, studies on how fish adapt to temperature variations)	30
Responses, activities, and actions	Adaptation responses	Mitigation, vulnerability (for example, studies using vulnerability frameworks as the principal theoretical approach)	16
Focus	Practical	Conceptual, theoretical, models (for example, conceptual frameworks and adaptation modelling)	4
Time	Present	Prehistoric, future (for example, studies aimed at the pre-historic adaptation of fisheries)	2
Industry	Aquaculture and/or integrated systems (rice-fish culture)	Others including fisheries (for example, offshore fisheries, agriculture, forestry)	7
Change	Climate-change-related	Not related to climate change (for example, globalisation, impacts of economic recession)	1

Table 2: Definitions of selected variables/terms.

Variable/Term	Definition/Description	Data Type
Year	Published year as mentioned in the WOS data extraction sheet.	Ordinal
Journal	Name of the journal as mentioned in the WOS data extraction sheet.	Nominal
Affiliation country	Name of the country based on the first author's affiliation.	Nominal
Affiliation institution	Name and address of the institution based on the first author's affiliation.	Nominal
Funding	Name of the key sources of research funding as mentioned in the acknowledgement section. We chose the first mentioned funding source when multiple sources existed.	Nominal
Location	Name of the target research location, e.g., specific region and country (for example, Mekong Delta, Vietnam).	Nominal
People	Specific vulnerable group of people studied, if mentioned (for example, scallop fish farmers).	Nominal
Theory	Key theoretical approach(es) adapted (for example, resilience thinking, economic assessments, and supply chain management).	Nominal
Methods	We captured the research design of the study (qualitative, quantitative, or mixed) and the type of data collected (primary and/or secondary). Further, we mentioned whether the paper used any specific methodologies such as remote sensing/GIS and satellite data.	Nominal
Climate change	Study aims regarding aspects of climate change impacts (for example, sea-level increase, temperature variations, climate extremes, or general climate change impacts).	Nominal
Fishery	What type of aquaculture was the study aimed at (for example, shrimp aquaculture, fish culture, and inland aquaculture)?	Nominal
Species	The species that the study was aimed at, if mentioned. We mentioned the name of the species or term 'multiple' when the study focused on multiple species in general.	Nominal
Adaptation	The specific areas (or associated areas) of adaptation applied or studied to examine human responses to climate change. For example, adaptation strategies, adaptive management, adaptation planning, adaptation options, community-based adaptation, adaptive governance.	Nominal
Policy	Whether the main text of the article mentioned the term 'policy' and what it refers to. If the study addressed any policy-related aspects such as recommendations, evaluated the existing policy, or proposed policy options, we considered the answer to be "yes" for our analysis. If the paper contributed to policies and did not mention the term 'policy', we looked for a minimum of three key policy-related references to characterise as 'yes'.	Binary (yes/no)

Table 3: Common adaptive responses and strategies in aquaculture (building on Smith et al., 2013, Arimi, 2014, Ahmed and Diana, 2016, Dey et al., 2016a, Dey et al., 2016b, Li et al., 2016, and Lebel et al., 2018a).

Response type	Response/strategy	Scale/level	Form
Common adaptive responses (for specific climate impacts)			
No-regret	Provide supplementary aeration as appropriate (weather-related stress/variations)	Farm	Technical
	Harvest fish early to reduce losses (extreme weather event)	Farm	Technical
	Frequently monitor water conditions and fish behaviour during high-stress periods (temperature variations, unexpected weather changes)	Farm	Information
	Keeping the pond's water outlet valve open during the raining season (raining seasons)	Farm	Technical
	Share rearing knowledge in fish farming groups and networks (in general)	Community	Institutional
	Adopt good disease management practices to reduce risks (raining seasons)	Farm/ Community	Technical
	Adopt good feed management practices to reduce risks from climate-related stresses (unexpected weather changes)	Farm	Technical
Low-regret	Shift stocking dates and adjust stocking density (floods and droughts)	Farm	Technical
	Buy fingerlings at a nearby site to prevent heat stress due to transportation (heat waves)	Farm	Technical
	Use groundwater to pump (refill) ponds (droughts)	Farm	Technical
	Adjust water infrastructure (stocking tanks) to regulate supply for aquaculture (droughts)	Farm	Technical
	Seek compensation assistance following disaster-related losses (extreme climate events)	Community	Institutional
	Prepare shade roof over hatchery tanks or cages (or grow aquatic weeds in ponds for shelter) (heat waves)	Farm	Technical
	Strengthen cages so that they are less likely to be damaged (floods, extreme climate events)	Farm	Technical
	Enter into contract farming arrangements (for example, leases) (in general)	Farm	Financial
	Stock and harvest multiple fish to reduce risk or switch species reared (floods, droughts, climate-change-influenced disease outbreaks)	Farm	Technical
	Dip ice bags in pond/hatchery to reduce water temperature (heat waves)	Farm	Technical
	Engage in frequent pond water exchange (temperature variations)	Farm	Technical
	Plant fruit trees on pond-dikes and vegetation on pond-slopes (temperature variations)	Farm	Technical
Common adaptive strategies			
Future benefit strategies	Protect and restore ecosystems for flood protection, water storage, and water quality services	Regional	Management
	Provide broad range of higher thermal tolerance breeding	National	Technical
	Introduce new technology at the farm level to improve water productivity through research and development	National	Technical
	Diversify into other business/income sources to subsidise risk reduction investments	Community /Regional	Institutional

	Increase savings to buffer household from losses and still make risk reduction investments	Community	Financial
	Engage in community-based watershed management	Community /Regional	Management
	Engage in research and development to improve climate risk information systems and accessibility	National	Institutional
	Install rainwater harvesting tanks and use rainwater for fish culture and pond-dike cropping	Community	Technical
Easier-early strategies	Engage in zone production so that aquaculture has sufficient water (volume/quality)	Regional	Management
	Support integrated water resources management in which aquaculture stake is recognised	Community/ National	Management
	Engage in on-farm value-added processing	Community	Technical
	Reuse waste and integrate resources into the farm to reduce input costs and dependencies on input suppliers	Community	Management
	Establish early-warning systems to seek information about floods, droughts, and heat waves	National/ Regional	Institutional
	Establish mutual or weather-indexed insurance for aquaculture	National	Financial
	Develop new export markets and strengthen existing markets for farmed fish products, to create higher farm prices	National	Marketing
	Develop standards to improve climate- and water-related risk management	National	Management
Up-front strategies	Construct large-scale water storage and infrastructure development to take into account aquaculture uses of water	National	Infrastructural
	Install water treatment equipment in storage ponds with recirculating technology	Community	Technical
	Provide a protective flood dike around aquaculture ponds	Community	Technical
	Avoid prone areas and shift production site to a lower-risk location	Community	Technical
	Seek opportunities for floodplain aquaculture	Community	Technical

Figure legends

Figure 1: Publications at the intersection of climate change, adaptation, and aquaculture per journal per year from 2008 to 2018.

Figure 2. Map showing research destinations for case studies and the country of the first-affiliated author of the case study.

Figure 3. Climate change impacts studied in selected papers, by percentage, with top study locations.