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Maladaptation to Climate Change Poses a Threat to Future Aquaculture Production

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ABSTRACT

As the effects of climate change become more prominent and impacts intensify, the aquaculture sector must make decisions on adaptation strategies and implement actions that will reduce risks and increase resilience. However adaptation is complex, and there can be many consequences of action or inaction. One of the major risks is maladaptation, when an action that is introduced to minimize a negative effect makes the situation worse, increases vulnerability, or has other undesirable impacts. This study considers how climate change maladaptation can occur across six defined Aquaculture Maladaptation Outcomes: (1) Increased emissions of greenhouse gases, (2) Negative impact on farmed species, (3) Negative ecological or environmental impact at local, regional or international scale, (4) Negative social impact on individuals, communities, or the global population, (5) Negative economic impact on individuals, companies, or the global food market and (6) Reduced adaptive capacity of aquaculture systems. The study further explains that maladaptation could arise through different routes, often unintentionally and could occur at all stages in the production line and associated supply chain (e.g., feed production), such as the farm-level or industry-wide scale, threatening future food production and sustainability of the sector. The distinction between adaptation and maladaptation is not always clear, changing over time and influenced by different factors, so the adaptation-maladaptation continuum is also discussed, as is the need for trade-offs. Finally, seven recommendations are outlined to help advance adaptation to climate change in aquaculture.

1 | Introduction

Across the world, the inevitability of climate change and the severity of impacts have become more apparent [1–3] and attention has turned towards climate change adaptation [4, 5]. Climate change adaptation (hereafter referred to as adaptation) is the process of adjusting to existing or expected future climate changes through reactive or proactive measures [6, 7]. In essence, adaptation should reduce climate risk, increase resilience, or exploit beneficial opportunities [1]. With the increasing severity of climate change impacts, adaptation is likely to involve more transformative approaches in addition to incremental adjustments [8, 9]. In aquaculture, climate change adaptation must aim at minimising impacts from climate change without compromising the biological performance, health and welfare of farmed species, whilst also ensuring the farm/sector has social acceptance, minimises environmental impact and still achieves the desired economic benefits.

Direct and indirect climate change impacts occur throughout the aquaculture sector [10, 11], but the type and extent of impact and the ability of the sector to respond and adapt, will depend on contextual factors such as the species being farmed, the stage of production/supply chain, the location and the level of exposure to climate stressors and potential combinations of stressors [12, 13]. For example, higher temperatures can bring health challenges [14], storms and typhoons can lead to losses of farm stock [15] and changes in upwelling and water circulation can affect the availability of wild seed [16]. For some impacts on aquaculture, there are a range of adaptation options that are already available, under development, or could be implemented if needed [12, 17, 18]. However, adaptation does not always work as originally intended and having a range of options is not necessarily an indicator of success [5], for example what works for one farm, or one part of the aquaculture sector, might not be appropriate for another, depending on several factors such as geographical region, oceanography, production system, or species. Ineffective climate change adaptation leaves a system vulnerable and may be considered a waste of time and resources, but this is not the worst possible outcome. Bad judgement, unwise choices and decisions based on wrong assumptions or insufficient information, may lead to maladaptation, a real danger when adjusting to climate change [7, 19].

In a climate change context, maladaptation is action(s) taken to reduce the negative effects of climate change that instead increase vulnerability or have other negative consequences on individual components of a system, the whole system or others [7, 19, 20]. Since climate change impacts, adaptation and maladaptation occur across different scales [21, 22], a 'system' could refer to any collection of interconnected components that interact for a specific function, for example individual fish, a cage or pond, a socio-economic system or ecosystem. Hence, in the aquaculture sector, maladaptation could arise at different scales and under different circumstances. Identifying maladaptation is complicated, since most adaptation decisions are made with incomplete information like uncertainties of future climate variability and change [23, 24] and it can take time for maladaptation to become apparent [20]. Rather than considering adaptation and maladaptation in a binary system of one or the other, the Intergovernmental Panel on Climate Change [25] states that maladaptation is on the opposite end of a continuum to successful adaptation and that every adaptation action can be placed somewhere along the scale.

To help evaluate adaptation choices, Barnett and O'Neill [19] defined 5 broad dimensions of maladaptation: (1) Increasing emissions of greenhouse gases, (2) Disproportionally burdening the most vulnerable, (3) High opportunity costs, (4) Reduced incentive to adapt and (5) Path dependency. Within each category, a potential action can be compared to alternative options (i.e., no action or other adaptation options). Much like the overall concept of maladaptation, each dimension of maladaptation has its own continuum, where actions can be placed somewhere in the spectrum between adaptation and maladaptation depending on scale and assessment criteria [26]. For example, snowmaking is a common adaptation action that allows the skiing industry to adapt to loss of snow days and changes in snow season due to higher temperatures and reduced snowfall [27, 28]. However, although snowmaking may help a ski resort to remain open, the methods of water extraction range across a continuum from actions that would be considered adaptation (use of reservoirs which also support flood control) to maladaptation (water extraction leads to water shortages and increased conflict with other water users) [28].

In the case of aquaculture, maladaptation may not be easy to recognise, as there are many different and often interacting, factors that influence how climate change will impact the sector and its opportunities to respond [12]. Hindsight may reveal maladaptation, but efforts should be made to avoid maladaptation in the first place as it may be difficult or impossible to correct at a later stage. Better characterisation of the adaptation-maladaptation continuum within the aquaculture sector could provide clarity for industry and stakeholders when setting priorities of adaptation action, including the selection of indicators for evaluation.

This study aims to review the concept of climate change maladaptation within the aquaculture sector and raise awareness that maladaptation to climate change could pose risks for future aquaculture production. Raised awareness improves the ability of industry, researchers, regulators and other associated stakeholders to identify and assess the risk of maladaptation. Potential maladaptation outcomes are identified and contextualised with some examples. The challenge of the climate change adaptation–maladaptation continuum within aquaculture is also highlighted, alongside recognition that trade-offs are required when making decisions on future strategies. Throughout this study, *adaptation* (and the potential for maladaptation) refers to actions and strategies that are intended for climate change adaptation by people, whether individuals, companies, communities, governments or organisations. Other types of adaptation, including evolutionary adaptations and behavioural adaptations by organisms or species, are not considered. *Adaptation strategy* refers to the overall high-level plan that aims to achieve the climate change adaptation goals; *adaptation actions* are the steps taken to implement and deliver the strategy; and *interventions* are deliberate efforts taken to adjust the course of events following an action, targeting a more desirable outcome. Aligning with the IPCC [1, 2, 25], we use the term adaptation when referring to the actions and strategies that aim to reduce the risks of climate change and improve resilience as the intention is to adapt to climate change, even if the outcomes are not adaptation. This study focuses on the routes to maladaptation, where there may be negative outcomes and is not a review of all the advantages and disadvantages of potential adaptation actions and strategies. The focus is on potential negative consequences, but as highlighted throughout, these are not universal or fixed outcomes as the success or failure of adaptation is dependent on multiple factors and specific contexts. Ultimately, the goal is to highlight the risks of maladaptation and the complexity of the climate change adaptation–maladaptation continuum and potential steps to reduce maladaptation risks and improve climate change adaptation in aquaculture.

2 | Recognising Maladaptive Outcomes in Aquaculture

Though a simple metric, searches of Scopus and Web of Science suggest that the term maladaptation is not commonly used in

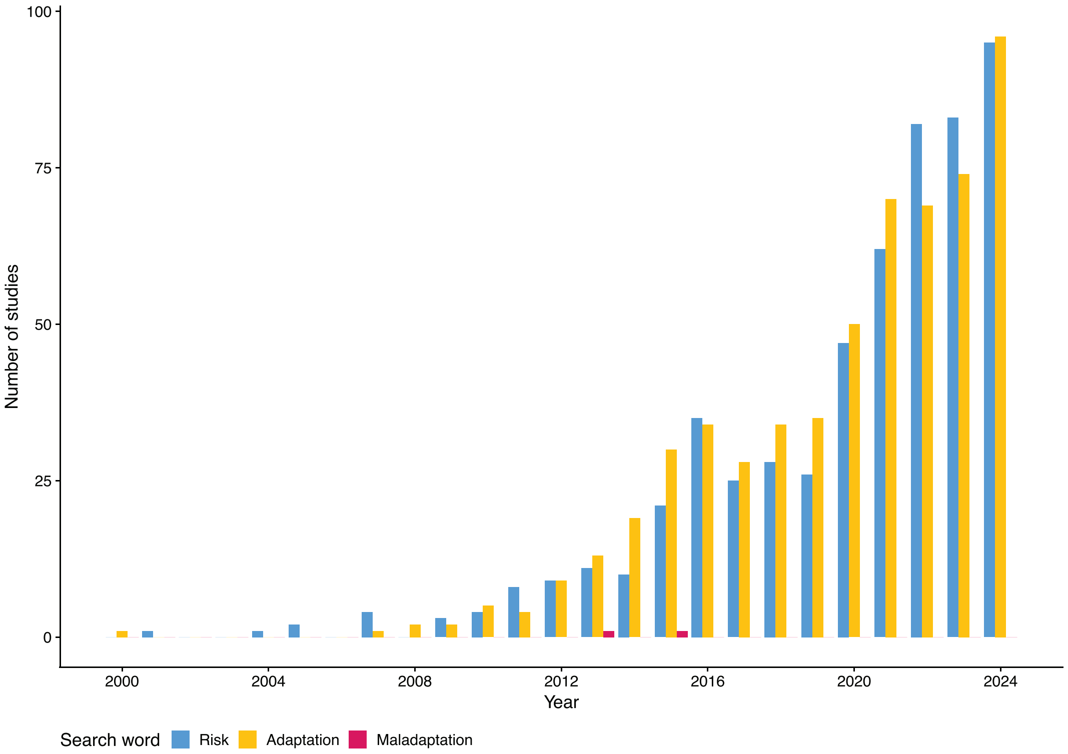

FIGURE 1 | Use of key terms (risk, adaptation and maladaptation) in aquaculture climate change publications.

aquaculture and climate change research articles or reviews (Figure 1). Figure 1 shows the number of records found via a search of Scopus (Titles, Abstract, Keywords) and Web of Science (Topic, Title, Abstract) databases, with Risk referring to the search terms 'Aquaculture' AND 'Climate change' AND 'Risk', Adaptation referring to the search terms 'Aquaculture' AND 'Climate change' AND 'Adaptation' and Maladaptation referring to the search terms 'Aquaculture' AND 'Climate change' AND 'Maladaptation'. The search was limited to Article or Review and was carried out in May 2025 so records were limited to 2024 which was the last full year. Duplicate studies and technical reports were removed. Only two papers were found when using maladaptation as a search term in comparison to 576 for adaptation and 557 for risk. This does not mean the challenges of adaptation are not understood, but specific use of the term maladaptation does not appear to be common.

To understand the risk of maladaptation in aquaculture, context-specific examples may be useful. Here, potential maladaptive outcomes for aquaculture are briefly explored by adapting the five categories of maladaptation defined by Barnett and O'Neill [19] to the specific context of aquaculture. The resulting Aquaculture Maladaptation Outcomes are (1) Increased emissions of greenhouse gases (GHG), (2) negative impact on farmed species (3) negative ecological or environmental impact at local, regional or international scale, (4) negative social impact on individuals, communities, or the global population, (5) negative economic impact on individuals, companies, or the global food market and (6) Reduced adaptive capacity of aquaculture systems (Figure 2).

Aligning with the notion that climate change adaptation and maladaptation are part of a continuum [25], each Aquaculture Maladaptation Outcome has its own continuum, with an opposing Adaptation Outcome (Figure 3). Most actions that aim to adjust to climate change and build resilience will have a place across all of the continuums and there will also be interconnections between strategies that could increase or decrease the risk of maladaptation. Inevitably, when decisions are made on strategies there will need to be trade-offs, as flawless solutions rarely exist and few strategies are entirely positive [7]. Each adaptation action will have advantages and disadvantages; for example the hypothetical Action 1 (Figure 4A) is a good choice for low emissions, but has more negative consequences across other outcomes, whereas Action 2 (Figure 4B) is not a good choice for emissions or the farmed species but is more positive for other outcomes. However, this is not necessarily fixed and interventions could be used to have a more positive effect across more outcomes. For example, the outcomes from Action 2 could be improved with an intervention that would reduce the negative effects on emissions and the farmed species, albeit for an economic cost (Figure 4C).

The different outcomes will not have the same relative importance to each other and the importance assigned to each outcome will depend on the context in which the action is examined. In some cases, there will be external factors that influence the importance of an outcome, for example regulatory thresholds. In other cases, it may be possible to use compensatory interventions to offset maladaptive outcomes with other activities. Ultimately, all choices involve trade-offs and compromise and an action could have maladaptive outcomes across multiple outcomes but still be a good choice overall compared to alternatives.

Deciding where an action would sit on each individual continuum is complicated as clear-cut boundaries are scarce [6].

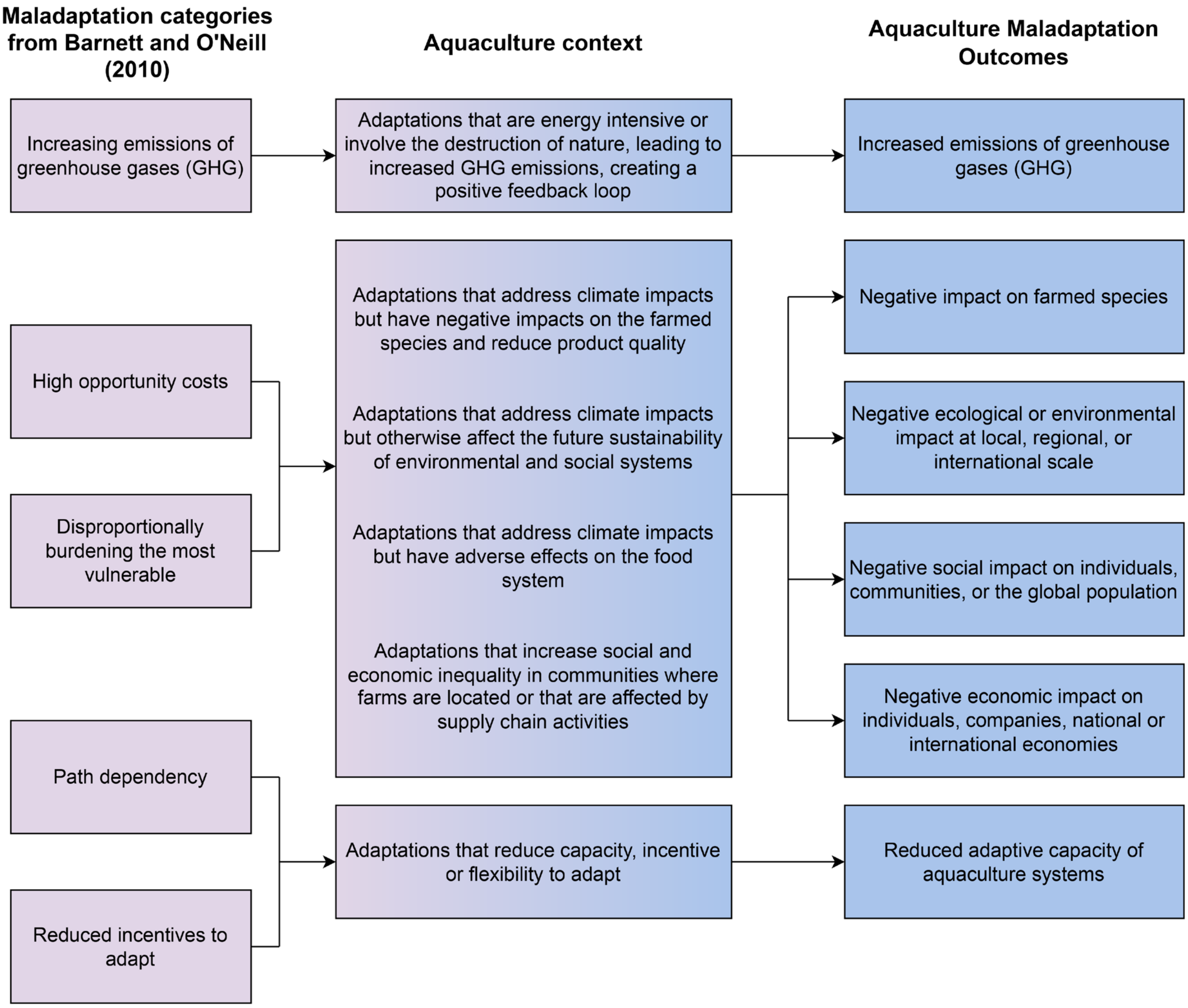

FIGURE 2 | The translation of the five maladaptation categories from Barnett and O'Neill [13] into six Aquaculture Maladaptation Outcomes.

There is likely to be higher consensus on what constitutes adaptation and maladaptation at the extreme ends of the continuum and greater disagreement towards the midpoint of the spectrum [28]. Most companies are used to responding to business risks, but the non-linearity, complexities and uncertainties associated with climate change may require new approaches to understanding risk in a climate context [30]. Within a company, or organisation, attitudes to adaptation will be shaped by internal and external factors [30, 31]. It may be difficult to obtain collective consensus within an organisation or between the organisation and others (e.g., other activities, local communities and wider society). Such conflicts arise because risk perception and attitudes of individuals towards climate adaptation are complicated and influenced by many different factors including emotion, responsibility, agency, personal beliefs and values [32, 33]. Furthermore, the context of adaptation (what, where, why, when, how) will also influence where on the adaptation-maladaptation continuums an action may sit and the same action could have different places on individual continuums for different farms, species and companies, as the context will be different.

An action's place on the adaptation-maladaptation continuum may change over time since adaptation is a process, rather than an end [7]. Accordingly, an action may have short-term maladaptation outcomes, but in the longer term may be a good adaptation strategy or vice versa. Under certain circumstances, it may be possible to predict where on the adaptation-maladaptation continuum an action may sit during the planning and development stage, but for others it may be more difficult, especially where there are knowledge gaps and uncertainties. For some actions, the degree of adaptation or maladaptation could improve or worsen over time or may even fluctuate depending on other factors. The complexity of the adaptation-maladaptation continuum is influenced by the real-world complexities of aquaculture, especially farming systems that take place in the open environment such as sea cages and ponds, since no two production cycles are the same and there are many different non-climate-related factors that could also influence the use and effectiveness of adaptation actions. In addition to changing environmental conditions and industry innovation, changing external factors such as politics and societal values may also influence adaptation and maladaptation at a given point in time. Lack of support, or inappropriate policy and regulation, could lead to maladaptation at the farm scale or industry level. Recognising who is responsible for enabling adaptation strategies and those responsible for implementing adaptation actions [34] is a critical factor as different stakeholders will have different roles that will

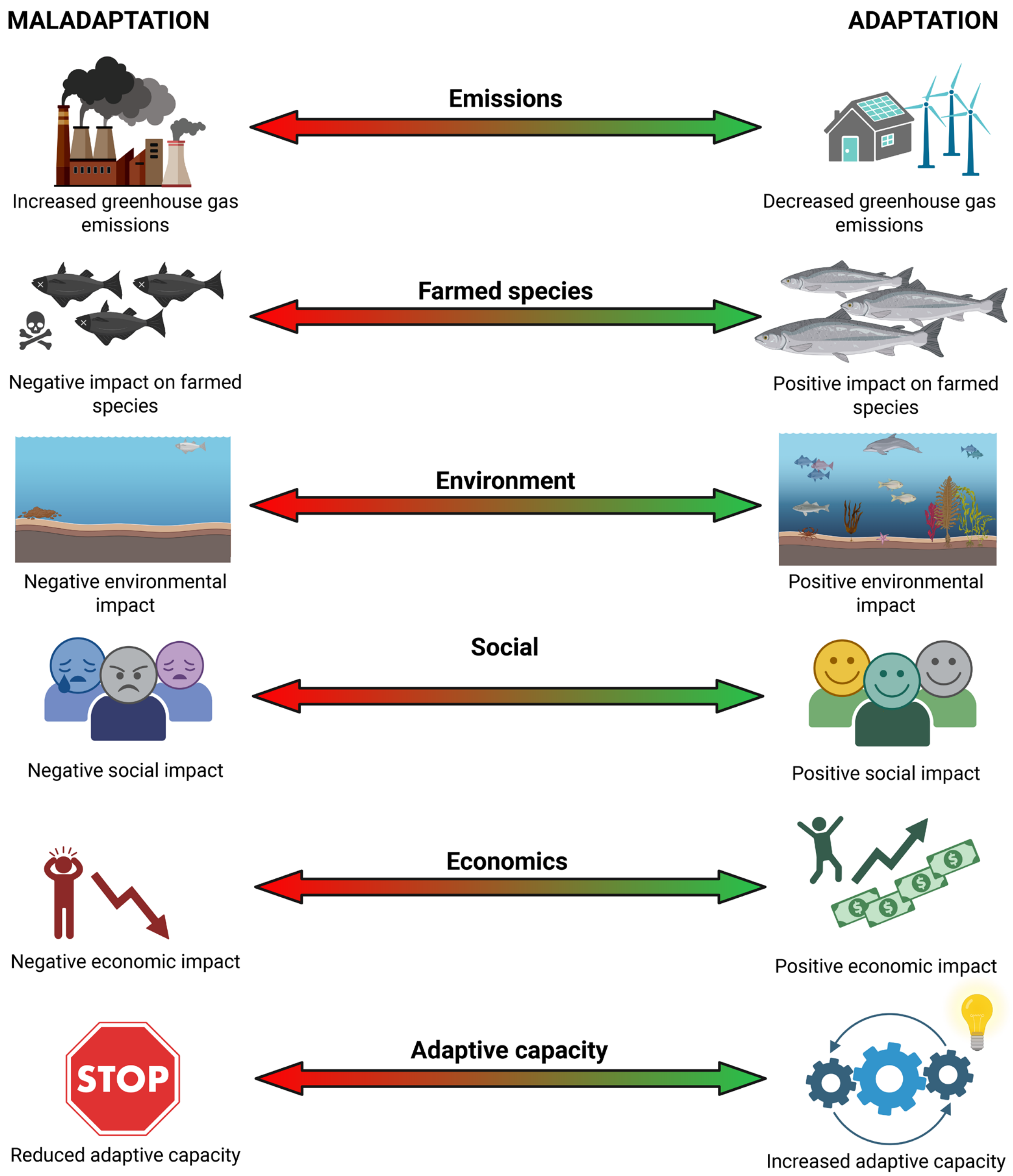

FIGURE 3 | The maladaptation to adaptation continuum for aquaculture and climate change across the six defined Aquaculture Maladaptation Outcomes. Created in BioRender [29].

influence the feasibility and success of adaptation and the risk of maladaptation.

3 | Examples of How Maladaptation Could Occur in Aquaculture

The following sections highlight some examples within each of the Aquaculture Maladaptation Outcomes. There is some interaction between the different outcomes and it is important to recognise that some actions will have multiple maladaptive outcomes, either in parallel or at different time points. One maladaptation outcome could lead to maladaptation in another (e.g., maladaptation leading to negative consequences for the farmed fish due to increased health challenges, will then have negative economic impacts). It is important to recognise that the Aquaculture Maladaptive Outcomes are intended to support efforts to increase awareness of the range of possible routes to climate change maladaptation within the aquaculture sector, rather than group actions into definitive outcomes.

3.1 | Increased Emissions of Greenhouse Gases (GHG)

Almost all countries have ratified or accepted the Paris Agreement, an international treaty that aims to limit global temperature rise to well below 2 degrees Celsius above pre-industrial levels and pursue efforts that limit temperature increases to 1.5 degrees Celsius [35] and any increase in GHG emissions affects this goal. Businesses have an important role to play in limiting emissions [36] and there may even be reputational risk for individual companies or even the entire aquaculture sector if there is a perception that the industry is not committed to climate action

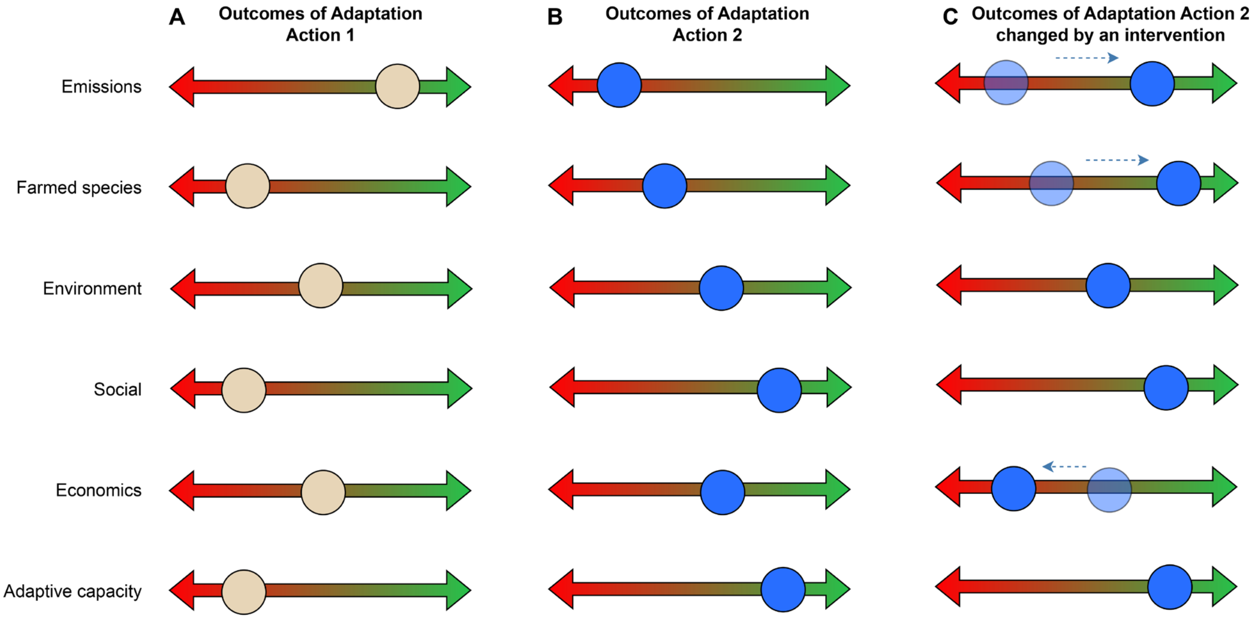

FIGURE 4 | Illustrative examples of actions and where they could be placed across the six different Aquaculture Maladaptation outcomes. (A) A hypothetical example, Action 1, to illustrate how one adaptation action would sit in different positions across the individual continuums for each Aquaculture Maladaptation Outcome. (B) An alternative adaptation option, Action 2, and where it is positioned across the individual continuums. (C) How a hypothetical intervention could move the outcomes of Action 2 (i.e., reduce emissions and environment impact but increase negative economic impact).

[37]. Maladaptation arises if adaptation strategies are responsible for an increase in emissions, directly or indirectly and actions that reduce emissions must be actively encouraged as part of adaptation.

Increased emissions of GHGs could occur through many different routes. Adaptation actions such as a change in farming technology could lead to higher emissions than the original production system. For example, recent analysis by the multinational professional service company, PricewaterhouseCoopers (PwC), found that the energy consumption per kg of produced salmon in land-based Recirculating Aquaculture Systems (RAS) is approximately 13.6 kwh/kg at present, with estimates of 5–8 kwh/kg for future production, higher than the estimated 0.15–1.2 kwh/kg for conventional net-pens [38]. Thus, moving from net-pens to land-based RAS would increase GHGs where energy is supplied by fossil fuels [39]. Similarly, adaptation actions that involve moving locations, for example moving to open-ocean aquaculture or relocating freshwater farms, could increase emissions due to the methods, routes and distances required to access the sites. It is also necessary to consider the supply chain, especially since the greatest proportion of GHGs in fish aquaculture is often associated with feed production [40]. Hence, adaptations that involve changes in the use of feed ingredients to improve fish growth and other production characteristics [41] could also affect the emissions associated with aquaculture production. Maladaptation could emerge if any stages of the supply chain are overlooked and not considered in the context of broader climate change mitigation efforts.

Emissions accounting is not straightforward in aquaculture. GHG emissions occur in numerous ways throughout different parts of aquaculture production and the wider supply chain; there are many complexities and uncertainties in quantifying GHG emissions and the availability and quality of data for GHG emissions is highly variable [40, 42, 43]. Lack of robust data, poor attribution and inadequate accounting of GHG emissions could lead to the misidentification of steps or processes that could be prioritized for adaptation. Similarly, where aquaculture is proposed as a climate mitigation measure, for example removing carbon dioxide with seaweed farms, there must be quantitative data and evidence in place to account for the balance between the total emissions/sequestration for each farm and all associated operations [44, 45]. Overestimates of sequestration potential at individual farms or at the sector level could lead to misguided investments and divert resources away from other climate adaptation strategies [46]. Hence, to avoid maladaptation related to emissions there is a need for robust data and methods for emissions accounting and attribution throughout all parts of the aquaculture sector (production stages, inputs and supply and the wider value chain) as well as the implications of different adaptation actions over the lifespan of their development and use.

3.2 | Increased Negative Impact on Farmed Species

The health, welfare and production potential of the farmed species is reliant on many different factors and so actions designed to alleviate one challenge can often have unwanted consequences and cascading impacts. For example, climate change may lead to new or increased disease outbreaks and health challenges [47, 48], but the necessary treatments could also have negative effects on the farmed species. In Norway, studies have suggested that rising sea temperatures will lead to increased sea lice infections [49, 50], but high use of treatments introduced to combat sea lice is also linked to mortalities and low welfare [51].

Introduction of new production systems intended to separate fish and lice, like the snorkel cage, has also encountered additional challenges, like vertebral malformations [52]. Likewise, adaptation actions that involve new feed ingredients and formulations to reduce the need for wild fish stocks or lessen other climate impacts may bring health and welfare challenges through altered nutritional components, introduction of toxins, or simply by not meeting the nutritional requirements of the farmed species [53–56]. In the case of bivalves, recurring heatwaves and hypoxic or anoxic events in shallow coastal waters can become an issue under climate scenarios [57]. Reallocation of growing sites could be an adaptation action, for example moving farms to deeper and colder waters, but these environmental conditions could impact the performance of the farm as food availability could be reduced, thus affecting species growth potential or product quality.

Breeding programs, technological measures, or development of infrastructure intended to address some climate change impacts may also have undesired effects on the health and welfare of the farmed species. Selective breeding programs are potential adaptation strategies [58] but selecting for one trait could result in a trade-off of others. Focusing breeding on growth [59] may compromise other important traits, like disease resistance [60]. Most farmed fish and shellfish come from stocks that have undergone little to no selective breeding and potential new breeding programs should consider the breeding strategies carefully to avoid important genetic trade-offs [61].

Technological strategies that aim to reduce exposure to climate change through fully or partially closed systems may inadvertently impact animal welfare, growth and product quality. For example, RAS and Closed Containment Systems (CCS) have been developed to better control the farming conditions and try to maintain more stable conditions [62, 63], but both have challenges related to stocking densities, water quality and complex technology that affects the farmed species [64, 65]. Such challenges underscore the need for increased experiments, research trials and modelling studies that investigate the range of consequences of new adaptation strategies and actions and support interventions to optimise farming conditions that result in good health for the farmed species.

3.3 | Increased Negative Ecological or Environmental Impact at Local, Regional or International Scale

Adaptation strategies that increase negative impacts on the environment whether in the farm setting, the surrounding area, or at a larger scale, are a type of maladaptation. In the ecological or environmental context, maladaptation could arise when actions intended to alleviate an impact instead threaten the health or integrity of the environment, reduce biodiversity, increase contaminants or pollutants and have wider effects on ecosystem functioning. This outcome encompasses many different aspects of environmental health and sustainability.

Climate change will not affect aquaculture farms in isolation, and there will be changes in the surrounding environment and wider ecosystem. Adaptation strategies must consider how the current and future farms will interact with the changing environmental conditions as maladaptation could occur if strategies fail to consider how climate change would affect the long-term ability of a location to support the desired form of production and associated adaptation measures. For example, bivalves rely on the delivery of phytoplankton by water currents, which can be altered by climate change [66] as can the phytoplankton community structure [67] so the carrying capacity and suitability of the location to farm bivalves could change over time. Hence, decisions on where to locate bivalve farms based on past environmental conditions or incomplete datasets may potentially risk negative ecological impacts on the food web and ecosystems in the long term. Similarly, in the case of finfish, the way in which aquaculture interacts with the environment depends on the site characteristics, for example sea farm locations with soft substrate versus hard-bottom substrate [68, 69]. To reduce the risk of maladaptation there is a need to understand how aquaculture interacts with the environment in the new locations and how this would differ from existing practices. Maladaptation could also arise if the potential impact is assessed using inappropriate methods, which may be due to inappropriate planning and licencing requirements (e.g., requiring use of procedures designed for one type of environment or technology that is not appropriate for another) [70]. It is also important to recognise that inappropriate assessments could also lead to lost opportunities to move production to more suitable locations. Hence, industry and regulators need to be proactive and revise the environmental impact assessments and monitoring processes for different ecosystem characteristics and new production technologies, for example offshore [71, 72]. For all species and farming systems, the need to understand how the changing environment will affect the suitability of a location to sustain production is of fundamental importance.

Actions aiming to reduce the impact of climate stressors may involve physical changes or modifications to the farm environment or the surrounding area. For example, in the case of ponds, this could include increasing the depth, the creation and use of additional water storage facilities and alterations of water flow through farming systems via new inlets, channels and outlets [73, 74]. Any hydrodynamic changes will have consequences, and for some small-scale on-farm modifications, farm operators should be able to take steps to remediate adverse impacts if noticed in time. On the other hand, there may be regional-scale initiatives involving landscape modifications where individuals and companies have less influence over how their farm environment will be affected. Vietnam's Mekong Delta, a region highly vulnerable to sea-level rise and flooding, provides an example of large-scale adaptation, as hydrological engineering is being used to reduce flooding risks through water management [75]. These anthropogenic changes have significantly altered the hydrodynamics within the delta, but the consequences are complex, with some areas benefiting from improved water management, while others are being disadvantaged including some aquaculture areas experiencing local-scale degradation of water quality and contamination of water resources [76–78]. This example highlights not only the challenge of developing and implementing effective adaptation strategies across spatial scales but also shows the influence that external factors can have on aquaculture production environments, affecting the ability to adapt and influencing the effectiveness of any actions in place.

In some locations there may be interest in introducing new or alternative species as an adaptation action [13, 79]. Potential introductions may include non-native species that are not found naturally in an area but have favorable characteristics for the environmental conditions. Escapes could lead to interactions with wild populations, causing ecological impacts and challenging environmental sustainability [80]. In addition, non-native species could introduce novel diseases and parasites that could affect native populations. For example, the translocation of infected bivalves has unintentionally spread fatal diseases, introducing pathogens to new locations [81], for example movements of Pacific oysters from Asia potentially introduced ostreid herpesvirus to Europe [82, 83]. Some introduced species are also highly invasive, and if conditions are suitable then they can outcompete and displace native species to establish their own populations in new locations [84–86] and climate change may even facilitate accelerated range expansion [87, 88], with negative consequences at a regional or international scale.

Environmental and ecological impacts could also occur due to resource inputs, such as feed. Climate change can affect both the availability and nutritional value of feed ingredients, including marine sourced ingredients [89–91], and terrestrial ingredients such as soy [92]. Hence, adaptation strategies involve moving to alternative feed ingredients and potentially diversifying the range of sources. Development and use of alternative feed ingredients is already an area of intense research focus, especially regarding their sustainability [93–95]. Each potential ingredient has advantages and disadvantages and some have greater possibilities for commercial scalability than others [96, 97]. From an ecological or environmental perspective, the scale of resource use is an important consideration, especially where the potential ingredient has a role in ecosystem functioning. For example, the mesopelagic zone (200–1000 m depth) is thought to contain vast amounts of fish resources that could potentially be used in feed [98, 99]. However, estimates vary and there are still huge uncertainties about the actual amount of biomass and species composition [100, 101], and climate change will also affect the availability and distribution of mesopelagic fish species [102, 103], adding further challenges for biomass estimations and changing food web dynamics. Therefore, the consequences of removing large quantities of mesopelagic resources for use in feed are unknown and so this potential feed ingredient could be a maladaptive choice if there are negative repercussions on local, regional, and global marine ecosystems.

3.4 | Increased Negative Social Impact on Individuals, Communities, or the Global Population

There are many social considerations in aquaculture including food security, employment and working conditions and competition and conflict with other activities for space and resources [104–106]. However, determining negative social impact is complex [106], with societal effects interpreted differently depending on context. Aquaculture communities may hold different beliefs and values that affect their experience and interpretation of social impacts [107–109], values that may or may not clash with wider societal values and goals. The same is true across the supply chain where the allocation or reallocation of resources to adaptation actions could affect other resource users. Adaptation strategies must account not only for what the negative social impacts of adaptation actions are, but also for who experiences those negative impacts to prevent the intensification of gender, racial and economic inequalities.

Aquaculture has commonly been viewed as a promising provider of high-quality proteins that can contribute to domestic and global food security [110]. Nevertheless, the growing global aquaculture sector requires increased feed inputs resulting in the composition of aquafeeds becoming more reliant upon the inclusion of terrestrial plant-based ingredients [111]. Such changes can greatly impact the nutritional composition and quality of the final product [112, 113]. Moreover, competition for crops will be further exacerbated by climate change, including pressure from other livestock productions, direct human consumption, reduced productivity (yields) and changes in production types of crops [114]. Hence, maladaptation could arise due to inefficient resource use, where the societal benefits of seafood consumption are compromised. Additionally, changing climate conditions are predicted to modify plankton populations in terms of their nutrition and availability [91, 115], and this may have further implications on the transfer of nutrients through the ecosystem, including species used to produce fishmeal and fish oil, as well as for non-fed aquaculture species such as molluscs who obtain their nutrients from the surrounding environment. Species diversification is also a potential adaptation strategy [13], but changing species could affect human dietary and nutritional benefits since edible yield and nutritional quality vary considerably between species [113, 116, 117]. Hence, shifting species or methods of production could lead to food and nutritional deficits if the actions have lower yields or limited nutritional value.

In some cases, adaptation strategies may be effective in minimizing direct risks to farmed species but could have negative consequences for farm workers, for example, where the farm environment or technology is adjusted to reduce exposure of the farmed species to climate stressors, for example submerged cages or deeper ponds, but the actions do not consider the working conditions for the farm workers. Farm workers could experience challenging conditions such as storms [118] or heat exposure [119, 120] that could affect their health and safety. Hence, operational procedures and emergency response plans will need to consider the human health and safety issues related to the changing climate and use of adaptation measures such as moving location, new production methods and alternative technologies [121, 122]. Some health and safety concerns can be reduced through actions and interventions that improve working conditions and minimize safety risks, for example use of technology to monitor farm stock if unable to access the site. However if the human health and safety concerns are too high, this will limit the feasibility of an action (likewise if the fish health concerns were too high that would also limit the feasibility, as noted in Section 3.2).

Aquaculture is sometimes promoted as an adaptation response for areas where traditional activities have been impacted by climate change, but there have been examples where this has had some maladaptive outcomes. For example, in response to sea-level rise and saline intrusion, agricultural farmers in Bangladesh converted croplands to shrimp ponds but although the initial results had societal benefits such as employment and poverty alleviation, longer-term negative effects became apparent, including salinisation of drinking water leading to human health problems [123]. Any decision to develop aquaculture in a new or alternative area must consider potential long-term negative effects on local communities and how they can be alleviated; this includes the communities where aquaculture is looking to enter, and those it might be leaving behind. From a farming perspective, it may be necessary to leave one location for another (e.g., rising temperatures beyond species tolerance range). As aquaculture has already grown to huge importance in some regions [124], such actions will also result in social impacts on rural coastal communities already facing challenges, like reduced fisheries employment, demographic changes and climate change [125–128]. It is also important to recognise that actions may just shift risks from one area/activity to another [129] or support one activity at the cost of another, with considerable social impacts. For example, technological innovations in new locations could ensure consumer access to products, like the use of RAS to farm tropical shrimp species in Europe [130]. However, if RAS-produced shrimp outcompetes or reduces the demand for pond-produced shrimp, then livelihoods could be lost in traditional pond farming locations that are still exposed to the effects of climate change, worsening impacts on the most vulnerable.

Climate change is likely to increase conflicts over access and use of space and resources among different activities and industries, as well as protected areas and biodiversity [131, 132]. This is particularly relevant for offshore and open-ocean farming, an emergent form of aquaculture that could compete for spaces with existing users but also other new users, such as offshore energy. The poor understanding of public perception, which is nuanced by local settings and the lack of clear regulatory frameworks for this industry can lead to governance issues and the creation of new social conflicts [133]. Furthermore, the high capital costs for operating these new facilities can become a barrier for small-scale producers, exacerbating the dominant position of large corporations and inequalities [133]. Low social acceptability is already a major barrier to the growth of aquaculture in some jurisdictions [134, 135]. Introducing a new climate change adaptation without considering context-specific social and economic outcomes could have negative consequences for social acceptance, potentially limiting the future production of farmed seafood. Therefore, the development of offshore aquaculture could lead to maladaptation if social and governance aspects are overlooked.

3.5 | Increased Negative Economic Impact on Individuals, Companies, National or International Economies

Adaptation actions that lead to negative economic outcomes for individuals, companies, or at larger economic scales, could be considered a form of maladaptation. Economic considerations can complicate and hinder adaptation, as aquaculture businesses are concerned over financial costs involved with introducing adaptation actions and are also driven by a need to ensure competitiveness [136]. Maladaptation may for instance arise if the sector moves entirely towards costly adaptation strategies that may not be feasible for small-scale companies and businesses without routes to raise finances or gain investors. At the same time, companies must also recognise the need to spend resources on adaptation. Businesses that focus solely on economics and demands for quick returns on investment, increasing profits and stock market expectations may not be flexible enough to develop and implement necessary adaptation strategies.

Adaptation planning will involve some degree of uncertainty, but as a starting point it should be assumed that planning leads to better outcomes and more rational economic decision-making than choosing actions without planning. There will be economic trade-offs associated with the costs of developing and implementing adaptation, with net benefits arising when the damage avoided is more than the adaptation [137]. Economic consequences of adaptation may vary across regions, though, as factors that drive production cost, like growth, mortality, disease, FCR and so forth [138, 139] may be affected differently by adaptation strategies. Higher production costs (and/or lower profit margins) will still be economically rational to implement if the increased cost of adaptation is lower than it would be without adaptation, or if adaptation is required to keep a profitable business running. This goes whether it is about using new technology, relocation, or any other changes in operations to try to keep the basic aquaculture production sufficiently profitable, or to meet regulatory demands for environmental or health and safety concerns, or other societal expectations. Hence, increased costs and lower profits are not necessarily maladaptive, especially if the alternative is for companies to reduce or cease production.

Adaptations involving large-scale technological innovations such as land-based, Closed Containment aquaculture Systems (CCS) or offshore aquaculture may turn out to be an expensive adaptation strategy, as they require higher investment costs and potentially higher production costs [140]. The higher investment, and some higher production cost elements, might be offset by reduced exposure to some climate stressors and associated impacts, but the innovations may also experience other challenges such as water quality and fish welfare [141] that affect product availability and product quality, leading to negative economic consequences. Furthermore, if the route to funding an adaptation action results in price premiums, that is higher price for species grown in a particular way [142, 143], then consumer willingness to pay becomes a consideration, and may lead to maladaptation if the consumers will not pay for higher priced products and returns on investments cannot be achieved. Pangasius farmers have identified costs and lack of price premiums as reasons against using RAS [144]. In line with this, economic maladaptation can occur if there is poor consumer acceptance and products are unaffordable or undesirable.

One of the challenges for adaptation is the complexity of climate change, with non-linear effects, multiple stressors and spatio-temporal variability [145, 146]. Gradual and predictable changes would be easy to adapt to, but that is not reality. Hence, decision-makers need to plan and select strategies and actions under an uncertain timescale, with considerable economic consequences. Adaptations that are unnecessary or inadequate, and do not reduce negative impacts are a waste of resources and a form of maladaptation, but on the other hand it is difficult to know precisely when an impact may occur so it may actually be a form of resilience to have adaptation actions in place, just in case they are needed. A recent example that demonstrates the need to prepare for potential shocks has been observed in Northern Norway, where salmon farms have historically benefitted from colder temperatures that have kept lice pressure low [147]. However, in 2024 the recorded and estimated lice numbers in the North strongly increased, reaching 3–4 times previous years [50, 148]. The sea lice 'explosion' created challenging operating conditions for companies due to the lack of treatment capacity and overwhelming demand for wellboats and treatment infrastructure [147]. Although it is too early to conclude why this massive increase in lice numbers occurred, high sea temperatures that were more than 4°C above average, are considered a contributing factor [50]. In this case, investments to increase treatment capacity, such as more wellboats, would have required planning several years in advance of the impact occurring.

Economic incentives could also help steer actors away from maladaptation and towards the right type and dose of adaptive actions [149, 150], especially for actions that have wider societal benefits beyond individual companies. As described previously in Section 3.1, adaptations that involve shifting to a more energy-intensive production technology or mode of operation may lead to higher emissions of greenhouse gases. Higher energy use will normally also imply higher production costs, but in choosing this as an adaptation measure, the company expects an overall better situation than without adaptation. However, if the company does not have any incentives to hinder (or reduce) extra emissions of greenhouse gas emissions from their chosen adaptation measure, this increases the risk for such maladaptation. Potential interventions include directly regulating the company's GHG emissions, or having a fee on the associated emissions. Increasingly, companies are being asked, or in some cases required, to report on their emissions as part of corporate sustainability reporting and disclosures may influence investor decisions, ability to leverage extra funds and overall company reputation [37]. Therefore, decisions on adaptation strategies must consider wider economic considerations beyond the direct cost-benefits.

Adaptations that have negative ecological or environmental impact (as described in Section 3.3), may also have economic implications, both at the farm/industry level and for society. One example is the use of pesticides for de-licing of salmon, that are later released into the waterbody, and which then may harm non-target organisms, including commercially important shrimp [151], leading to an economic loss both for fishermen and the shrimp-processing industry. Negative effects on ecosystems and species from maladaptation in aquaculture can reduce profits in other industries, like fishing and tourism [152], with further impacts on the local and regional economy through economic ripple effects [153] and on the distribution of income and welfare. Degradation of nature can also affect recreation and human well-being and give indirect economic losses through impacts on somatic and mental health [154]. It can also affect how attractive an area is to live in and affect house prices [155]. People's willingness to pay to maintain and protect biodiversity [156] also implies that environmental degradation can represent an economic loss in that sense.

3.6 | Reduced Adaptive Capacity of Aquaculture Systems

Adaptive capacity refers to the ability of an individual, group, or system to prepare in advance of climate change impacts, or the ability to respond to stressors and events when they occur [157]. Since adaptation is a process rather than an endpoint [7, 158], the emphasis here is on the need for strategies that will enhance long-term resilience with enough flexibility that they do not become obsolete under changing conditions, and do not become barriers to future action. Recognition of potential issues that could affect adaptive capacity is essential in efforts to reduce risks of maladaptation.

Amongst the climate change adaptation literature, path dependency is frequently mentioned as a key route to maladaptation that would affect future actions [19, 20, 26, 158–160]. Path dependency occurs when actions and decisions in the past limit future events or choices; hence strategies are then 'locked-in' to a particular path even if it is not the best route to take [161]. For example, large-scale coastal protection and flood defences that lock budgets, limiting the potential for other adaptation actions [162–164]. Policies and regulations that effectively bind industry to a specific adaptation strategy, for example focusing on a single species or production system, are also a form of path dependency. Similarly, 'techno-optimism,' the belief that technology will be able to address all problems without the need for other strategies or ignoring knowledge gaps, can lead to path dependency [165–167].

A similar concept to path dependency is the sunk cost fallacy, when people choose to continue with an action or behaviour and are hesitant to change direction due to costs (financial, time and other resources) already incurred, despite evidence showing it is a suboptimal strategy [168]. For example, producers may be reluctant to move to new farming methods due to the sunk costs involved in their existing farm setup [169] or an attachment to the place and systems [170]. The sunk cost fallacy can also be a problem during research and development if there is a belief that the scale of investment, effort and persistence will lead to an eventual discovery or solution, despite no or limited evidence that the research direction will have the desired outcomes [171].

Delayed action and reduced adaptive capacity could also arise through the use of insurance, a financial and compensatory mechanism for managing risk across most parts of society [172] and a potential climate adaptation strategy [173–175]. Financial support from insurance can help the insured parties recover faster in the aftermath of an event, and conditions set by insurers can also encourage incentives to minimize exposure to climate change [176]. However, a misguided sense of security could mean that other adaptation strategies are missed or ignored, causing harm in the longer term by reducing adaptive capacity [175, 177]. Insurance is limited to certain operations, and excludes most low value species, so further options would be needed anyway to increase adaptive capacity. Excessive and inappropriate insurance policies that leave a company over-insured and paying more than the value of the risk or insured for unnecessary events, would also be a form of maladaptation.

A further example of delayed action is the use of coping strategies, short-term response measures that will maintain the status quo or restore a previous state [178, 179]. Coping strategies may be used where people have limited capacity to implement other options, or they do not recognise a need for greater change. In some cases, coping strategies may be a necessity or the only choice available, but it is also important to recognise that some may deliberately choose to use coping strategies to maximize short-term gains, and they will disregard or ignore the risk of maladaptation [158]. Examples of short-term reactive coping strategies identified by aquaculture stakeholders include repairing and strengthening pond infrastructure after cyclone damage [180] and replanting seaweed following wind and wave damage [181]. Repairing and replacing may allow production to continue, but the system will still be vulnerable to stressors. As such, coping strategies can become maladaptive [7], particularly if they delay or prevent systemic change (Figure 5A). As a coping strategy becomes maladaptation, interventions such as the deployment of additional resources could be used to return to a coping state and this may even occur over several cycles, but eventually this would become maladaptation as it is difficult to remain in a coping state over the long term (Figure 5B). However, coping strategies could be an important part of an adaptation strategy (Figure 5C), helping to increase resilience by maintaining ongoing activities over a difficult period rather than halting them completely following an initial stressor, thus providing some time to facilitate a more incremental transition to adaptation [182]. To break a cycle of coping-maladaptation there may need to be a significant intervention that repositions the strategy, or introduces an alternative adaptation measure and moves towards adaptation (Figure 5D). For example, if replanting the seaweed is no longer a viable option then a significant intervention would be to move location and farm in a new area. The availability and feasibility of interventions will be context-dependent and of course could also have other consequences that would need to be considered.

Policies, legislation and regulations will be essential in supporting adaptation strategies and actions [183, 184], but if poorly designed, inflexible or inadequate, they could also lead to reduced adaptive capacity, and maladaptation. Maladaptation could occur if policies or regulations force adaptation in a certain direction and prohibit other options (i.e., path dependency), or if they are too fixed and do not provide enough scope to fully implement the necessary adaptation strategies. Similarly, some of the challenges already encountered in marine aquaculture licensing such as overly complex administrative procedures and permits that take a long time to obtain [70] would also reduce adaptive capacity if companies are not able to implement a desired adaptation action in the necessary time window. On the other hand, if the absence of regulations means that companies are not able to proceed with their desired adaptation action, then this is also a form of maladaptation. Such challenges are likely to

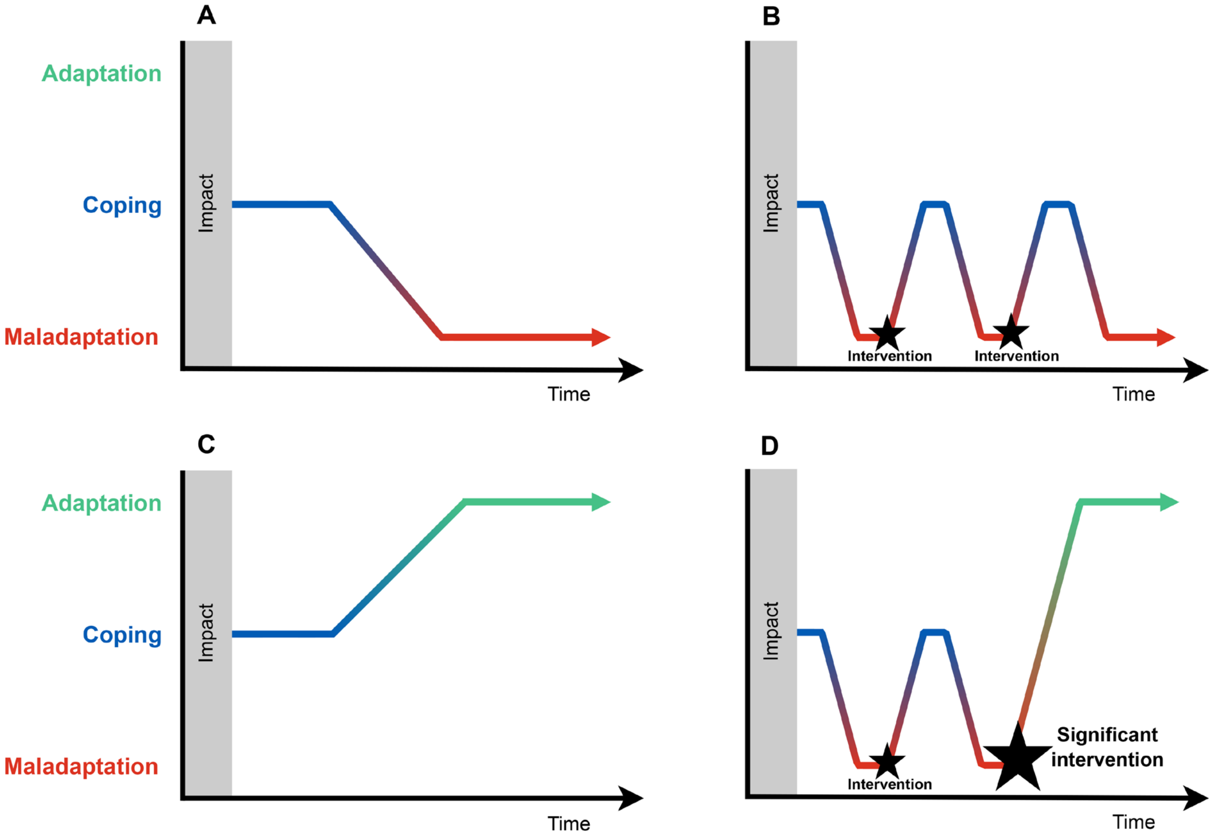

FIGURE 5 | Illustration of how coping strategies can (A) become maladaptive over time, (B) be a cycle between coping and maladaptive if interventions do not permit significant change, (C) maintain activities, allowing an incremental increase towards adaptation or (D) require a significant intervention to break the cycle of coping and maladaptation and make the move to effective adaptation.

arise since innovation tends to occur at a faster pace than policy and regulatory changes [141, 183], and so there can be a mismatch between what adaptation actions are available, and what adaptation actions are allowed. Regulations can also be a driver that forces companies to innovate in order to maintain or increase production [185], but in the case of climate adaptation, if the regulation prioritizes existing challenges and limits options to develop, test and use a range of alternative systems, this could leave the sector vulnerable to future impacts, especially those that require a long lead-in time to develop. Challenges with existing legislation and regulatory frameworks have been identified as a major bottleneck in the move towards circular solutions in aquaculture production, such as the use of alternative ingredients and waste streams [186, 187].

4 | Avoiding Maladaptation

The main driver of maladaptation is poor planning, so the risk of maladaptation should be recognised and included in climate change adaptation decisions [20]. Identifying potential maladaptation early would allow individuals, organisations, regulators, and perhaps even the entire sector, to change strategies or implement interventions that shift direction towards adaptation. However, one of the main challenges is how to measure the effectiveness of an adaptation response and to detect maladaptive development [188, 189]. Measurement of adaptation effectiveness is dictated on one hand, by the nature of a system's vulnerability to climate change, which is a function of exposure to specific stressors, sensitivity to their impact and the adaptive capacity of the system [190, 191]. On the other hand, effectiveness is relative to time, space, beneficiary and cost dimensions of the adaptive action [192, 193]. All these complexities create challenges for practitioners seeking to avoid maladaptation as there are multiple ways to frame effective adaptation [189], and no single universal approach that can be used for monitoring and evaluation [194]. Like many sectors, aquaculture needs to develop effective monitoring and evaluation approaches, including indicators and metrics [195], that can assess adaptation across multiple scales and from different perspectives. Monitoring and evaluation strategies need to be evidence-based and meaningful; otherwise they could fail in their objectives, miss maladaptation, or in some cases they could even encourage maladaptive actions [158, 196].

Monitoring and evaluation are not only useful to those directly involved in the adaptation process, but important information will also be generated for others across the sector that can help reduce risks of maladaptation. Sharing experiences and examples of adaptation progress could lead to more efficient use of time and resources, avoiding 'reinventing the wheel' and supporting better identification of opportunities for transformative action. Studies reviewing business adaptation across different industries have shown that there are many knowledge gaps and inconsistencies in sharing information and understanding of private-sector adaptation progress [30, 197–199]. Hence, there is a need for mechanisms that help report adaptation and progress and enable knowledge sharing between companies and sectors. In the aquaculture sector, existing knowledge exchange structures could be used to facilitate climate change communication between companies and organisations. Partelow et al. [200] note that knowledge sharing in the aquaculture sector can range from informal social networks to more formal routes with governments organising capacity building and knowledge transfer programmes.

It is widely recognised that adaptation is a process [7], but it should also be acknowledged that there may still be limits to adaptation [201, 202]. Limits can occur where the rate and magnitude of change are too large to overcome, the required resources and financial support make the action unfeasible, or the societal consequences would be unbearable. Hence, limits can be physical, financial, environmental, social and emotional [7] and they are absolute, in the sense that beyond these limits, loss is irreversible regardless of action [203]. Underestimating limits to adaptation within the aquaculture sector could result in maladaptation if time and resources are spent on actions that make the situation worse and do not lessen the risks as intended. On the other hand, overestimating limits to adaptation could lead to maladaptation through inaction, apathy and short-sighted decisions due to a sense of hopelessness and futility.

In some cases, perceived limits may be mistaken and they are actually barriers, rather than absolute limits and can be overcome with a change in thinking, additional or new resources, community support and political will [203–205]. Barriers can include limited resources, conflicting timescales and priorities, uncertainty, beliefs, behaviours, lack of awareness and communication, operational, policy and regulation, insufficient resources, and no capacity or authority to implement adaptation strategies [206–208]. Barriers slow down or prevent climate adaptation, putting aquaculture systems at further risk from climate change impacts and challenging conditions. The effort required to address a barrier could lead to additional costs and lost opportunities, and possibly maladaptation. Hence, to avoid maladaptation it is useful to identify potential barriers and the means to overcome the barriers as this could also influence decisions on adaptation strategies.

An understanding of barriers and limits is essential in reducing the risk of maladaptation, but at the same time it is also important to recognise the role of adaptation enablers [209]. Adaptation enablers can remove or reduce barriers, increase adaptation capacity and help make adaptation possible [210–212]. Few aquaculture studies have considered climate adaptation enablers, but looking to other sectors, examples of enablers include access to finance, good quality data, participatory approaches, technology, digitalisation and arenas for knowledge exchange and collaboration [211–214]. Clear policies and regulatory frameworks for aquaculture can create an enabling environment that supports and encourages climate adaptation [215] and reduces the risk of maladaptation.

Knowing how an action is performing over time against intended goals and other potential outcomes is crucial in avoiding maladaptation. This requires effective monitoring and evaluation points where it is possible to do a stock-take of the situation, recognise barriers, identify potential enablers and select alternative actions that may be more effective. Adaptation actions may be abandoned or stopped, either temporarily or permanently for several reasons. For example, if they are not working as expected [181], they have unacceptable maladaptive outcomes, or they cannot be sustained (e.g., insufficient resources, change in priorities). The impact and costs of discontinuing an action will depend on circumstances, since some measures will be more flexible than others (e.g., those that are reversible) and others may be more difficult to abandon [23]. On the other hand, after evaluating the performance of an action, it may be decided there is a need for additional intervention or enablers, such as extra resources, moving the action towards more desirable outcomes.

Figure 6 shows how a farm may consider different responses to climate change impacts, and how their effectiveness can vary over time. Although this review is focusing on strategies and actions that go wrong (maladaptation), it is also important to acknowledge that inaction could also have negative consequences, as shown in the first option 'Do nothing.' In this hypothetical case, inaction would mean the farm is no longer able to continue producing fish at this location because the health challenges are too severe and the operation is no longer sustainable. Each of the five potential actions (A—E) obviously has their own strengths and weaknesses, and it is important to stress that this is just a narrative illustration to demonstrate how maladaptation can arise. Action A involves using new submersible cage technology, a strategy that could function as an effective approach for at least several years at this location if the water is cooler in the depths. Action B involves changing species, where the first 5 years will involve high economic costs and knowledge generation, two important barriers to successful adaptation. Such barriers are overcome through interventions involving specialised training and collaboration with companies highly experienced in farming the new species, reducing the challenges and expediting the process to successful commercial scale production. Action C involves using a new feed formulation, but illustrated here as an incomplete adaptation resulting in maladaptation, as the feed is unable to reduce the fish health challenges to a desirable level. Rather than abandon completely, this example shows that a new adaptation action emerges, which is to move location and the new location appears suitable for fish production, at least in the short-term. Action D is a selective breeding programme which

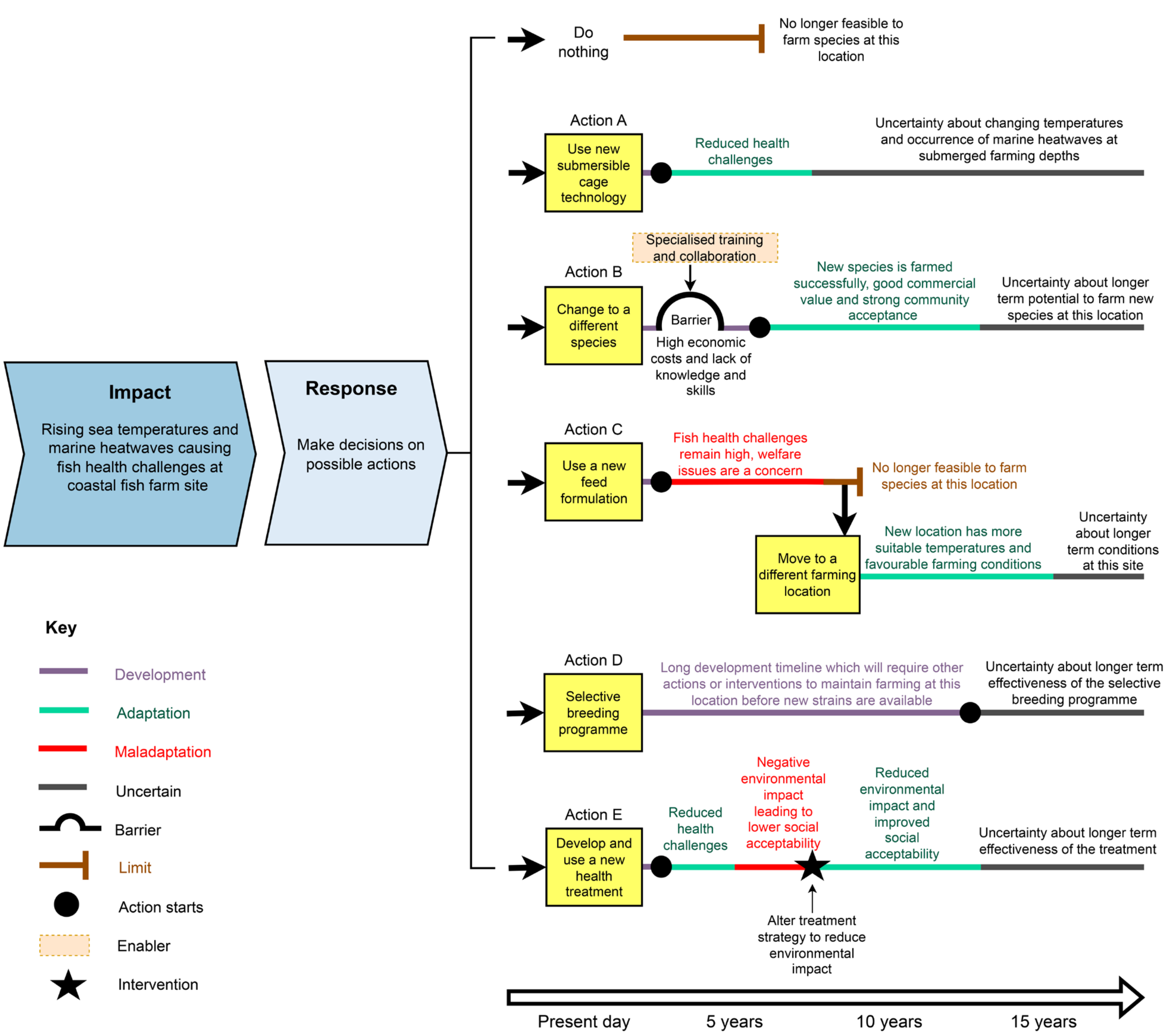

FIGURE 6 | Diagram showing the potential adaptation pathways of 6 possible responses (no action and Actions A–E) to climate change impacts experienced at a hypothetical coastal fish farm, adapted from Haasnoot et al. [216]. The circles are evaluation points where the adaptation status is evaluated and the lines represent the adaptation status (green is adaptation, red is maladaptation and mixed red and green is uncertain). This example shows how actions may evolve over time.

TABLE 1 | Recommendations to help limit maladaptation to climate change in aquaculture.

Recommendation	Description
1. Recognise the need for context-specific adaptation	Although there are many potential adaptation actions available within the aquaculture sector, successful implementation depends on the context to which they are applied. Contextual factors such as the species' requirements, the farming situation, the site characteristics, company resources, community perspectives and degree of exposure to climate change, all influence the climate change impact and effective adaptation actions. Some issues will be site-specific whilst others will be sector-wide, and some will be short-term acute challenges whilst others will be more chronic. Ignoring context and aiming for generalised approaches increase the risk for maladaptation. This should be recognised in industry, research and policy.
2. More research into the effects of different combinations of stressors and context-specific research	To reduce the risk of maladaptation and move towards sustainable adaptation actions there is a need to understand the combination of stressors that lead to an effect and also conduct research into context-specific realities that affect aquaculture farms and the potential for adaptation. Climate change impacts do not occur in isolation, and a combination of climate and non-climate related stressors affect aquaculture. Hence, research that considers the effects and interactions of multiple stressors, impacts and adaptation, as well as the context-specific factors influencing these, is necessary to provide a knowledge base from where adaptation strategies can be developed in a more holistic way.
3. Test adaptation actions under different circumstances	Adaptation actions may have different effects depending on the context to which they are applied. Therefore, it is important to test adaptation actions under different circumstances to understand what effects they may have and potential interactions with other aspects of aquaculture (e.g., feedback loops that amplify other effects). Regulators and policymakers also need to ensure that the regulatory environment supports research, innovation and testing adaptation actions up to commercial scale, as well as funding to enable testing and verification projects, and that this is needed for different contexts.
4. Assess trade-offs in decision-making process	Choices on adaptation strategies and actions will involve trade-offs. Hence, there is a need to develop approaches and tools that can help the aquaculture industry, policymakers and other associated stakeholders assess the advantages and disadvantages of adaptation strategies and actions and help identify the most appropriate.
5. Facilitate knowledge sharing	Knowledge sharing within and across different geographic scales (e.g., local, regional, national and international), different parts of the aquaculture sector (e.g., production, supply, market), different species and production technologies will be important for enhancing adaptive capacity throughout the aquaculture sector. In addition, the aquaculture sector should also need to participate in knowledge sharing activities that include individuals and organisations outwith the sector, for example climate scientists, oceanographers, economists, insurance sector or other activities and industries. Examples of knowledge exchange initiatives include collaborative research and innovation projects, establishing communication platforms, workshops and taskforces.
6. Enablers for collective action	Many adaptations will require a collective effort across different stakeholders and groups, some occurring at local level (e.g., community flood defences) and others at national or sector level (e.g., legislative changes) to be successful. Hence, there is a need to ensure that enabling factors are in place to initiate collective action and sustain cooperations over time.
7. Develop monitoring and evaluation schemes to track adaptation progress	Monitoring and evaluation are vital to track progress and analyse effectiveness of adaptation and to identify if there is a need to change strategy or introduce interventions. Throughout the aquaculture sector there is an urgent need to develop and implement monitoring and evaluation programmes that document and report adaptation progress and facilitate analyses of effectiveness and appropriateness in a consistent, comparable and transparent way.

has a long development time (10 years), leaving the farm at risk during this period, unless other actions, coping strategies or interventions are implemented. The farming environment also undergoes other changes during this time and it is uncertain whether the action is effective over the long-term. Action E is to develop and use a new health treatment which initially seems to be an effective adaptation action as there are reduced health challenges, but then after several years this becomes maladaptation due to unacceptable negative environmental impacts which leads to lower social acceptability. The company then deploys interventions to address the concerns, altering the treatment strategy and reducing environmental impact whilst maintaining the benefits for the fish health, leading to improved social acceptability and the action moves from maladaptation to adaptation. Across all adaptation actions there is uncertainty over the long-term effectiveness and risk of maladaptation. It is also important to note that beyond adaptation and maladaptation there will be other aspects associated with each action that will influence decisions, like ease and net cost of implementation as well as regulations and societal opinions.

5 | Prospects and Challenges for Aquaculture Adaptation

This study has outlined how climate change maladaptation could arise within the aquaculture sector, providing examples across the different outcomes and discussing the complexity of the adaptation–maladaptation continuum. Evidently there are many challenges in developing and implementing successful, sustainable adaptation strategies and actions. However, as climate change impacts become more pronounced across the sector, the urgency for climate adaptation grows. Delays or inaction will leave the sector vulnerable, so there is a need to identify routes to help industry, researchers, policymakers, governments and other associated stakeholders to identify the most appropriate adaptation strategies and actions. From this study, the majority of challenges seem to stem from knowledge gaps, uncertainties, siloed thinking and different priorities. Here, we present seven recommendations to help address these challenges and advance climate change adaptation in aquaculture (Table 1).

6 | Conclusions

There are many different options and strategies for climate change adaptation in the aquaculture sector, and with the knowledge and understanding available at present it can be difficult to decide the most appropriate actions to select. Actions will almost always have multiple consequences and there may even be a butterfly effect, where relatively small actions can have a series of knock-on effects that have major consequences further down the line. Hence, in most cases, it is impossible to view adaptation and maladaptation as an either-or situation as the reality is far more complex. The adaptation-maladaptation continuums presented in this study serve as a tool for discussion amongst relevant stakeholders in aquaculture to allow more informed decisions rather than fixed answers of right and wrong approaches. The categories are used as a way of illustrating the wide range of potential routes to maladaptation, but these categories do not occur in isolation and there are overlaps. Likewise, there will be other routes to maladaptation that have not been considered here.

The primary takeaway from this work is that all stakeholders need to acknowledge and understand the potential for climate change maladaptation in aquaculture. Greater awareness of the risks of maladaptation will also encourage the development of practical approaches that can support adaptation. Alongside the development and testing of adaptation strategies and actions, a key priority must be the establishment of effective methods to monitor and evaluate adaptation progress and identify maladaptation. Ultimately, when adapting to climate change, the aquaculture sector must strive for the best possible solution across all factors and use adaptation as a mechanism to drive ambitions forward on sustainable and responsible aquaculture production.

Author Contributions

Lynne Falconer: conceptualisation, writing – original draft, writing – review and editing, visualization. **Megan Rector:** writing – original draft, writing – review and editing. **Suleiman O. Yakubu:** writing – original draft, writing – review and editing. **Ramón Filgueira:** writing – original draft, writing – review and editing. **Audun Iversen:** writing – original draft, writing – review and editing. **Eirik Mikkelsen:** writing – original draft, writing – review and editing. **Matthew Sprague:** writing – original draft, writing – review and editing. **Elisabeth Ytteborg:** conceptualisation, writing – original draft, writing – review and editing.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Data sharing not applicable to this article as no datasets were generated or analysed during the current study.

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