# ENSURING RESILIENCE TO MARINE CLIMATE SHOCKS THROUGH INSURANCE

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**Keywords:** resilience, adaptive capacity, climate change, climate shocks, insurance, fisheries, aquaculture, conservation finance, sustainability, marine heatwave

## Abstract

For the Blue Foods economy -- those sectors that gain value from the biological productivity of the oceans such as fisheries and aquaculture -- climate shocks pose an existential threat. Species range shifts, harmful algal blooms, marine heatwaves, low oxygen events, coral bleaching and hurricanes all present a serious economic risk to these industries, and yet there exist few financial tools for managing these risks. This contrasts with terrestrial analogues such as agriculture where financial tools such as insurance are widely available for managing droughts, hailstorms and other weather-related shocks. Designing financial tools to aid risk management, in particular insurance, for equitable resilience against marine climate shocks will give coastal communities access to the necessary means for facing climate change, reducing their sensitivity to climate shocks and improving their long-term adaptive capacity. We suggest that a convergence of the insurance industry and marine sectors, fostered through collaboration with governments and NGOs will help usher in new forms of insurance that will strengthen the economic resilience of coastal communities, while engendering sustainable use of living marine resources. We propose that securing environmental and economic benefits through insurance, while delivering equitable resilience to climate shocks in coastal communities, is also a necessary condition for coping with long term climate change.

# Coping with marine climate shocks

Globally, “blue foods” – fish, invertebrates, and algae captured or cultured in marine ecosystems (Naylor et al. 2021) – are crucial for the food security of billions of people (Bennett et al. 2021). As a critical source of protein, fatty acids and micronutrients, blue foods are essential in combating conditions related to under-nutrition or diseases (e.g., Dalton et al. 2009; Weiser et al. 2016; Headey et al. 2018; Kokubun et al. 2020), and are the foundation of the cultures (Turner et al. 2013; Toniello et al. 2019) and economies (Teh and Sumaila 2013) of communities around the world. With global demand for blue foods expected to double over the next ca. 30 years (Naylor et al. 2021), increasing the resilience of the supply of blue foods, especially in the face of climate change, is urgent (Barange et al. 2018; Davis et al. 2021). We argue that modern financial risk management tools, in particular insurance (Beach and Viator 2008), is central to our ability to bolster the resilience of blue food supply chains, and coastal communities more broadly, to climate shocks. In land-based food productions systems insurance is an omnipresent tool across a number of social and economic contexts for improving food and income security (Hazell and Hess 2010). It is used by agriculturalists and cattle farmers to protect their livelihood against adverse weather events (e.g., McIntosh et al. 2013), and for accessing credit, which can be important for maintaining equipment, buying seeds and fertilizer (Farrin and Miranda 2015; see Figure 1 for a basic illustration of the parallels between terrestrial and marine climate shocks). Currently, however, there is nearly a complete lack of financial mechanisms such as insurance to help operators in fisheries and aquaculture sectors manage marine related environmental risks (Watson et al. 2018; Henriksson et al. 2021).

Climate change in our oceans is having increasing impacts on marine industries and coastal communities globally (e.g., Jardine et al. 2020). Long term shifts driven by climate change include changes in marine species ranges, diversity and abundance, species migration pathways and habitat distributions (Ainsworth et al. 2011; Hobday and Lough 2011; Cheung 2018; Payne et al. 2021; Pinsky et al. 2021). Against this increasing background pressure, *climate shocks* such as marine heatwaves, harmful algal blooms, low oxygen events and hurricanes can have devastating impacts (Frölicher and Laufkötter 2018). These events can lead to reduced growth, coral bleaching, poor productivity, increased disease risk and fish kills (Jardine et al. 2020). Climate shocks thus give rise to increased costs and reduced profits for blue food producers (Fisher et al. 2021) and can reduce both the overall resilience of communities to these shocks, and their ability to adapt to the longer-term impacts of climate change (Daw et al. 2009). The continued exposure to these shocks is a serious threat to the maintenance of blue food supply chains, and the associated food and income security of those individuals that work in these industries. These risks can dictate short and long-term profitability, and ultimately solvency, across the full range of blue food sectors from artisanal fisheries to industrial fisheries to transnational aquaculture firms (Burgess et al. 2018; Klinger et al. 2018).

Vulnerability to climate change has been widely conceptualized as a combination of exposure to climate change (the likelihood of an event of a given magnitude occurring), the degree to which a system is affected by climate change (i.e., sensitivity), and the capacity to adapt to that change (Adger 2006). In terms of vulnerability to a climate shock, a fishery or aquaculture operator can reduce their exposure through a variety of means. For example, fishers may move to new fishing grounds to avoid being directly exposed to local climate stressors (Seldon et al. 2020) or by diversifying the portfolio of species that are captured or farmed (e.g., Kasperski and Holland 2013; Fuller et al. 2017; Nomura et al. 2021), thereby reducing climate vulnerability (Barnes et al. 2020).

Fishers and seafood farmers can also reduce the vulnerability of blue food industries to climate shocks by increasing their adaptive capacity (Cinner et al. 2015; Barnes et al. 2019; Barnes et al. 2020; Fisher et al. 2021). This can be done using financial tools like insurance to enhance their ability of blue food providers to absorb and recover from climate shocks (Cinner and Barnes 2019, Mason et al. 2021). By reducing the volatility in income, insurance maintains the capital reserves that blue food actors have, with which to invest in the means to better cope with future shocks. More specifically, insurance does not simply provide access to financial assets - insurance transfers risk (Sethi 2010), typically via an insurance contract between the actor experiencing the realized risk (e.g., a fisher or aquaculturalist) and a different actor that has the ability to absorb the risk (i.e., an insurance firm). For example, it is commonplace to protect against agricultural losses incurred by climate shocks such as droughts and storms through insurance contracts. Farmers generally agree to pay a premium to an insurance company, who will in turn pay an amount back should a loss in production occur due to one of these events, helping maintain solvency. See the Appendix for an overview of terms relating to climate and financial risk. We are slowly seeing the emergence of these kinds of relationships (between insurers and those seeking insurance) in blue food sectors, but uptake has been relatively slow (Mumford et al. 2009; Sainsbury et al. 2019; Maltby et al. 2022).

In the absence of insurance and thus the ability to transfer risk, climate shocks have greater impacts on production and profit margins for sectors, and the overall adaptive capacity of actors is reduced (Mills 2005; Falco et al. 2014). Greater economic losses engendered by marine climate shocks result in less capital to pay for key necessities, including the means to adapt to future shocks. Capital reserves are a vital part of an actor's overall ability to adapt to climate change, for example facilitating a transition to new fishing grounds, or buying new equipment and targeting different species. As risk exposure increases due to climate change, historical methods of risk management through avoidance and absorption by blue food sectors (Sethi 2010) will be less effective, as the accrued negative impacts of multiple climate shocks over time will seriously hamper adaptive capacity. The development and uptake of effective insurance tools to transfer risk and increase adaptive capacity in blue food sectors is thus a critical challenge (Barange et al. 2018; Sainsbury et al. 2019; Turner et al. 2020).

## How are blue food sectors vulnerable?

Blue food sectors cope with climate shocks in a variety of ways (Sethi et al. 2010), depending on the operational nature of the business (e.g., aquaculture vs wild fisheries), scale of the industry (e.g., commercial fisheries vs artisan fisheries), agility of the sector to make changes, value and location of the activity (e.g., proximity to highly productive fishing grounds). The frequency and severity of climate shocks also determines the vulnerability of sectors (Barange et al. 2018). Case studies of illustrative historical events and their impacts on blue food sectors – commercial fisheries and aquaculture – are presented below.

## Commercial Fisheries

Commercial fisheries in the Global North (including those from Australia) have been affected by numerous climate shocks in recent decades (Bellquist et al. 2021; Smith et al. 2021). Over the period 1989-2020, 71 large scale climate shocks have impacted fisheries in the US and been classified as federal disasters, amounting to approximately $3.2B (2019 USD) in direct revenue losses. For example, in 2015/2016 the highly important Dungeness crab fishery on the US west coast was closed due to a harmful algal bloom, driven by a multi-year marine heatwave known as the "Blob" (Cheung and Frölicher 2020). The Dungeness crab fishery accounts for 26% of all annual fishery revenue and supports >25% of all commercial fishing vessels in California alone. California Dungeness crab landings for the 2015–16 season reached only 52% of the average catch of the previous 5 years, with total value lost estimated at US$97.5 million (Jardine et al. 2020; Frankowicz 2021). The event attracted $27.3 million in federal disaster relief funding; however, this assistance has been criticized for being ad hoc and unfair in terms of benefit allocation. Critically, financial assistance was only available to fishing communities several years after the climate shock occurred (Bellquist et al. 2021).

In addition to heavily industrialized commercial fisheries in the Global North, smaller scale fisheries in the Global South have also been heavily impacted by climate and weather extremes (e.g., Turner et al. 2020). For example, fisheries in Puerto Rico were devastated by Hurricane Maria in September 2017 (Agar et al. 2020; Villegas et al. 2021): the hurricane caused commercial landings to fall by 20% due to the loss of productive assets, power for extended periods and reduced demand; economic losses have been estimated at US$17.8 million; damaged fishing capital (i.e., vessel, engine, gear) and shoreside infrastructure accounted for 51% of the losses and forgone fishing revenue the remaining 49%. It was not until three years later (2021) that the US Federal Emergency Management Agency (FEMA) announced that it would provide US$1.8 million in grants to fishers in Puerto Rico, to help cope with the impacts of the hurricane. Prior to Hurricane Maria, there were more than 44 fishing villages on the island, whereas by 2021 only around 20 villages operating full or part-time remained (Agar et al. 2020). The inefficiency and delay in federal emergency funding to support the local fishing industry has failed to reduce the vulnerability of these small communities to climate shocks such as hurricanes; the intensity and frequency of which are projected to increase in the Atlantic under climate change (Mudd et al. 2009). Marine insurance provides an alternative mechanism (to federal disaster relief) to reduce the vulnerability of these small fisheries to these shocks.

## Aquaculture

Aquaculture industries have been heavily impacted in recent years by harmful algal blooms driven by anomalously warm ocean conditions (Díaz et al. 2019; Brown et al. 2020). For example, in 2016 the convergence of extensive blooms of two harmful algae species in Chile led to the most catastrophic event in Chilean aquaculture to date. The event, known as the "Godzilla-Red tide" event, was linked to strong El Niño conditions and the positive phase of the Southern Annular Mode, and caused the largest fish farm mortality ever recorded worldwide (Trainer et al. 2020). This resulted in an export loss of approximately US$800 million which when combined with shellfish toxicity, led to major social unrest and rioting in coastal communities. Even with insurance, the large international salmon aquaculture firms that operate in Chile were exposed to heavy economic losses, with subsequent impacts on the global supply and price of salmon (Terazono and Mander 2016). Insurance against harmful algal blooms and aquaculture-specific diseases like lice are available, though not widely available, tending to be only an option in certain regions of the world (Secretan 2008). Innovative solutions are being sought, and there are examples emerging from the technology sector to help aquaculture firms manage ocean/climate risks (e.g., https://www.scootscience.com/).

## Why is there not more blue food production insurance?

Marine disasters, such as those seen in Chile, Puerto Rico and the Northeastern Pacific, could be prepared for proactively through insurance rather than reactively through government disaster relief. Disaster relief is usually funded by taxpayers and provides financial support to fishers and seafood-farmers who have lost revenue due to a marine disaster. Similarly, but with obvious differences, customers pay premiums to an insurance company which then provides payouts to those who have suffered a loss. The key differences between the two approaches are the scale at which financial support is maintained and the efficiency of the two programs. While government relief is a vital component of a country's resilience to a broad range of environmental disasters, it can take a long time to materialize (Bellquist et al 2021). This delay in financial support can be detrimental to fishers and fish-farmers, whose financial solvency hinges upon small margins and seasonal timescales. In contrast, financial payouts from private insurance sources have the potential to be much timelier. The lack of insurance products currently available for fisheries and aquaculture sectors suggest that it is perhaps not yet possible to accurately price the risk of marine climate shocks, or make financial products like insurance general enough for large-scale use (Secretan 2008). However, new advances in data collection, predictive analytics and certain governance institutions are creating the necessary conditions for effective insurance policy offerings. We are seeing early examples of such offerings presented to the blue foods sectors through groups such the Ocean Risk Alliance (https://www.oceanriskalliance.org/), and through collaborative programs between fishers/aquaculturalists, academics and insurance companies such as Willis Towers Watson and Axa.

A primary challenge in developing insurance solutions for production losses for fishers specifically is the economic uncertainty associated with harvest of wild fish stocks. Fisheries are common pool resources where access is non-exclusive and competitive, meaning the actions of one fisher can diminish the returns of another (Ostrom 2008). These properties mean that fish stocks cannot be treated as private goods. The challenge is that insurance policies are generally developed for private goods, where ownership is clear, distinct and non-rivalrous. In general, it is a challenge to create insurance policies for public goods and/or common pool resources (Quaas and Baumgärtner 2008). However, recent advances in fisheries management include creating semi-private systems, such as individual transferable quotas (ITQs) and catch shares more broadly which are privately held rights to fish (Costello et al. 2008). Insurance could be offered on these contracts or “fishing tickets”. In contrast to wild-capture fisheries, aquaculture more closely resembles a private good, i.e., coastal marine areas that are privately owned or leased to grow seafood. The relatively minor role of insurance in the aquaculture sector (globally) seems surprising then, though is likely explained by the sector’s relatively short history and explosive growth. Aquaculture is the fastest growing food production sector globally, expanding rapidly in recent decades. Insurers have improved the pricing of risk for aquaculture, and there are existing insurance solutions used by the larger aquaculture firms that operate internationally. However significant challenges remain for the majority of operations worldwide, especially small-scale aquaculture operations in the Global South, which are exposed to other pressures in addition to those related to ocean/climate events (Zheng et al. 2018).

Another significant factor potentially hindering the uptake of insurance in blue food sectors, is the absence of quality data with which to quantify and price risk, and methods to attribute a loss to a particular climate shock (Kaplan et al. 2016; Siedlecki et al. 2016; Malick et al. 2020; Norton et al. 2020). Data is needed for the quantification of both risk, defined as the probability of a disaster happening, and the potential impacts of a given shock (e.g., a marine heatwave) on value, specifically the magnitude of the event’s impact on revenue of a fisher or fish-farmer for example. Quantifying the risk of ocean climate shocks is a growing area of research but data have not always been available. Observations of critical ocean properties such as temperature, oxygen levels and nutrient availability are simply not available for long enough periods and for all locations. Teleconnections between spatially distant parts of the ocean and the role of the atmosphere in driving these events are complex, as is the accurate forecasting of these events weeks to months ahead at spatial scales relevant to blue food production from fisheries and aquaculture (Hobday et al. 2018). At longer timescales, the impacts of climate change on the world’s oceans are difficult to quantify at these same scales of the production of blue foods. Similarly, attributing a drop in fishery or aquaculture production to a specific marine shock is challenging. Coastal systems have open ocean boundaries and so are exposed to both local risks and risk originating elsewhere. In the case of wild fisheries, animals can move and interact with other species or more importantly, a multitude of stressors (McClanahan et al. 2014). Impacts on a particular marine system may not always be visible in the way that the effects of a hurricane or drought are obvious on land. These all complicate the attribution of direct revenue losses in marine systems to a given climate shock. However, the accuracy of ocean forecasts, understanding of causal pathways and our ability to predict fish population dynamics and fisheries/aquaculture production is improving (e.g., Siedlecki et al. 2016, Tommasi et al. 2017, Malick et al. 2020), with great scope for use in future insurance applications.

Another reason why insurance has played a minor role in fisheries and aquaculture to date, is related to the health of marine ecosystems from which blue foods are extracted and the overcapitalization of these industries in some regions. Historically, there are numerous examples from around the world of poorly managed fisheries with unsustainable effort levels (Costello et al. 2010, Teh et al. 2013). In these cases, employing financial mechanisms to boost the economic resilience of seafood producers can lead to further degradation of marine ecosystems, and thus threaten the long-term economic viability of these industries. The reduction or cessation of fishing as a result of a climate shock may actually improve ecosystem health for a short period of time (perhaps similarly to the 2020 pandemic; Bennett et al. 2020), however the chronic issues of overcapitalization and poor management will persist. Government support is often necessary to initiate an insurance scheme (Mills 2005), and it is possible that governments tasked with balancing both the economic productivity of coastal communities and ecosystem health, are reluctant to increase the resilience of these maladapted marine systems. Conversely, if a fishery is well managed, creating financial tools like insurance to keep fishers working is acceptable (Hodgkinson et al 2014). We argue that it is only in marine regions where sustainable fisheries management exists that insurance can be deployed to effectively achieve both economic and environmental wins.

In and around these issues specific to marine systems, insurance itself has several core challenges: specifically *moral hazard*, *adverse selection*, actor *heterogeneity* and *loss verification* (Mills 2005; Müller et al. 2017; see the Appendix for a description of the major terms used in financial risk management). Moral hazard describes perverse behaviors that insurance can engender. For example, pastoralists have traditionally employed a range of risk management techniques, notably farming a diverse portfolio of crops. However, when insurance is held, farmers will often start farming monocultures in the knowledge that should their crop fail, they will receive a payout (Müller et al. 2017). This attitude could potentially be adopted in fisheries, where fishers who would typically rely on a diverse catch portfolio to minimize income risk, end up targeting a single species, knowing that they have insurance to back them up. Adverse selection and heterogeneous actors are challenges that go hand in hand. A poorly constructed marine insurance policy may only be affordable for relatively wealthy actors, for example large fishing companies, in a similar fashion to medical insurance schemes in the US which are biased against economically disadvantaged individuals (Handel 2013). Individuals involved in fisheries and aquaculture sectors range from deckhands on fishing vessels, to skippers that lease or own the vessels, to transnational fishing companies with fleets operating around the world. To provide insurance to this wide range of people – which must be the goal for equitable and effective types of insurance -- and to bolster the resilience of whole coastal communities against marine climate shocks, careful thought must be put into the design of insurance policies so all actors across the production chain benefit (Müller et al. 2017). The last challenge with insurance is the accurate verification of losses. A large fraction of an insurer's costs come from verifying the truthfulness of a claim (Miranda and Farrin 2012), and in blue food sectors this can be a crippling challenge.

# Insurance as a solution for managing marine climate shocks

Insurance solutions for fisheries and aquaculture which minimize the risk posed by marine climate shocks could take many forms, including *indemnity insurance* and *parametric insurance*. Indemnity insurance is the most common form of insurance, where the insured (e.g., a fisher) pays a premium cost to the insurer (i.e., the insurance company) for the policy, and in return the insurer pledges to pay the insured a certain sum of money should a loss occur (i.e., similarly to everyday-type insurance, such as car or home insurance). In this case, the nature of the loss must be specified and verified. Specifically, where a fisher has suffered a loss in revenue, this loss must be attributable to a climate shock (such as a marine heatwave), for indemnity insurance to be viable. This can be very difficult for wild fisheries, as many factors in addition to the climate shock can contribute to the loss of revenue. In aquaculture it is easier to assess the direct impact of a climate shock on production, and as a consequence various forms of indemnity insurance are available to the sector in certain parts of the world (Beach and Viator 2008; Barange et al. 2018). The verification that a loss has occurred is however contentious and expensive, with a large fraction of the costs of operationalizing an insurance product arising from monitoring and verification. The contentious nature of loss verification and the costs of monitoring are the main challenges that limit the take-up of indemnity insurance programs in economically vulnerable communities (Miranda and Farrin 2012).

Another form of insurance is parametric insurance (otherwise known as index insurance; Maltby et al. 2022). Parametric insurance policies oversee premium payments that provide a payout from the insurer, triggered by an objective measure of a correlate of losses (i.e., an environmental index). For example, a parametric insurance policy would include an automated payout of some amount to an insured party (i.e., a fisher or fish farmer) when some critical environmental threshold is exceeded (e.g., prolonged sea surface temperatures above some level). The advantages of parametric insurance over traditional indemnity insurance are greatly reduced costs, as verification is not required, and more timely payouts as actual losses are not required to be verified post-event. However, the main challenges with parametric insurance relate to the dimensionality of the environmental index, and its error with losses – this is called *basis risk*. Fisheries and aquaculture production is influenced by many factors (e.g., ocean temperature, oxygen levels, disease risk), and as a result so is revenue. This multidimensionality means a simple environmental trigger (e.g., high ocean temperatures) is not adequate, which can be confusing for both insurers and the insured. While there are several approaches for accounting for multiple environmental factors (e.g., sophisticated statistical and machine learning methods), marine parametric insurance is likely to be complicated which makes it difficult for the insured to understand the product, which can again lead to contention over claims (Maltby et al. 2022).

Additionally, the error between the environmental index and actual losses (i.e., basis risk) can lead to inefficiencies in the parametric insurance policy that can greatly diminish its uptake by potential customers. Errors in the index-loss relationship can lead to situations where a payout is made because the environmental index was triggered, but no losses occurred. The converse problem occurs when losses are experienced but no payout is made. A solution to this is to verify losses, but this leads to the same cost issues that limits the scope of traditional indemnity insurance. Basis risk is the main constraint limiting the applicability of parametric insurance to blue food sectors. However, as fisheries and aquaculture productivity datasets and ocean observations grow, coupled with technology advances such as machine learning in environmental prediction (e.g., Lee and Lee 2018), these index-loss relationships can be refined to better model the economic impacts of marine climate shocks on these sectors.

Insurance is typically thought of a contract between an individual and an insurance company, but it can also involve a collective/cooperative or *risk-pool* more generally (Tilman et al. 2018; Santos et al. 2021). A risk-pool cooperative is where a group of insured (e.g., fishers) form a group, which then engages as a collective with insurers. The cooperative can take the role of the insurer, paying for small losses for example, with the insurance company acting as the reinsurance company, funding the cooperative should a large risk be realized that affects all members of the cooperative. Insurance cooperatives have several attractive aspects, resulting in implementation in several places around the world (e.g., small-holder agriculture; Trærup 2012). Firstly, as a cooperative (otherwise known as a mutual insurance company), social norms can monitor issues relating to moral hazard and adverse selection. Secondly, marrying an insurance policy to existing social capital greatly increases the chance of uptake of the insurance policy. Thirdly, as a cooperative, groups of insured (i.e., fishing communities) have more leverage with insurance companies, and can secure lower costs for their insurance. Lastly, new distributed computing services such as Blockchain technologies and the emerging Web3 are enabling new forms of collaboration online (Aggarwal et al. 2019). These technologies have already made a large impact on the insurance sector (Sheth and Subramanian 2019) and will likely play a key role going forward in terms of (cooperative) insurance programs.

Another factor to consider is that to ensure the success of insurance programs that are designed for developing the resilience of vulnerable communities (i.e., programs that do not just target relatively wealthy firms/actors), outside support is often required, typically from government and/or NGO (non-government organization) sources (Müller et al. 2017). Premium prices for indemnity or parametric insurance can be beyond what a potential purchaser could afford and who may lack the extra income required to pay the recurring costs of an insurance premium. This is the case for many sectors across many of the most vulnerable communities around the world. For example, this challenge is present in insurance designed for small-holder farms in sub-Saharan Africa and India (Miranda and Farrin 2012). How then do these communities (who are in most need) afford insurance? One solution is subsidies provided by governments. In doing so, governments can support communities proactively by paying for premiums or offering tax credits for example, rather than through retrospective disaster relief. The increasing engagement of NGOs through financial instruments (Shiiba et al. 2021) is another potential funding source, that can potentially initiate a climate-shock insurance program. Crowdsourced and micro-lending platforms are also popular methods of aggregating public support for commercial activities in developing nations (Clarke and Grenham 2013), and could offer another route by which new insurance policies are made affordable to fishers and aquaculturalists.

## Theoretical example: insuring fisheries against marine heatwaves

To demonstrate how insurance can help protect fishers and aquaculturalists from marine climate shocks, we present the following theoretical example of an insurance policy developed for a fishery impacted by marine heatwaves. The southern and eastern scalefish and shark fishery is the most valuable federally managed fishery in Australia ($80M AUD in 2020), targeting over 100 species. Despite active management and historically low fishing effort, over 65% of stocks are experiencing declining catch rates and stock abundance, and several overfished stocks are not recovering. The fishery is located in the southeast marine waters of Australia, a recognized global warming hotspot where the ocean surface is warming at a rate four times the global average (Hobday and Pecl 2014). Many species have extended their distributions southward, with changes in local abundance. Climate projections show that these changes will continue for the next century (Hobday and Lough 2011).

Little et al. (2014) suggested insurance as an approach to managing these risks, and subsequent losses, of two healthy stocks in the fishery. Specifically, imagine that the goal is to develop a parametric insurance product to protect this fishery from marine heatwaves (to simplify things, we will assume that the fishery is affected only by marine heatwaves). The risk associated with marine heatwaves impacting the fishery is valued by calculating the expected losses, $E[X]$, where $X$ is the loss to the fishery as a function of the value $V$ of the fishery, the effect of the marine heatwave temperature *temp*, the probability of the heatwave *p(temp)*, and the temperature dependent damage function *D(temp)* scaled between 0 and 1 (Equation 1):

$$X = V \times D(temp) \times p(temp), \quad \text{Eq. 1.}$$

Expected values provide the basis for determining the premium for parametric insurance, but should also include the variability in expected losses, and associated subjective risk tolerances. Expected losses depend on both the probability of a marine heatwave occurring and intensity in terms of temperature and duration. We can assume that the probability of a marine heatwave *p(temp)* is described by a negative exponential distribution with $\lambda=0.1$, which reflects a mean return time in the fishery region of $\mu=10$ years, and the intensity with a log-normal distribution:

$$p(temp;\ T, \sigma)$$

where $T$ and $\sigma^2$ are the mean and variance respectively of temperatures during a marine heatwave. The expected loss of a marine heatwave on the fishery then is a weighted mean:

$$E[X] = \lambda V \int p(temp)\, D(temp) dtemp$$

In this example, the expected loss *E(X)* to the entire fishery from a marine heatwave is approximately $4 million AUD (Smith et al. 2021). The fishery is managed with output controls and statutory fishing rights expressed as individual transferable quotas, which provide a share of the total allowable catch, over 30 species. The value of the resource to individual operators, and thus the financial risk from marine heatwaves, depends on individual quota holdings. These can be quite complex and variable across the fishery operators. Since parametric insurance does not require demonstration of actual loss, operators can seek to insure the value of their fisheries quota portfolio ($V$) against losses they would not be able to incur. Premiums would be set based on the expected losses, $E[X]$ including the amount insured $V$. If a heatwave were not to occur the insurer would keep the premium; if it did however, then the insurer would be required to pay-out the value insured, $V$. As the insured value ($V$) increases however, so too would the basis risk for the insuring party, which would increase the “risk premium”, i.e., the additional price or return required by an investor to incur risk above the risk-neutral return. It is worth noting that this example does not explicitly consider time. An alternative approach could use forecasts of biophysical models (Little et al. 2015). This approach is not limited to marine heatwaves - other shocks associated with harmful algal blooms, ocean acidification and hypoxic events could also be insured in a similar way. As these events are likely to be correlated, a challenge for the future is developing insurance products that integrate across the multitude of potential climate shocks.

## Looking to the future

As a warming climate increases pressures on marine systems, there is a growing need for new tools to improve the resilience of blue food industries and businesses (Davis et al. 2021). In particular, financial mechanisms that minimize the economic impacts of climate shocks will greatly improve the ability for marine operators to remain profitable and continue to support communities and food security (Little et al. 2015). In other words, the blue foods industry is vulnerable to climate shocks, and insurance can help bolster the resilience of blue food supply chains and industries.

One of the most important considerations when designing insurance for managing marine climate shocks is the equitable nature of the product. New insurance products should not suffer from adverse selection, that is only being accessible to those wealthy enough to afford them. Insurance designed for climate resilience is faced with many challenges, in particular an efficient insurance contract (in the financial sense) may simply be too expensive for certain marine climate shocks. For example, impacts of mass coral bleaching on reef systems could be insured against, but if these events were to occur more and more frequently (as is expected under climate change; Wolff et al. 2018), then the premium will eventually become too costly and not worth purchasing by the insured. If this is the case, an insurance option now can help reef stakeholders (e.g. tourist operators) maintain capital reserves required to transition to alternative forms of income. It is critical to leverage economic incentives to help in these long-term transitions, in conjunction with insurance products designed for immediate resilience, to achieve broad-scale and efficient means for adapting to climate change. This will achieve far more for the adaptive capacity of coastal communities than existing public mechanisms such as federal disaster relief.

The complex nature of income landscapes for coastal communities is also important in the design of equitable insurance tools. Low-income workers such as deck-hands and fish-process factory workers tend to work several jobs, many of a seasonal nature (Mishra et al. 2013; Wiederkehr et al. 2019). This is a key example of adaptive capacity i.e., should income from one job cease, there are others that can maintain a living. Insurance must be carefully designed so as to not reduce this natural form of adaptive capacity and thus the diversity of employment in coastal communities. Just like small-holder farmers who move from cultivating a diverse set of crops to harvesting monocultures once insurance was available (Müller et al. 2017); insurance deployed for marine climate shocks could engender similar behaviors. Broadly applicable and scalable insurance programs for coastal communities could also promote the collapse in income diversity across sectors. It is important to ensure that insurance can provide economic resilience not only to the individuals that buy insurance policies, but also to the sectors that they work in. This may otherwise lead to adverse selection among economic sectors. For example, if insurance against marine climate shocks were only to be made available to the aquaculture sector, a migration of labor from wild-capture fisheries to the aquaculture sector may occur, simply because the jobs are more stable (as a direct outcome of the insurance). Reducing the diversity of industries supporting coastal communities can lead to lower resilience overall to climate shocks. In general, it is important to recognize the connectivity of supply chains: risks at the base of a supply chain (i.e., in terms of the supply of blue foods) will propagate up through the fish-processing plants, the distributors, the retailers and ultimately the consumer (Davis et al. 2021). Protecting the base of blue food supply chains through the use of insurance designed for climate shocks, will help increase the resilience of entire blue food supply chains to climate change.

It is important to acknowledge that the diversity of the blue food industries that coastal communities engage in is much greater than just commercial fisheries and aquaculture (Fisher et al. 2021). Marine tourism and recreational fisheries are also important alternative or main livelihoods for people in coastal communities, and they also rely on access to healthy and abundant marine species and habitats. Disruption of tourist activities such as diving, fishing, whale watching, visits to seabird and marine mammal colonies, can occur as a result of marine extreme events. Coral bleaching as a result of marine heatwaves disrupted national (e.g., Seychelles) and regional (e.g., Great Barrier Reef) economies, with individual operators idle as tourist visitation was reduced. Cyclones damage both habitats and infrastructure and disrupt tourism businesses for some time after the event. For example, the Tropical Cyclone Winston led to nearly F$600 million in losses in Fiji, due to changes in the economic flows of the production of goods and services, with F$120 million from lost tourism alone (Mansur et al. 2017). Traditional insurance products may cover losses to infrastructure (e.g., damage to boats), but not to loss of amenity due to environmental damage. Furthermore, federal disaster relief payments rarely cover the period of lost income following an extreme event for marine tourism operators (Bellquist et al. 2021).

Climate shocks also have the potential to greatly impact the food security of Indigenous peoples. The cultures and economies of many Indigenous communities are place-based and environmentally connected, making them highly susceptible to the impacts of climate change and associated shocks (Wildcat, 2013). Indeed, Indigenous communities face disproportionate risks to their food security (Ford, 2009; Marushka et al., 2019; Satterfield et al., 2017) as climate change exacerbates other social vulnerabilities rooted in the legacies and contemporary realities of colonialism and capitalism (Whyte, 2015). The aforementioned "Blob" in the California Current affected a number of culturally important species, including Pacific herring (Brodeur et al. 2019). A reduction in ocean productivity likely led to commercial overfishing (Stier et al. 2020), and the depletion of herring in sites accessible by indigenous fishers (Okamoto et al. 2020). While there were fish that could be harvested by highly mobile commercial fishers, traditional harvesting could not be conducted. In some Indigenous communities, such as the Haida Nation, herring roe is traditionally gathered near village sites by women and children (Haida Marine Technical Team 2011). Ultimately, the Blob and subsequent changes in commercial fishing behavior may have impacted this important time for the intergenerational transfer of cultural knowledge (Marshall and Levin 2017).

Another important challenge in designing effective insurance tools will be to account for the non-stationary nature of climate change. Non-stationarity in the earth system means that the risk (i.e., the probability of an event happening) and its potential impact will change over time, and so insurance policies must adapt and change accordingly (O'Neill et al. 2017). Risk adjustments are commonplace in most insurance sectors; however, it is yet to be determined how frequently a marine insurance policy, designed for today's conditions, would need to be updated in the future. In addition, the magnitude and frequency of certain climate shocks (e.g., marine heatwaves) are likely to increase nonlinearly under climate change (Hobday et al. 2018). As we have previously mentioned, this will likely make insurance policies that protect against these events increasingly expensive. Consequently, the risk of adverse selection will also likely increase, and at some point, it will not be possible to afford protection against certain shocks. This is not necessarily bad; the rising cost of insurance is often used as an indicator that alternative risk management measures should be taken. In many cases of climate shocks, the long-term alternative might be to take relatively drastic action, for example moving to locations where risks are lower (Sethi 2010; Selden et al. 2020). Insurance can help actors conserve capital reserves as they are hit by climate shocks, which can then to bolster their adaptive capacity, ultimately helping them transition to new locations or sources of income should climate change be detrimental to a particular way of life.

A related concern around the use of insurance is that it may serve to prop up failing industries. Many marine species ranges are shifting spatially (Pinsky et al. 2020) and at some point, certain species will no longer be found in areas that have been historically fished (Seldon et al. 2020). For some communities, the extra fuel costs for tracking these shifting distributions means that this fishery will not be a viable option in the future. In this case, insurance may encourage fishers to continue working in this fishery, rather than incentivizing a gradual shift away to a more viable alternative such a different local fishery. Delaying a move to another source of income could be more harmful than if fishers were left to be exposed to income shocks early in the absence of insurance. The key here is to implement insurance mechanisms that provide economic resilience in the near-term, combined with support mechanisms for long-term planning. Migration of populations from coastal zones that are at high risk of impacts from sea level rise is termed “managed retreat” (Hauer et al. 2020). In terms of the production of blue foods and marine climate shocks, we can imagine a similar process to managed retreat, where insurance helps people move to other sources of income or move into other fisheries.

**Implementation: from concept to creation**

Given the current lack of insurance options to reduce risk from extreme marine climate events, what is the pathway to implementation? We suggest that several stages are likely required before the ultimate goal is achieved - to improve the sustainability of the environment and the resource users (Figure 2). The first stage is to provide insurance design concepts that would reduce sensitivity and enhance adaptive capacity via risk management and raise industry awareness of these risk-based instruments. Demonstration opportunities can occur in a second stage, perhaps taking advantage of pre-conditions, policy windows, or at worst, clear evidence of threats or impacts such as an extreme climate event. An increasing frequency of shocks such as repeated marine heatwaves may provide additional impetus, and existing coping mechanisms for single shocks may be overwhelmed. Preconditions may result from recent technical advances, including decentralized finance (DeFi) such as block chain and/or Web3, or advances in forecasting of extreme events. Social characteristics of a region can also help, such as leadership and influence, or an acceptability around climate change (vs a culture of denial; Figure 2). These demonstrations will require willing and interested users/purchasers of insurance (e.g., fishers) or external support for a pilot project. Stage 3 is to access or build an enabling pool of capital to support ongoing insurance access. This might be provided by traditional insurance operators, or by new underwriters, such as NGOs or philanthropic organizations. Over time this will mature to a self-sustaining model that can adjust to changing conditions and risk profiles via insurance premiums, as exists for terrestrial situations. In the case that extreme events become too frequent to allow business to continue, insurance premiums can also send a strong market signal that adaptation is required which may be more rapid than legislative reform or direction. These stages ultimately result in reduced financial loss for resource users, such that both livelihoods and environmental sustainability are improved.

## Conclusions

As our oceans warm, and climate shocks become more frequent and intense, it is vital that coastal communities have access to a wide range of tools for protecting against the worst impacts of climate change. Protecting coastal communities from the economic impacts of marine climate shocks using insurance has the potential to increase economic resilience in fisheries, aquaculture and marine tourism. In addition, environmental wins could be achieved through incentivizing sustainable behaviors and could open up new markets for insurers and reinsurers. Fishing communities in particular have for decades seen a slow but steady degradation of their industry in many parts of the world (Zeller and Pauly 2005), with climate shocks risk pushing these industries to collapse. Designing and developing new insurance products to bolster the resilience of these communities, without engendering moral hazard or adverse selection, will improve their ability to cope with climate change in the long-term (Mills 2005, Sainsbury et al. 2019). These approaches are commonplace in terrestrial food-producing sectors, but currently lacking in blue food sectors. Leveraging advances in data availability, predictive analytics and in insurance policy design can help give blue food sectors that are reliant on the biological productivity of the oceans the necessary access to financial risk management tools for long-term survival and even prosperity under climate change.

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# Appendix: A Primer on Climate Adaptation and Financial Terms

## Climate Adaptation Terminology

The financial terms listed above can be used in parallel with those terms used in the climate adaptation literature. Specifically:

**Vulnerability** is a term broadly used to describe how a certain community might be negatively impacted by climate change. There is an equation that defines vulnerability as exposure multiplied by sensitivity, divided by adaptive capacity. These additional terms are described below. In this way, the vulnerability of a given actor or group or community is increased by sensitivity and exposure, but reduced by adaptive capacity.

**Exposure** to a stressor (e.g., climate event or trend) can be thought of as being directly analogous to risk, the probability of a stressor/threat/hazard being realized. The greater the risk, the more frequently the community is exposed to the stressor. For example, certain coastal communities are periodically exposed to marine heatwaves, and this directly impacts their vulnerability. Reducing the exposure to a stressor (or reducing the probability of being hit by a shock) is achieved through three means: risk avoidance, and transfer.

**Risk avoidance** is simply when people/communities move away from the area exposed to the threat. In the case of fisheries, this would be when fishers move away from geographies affected by marine heatwaves to different fishing grounds. **Risk transfer** is when the negative impacts of a shock are transferred to someone else (for example an insurance company). This is essentially what insurance facilitates.

**Sensitivity** describes the intrinsic properties of the focal element (e.g., a community of fishers) in its ability to withstand a shock. For example, sensitivity to marine heatwaves is increased for fishers dependent on one species that dies during marine heatwaves. Reducing the sensitivity is traditionally through diversification (e.g. change target species for a fisher, change the prey species for a predator, change the diet for an aquaculture operation).

**Adaptive capacity** describes the ability to cope with a stressor, as a result of extrinsic properties of the system in which the focal element lies. Increasing the adaptive capacity increases the coping range. For example, quite simply, the greater the capital reserves (i.e., money in the bank) that a fisher of aquaculturalist has access to, the better able they are to buy gear and technology, and invest in their teams and knowledge, with which to minimize the negative impacts of a shock.

**Resilience** - a broadly used term in both qualitative and quantitative ways. For example, the term resilience has been used to describe a system's general ability to cope with shocks/change, but it also describes the width of a basin of attraction of an equilibrium point in a dynamical system. The term resilience is often used in conjunction with vulnerability, to describe the general ability for a community to withstand a shock (or not).

## Financial Risk Management Terminology

Financial risk can be mitigated several ways, through insurance or derivatives. Below we list the major terms used when discussing insurance.

**Insurance** is a form of risk management represented by a contractual arrangement, called a policy, in which one party is indemnified against financial losses by an insurer. The insurer pools funds across similarly insured parties, who pay a premium to the insurer based on the loss risk. Pooled funds are used to compensate for realised losses.

In contrast to traditional insurance which indemnifies against actual loss, **parametric insurance** covers the probability of a predefined event triggered by an index or metric. Parametric insurance has **basis risk,** which is the risk that the triggered index does not represent the underlying risk exposure. Negative basis risk results when a loss is incurred without the contract being triggered, while a positive basis risk results in a payout without a financial loss.

Derivatives are another form of financial risk management. A **derivative** is a security whose value depends on the value of another asset. (A **security** is a fungible, negotiable, financial instrument that holds monetary value.) The main types of derivatives are futures, forwards, options, and swaps. All represent contractual arrangements used to manage the risk associated with an underlying asset. Derivatives are exposed to **counterparty risk**, which is the risk that one of the parties involved in a derivatives contract defaults on the contract. A **risk premium** is the additional return required by an investor above the risk-neutral return.

**Weather derivatives** are financial products similar to parametric insurance that derive their values from indices such as temperature, precipitation, wind, heating degree days and cooling degree days. In the case of weather derivatives, the underlying asset is number of degree days or some other environmental variable. They are not pooled, but instead represent a transaction between the risk mitigator, and a party that willingly takes on the risk, for a fee.

The primary difference between derivatives and insurance mechanisms to manage financial risk is reflected in the party that takes on the risk. Insurance relies on the insurer pooling capital based on premiums to compensate for losses, while a derivative relies on the solvency (and liquidity) of the counterparty.

In both insurance and derivative products, a primary market occurs between the insured/party and insurer/counterparty. Both products also have secondary markets where the product can be transferred. In insurance this is often referred to as re-insurance. Catastrophe bonds are another form of secondary market for insurance products. Derivative exchanges provide a secondary market for trading derivative contracts. The specific solution for managing ocean risks can take the form of either an insurance product or a derivative product.

**Commodification**: The transformation of goods into commodities as objects of trade. A commodity is the instance of a good regarded as equivalent. A commodity is a raw material used to manufacture finished goods. A product, on the other hand, is the finished good sold to consumers. There is little difference, if any, among commodities. They are taken from their natural state and, if necessary, brought up to meet minimum marketplace standards. No value is added to the commodity, and all commodities of the same good sell at the same price regardless of the producer. Most of the world's widely traded commodities have well-established markets and are traded on exchanges primarily in the form of futures; contracts to buy or sell the commodity by a specified time in the future at a certain price. The settlement of a contract means the delivery of an actual asset or cash. Trading commodities has the potential for significant market volatility. Exchanges standardize the amount and grade of the commodity being traded.

**Moral hazard** and **adverse selection** are both terms used in economics, risk management, and insurance to describe situations where one party is at a disadvantage to another. **Moral hazard** occurs when a party changes their behavior after an agreement has been made because they believe that they won't face any consequences of actions. **Adverse selection** occurs when there is asymmetric information between parties such as the tendency of parties in high-risk circumstances to purchase insurance.

# Figures

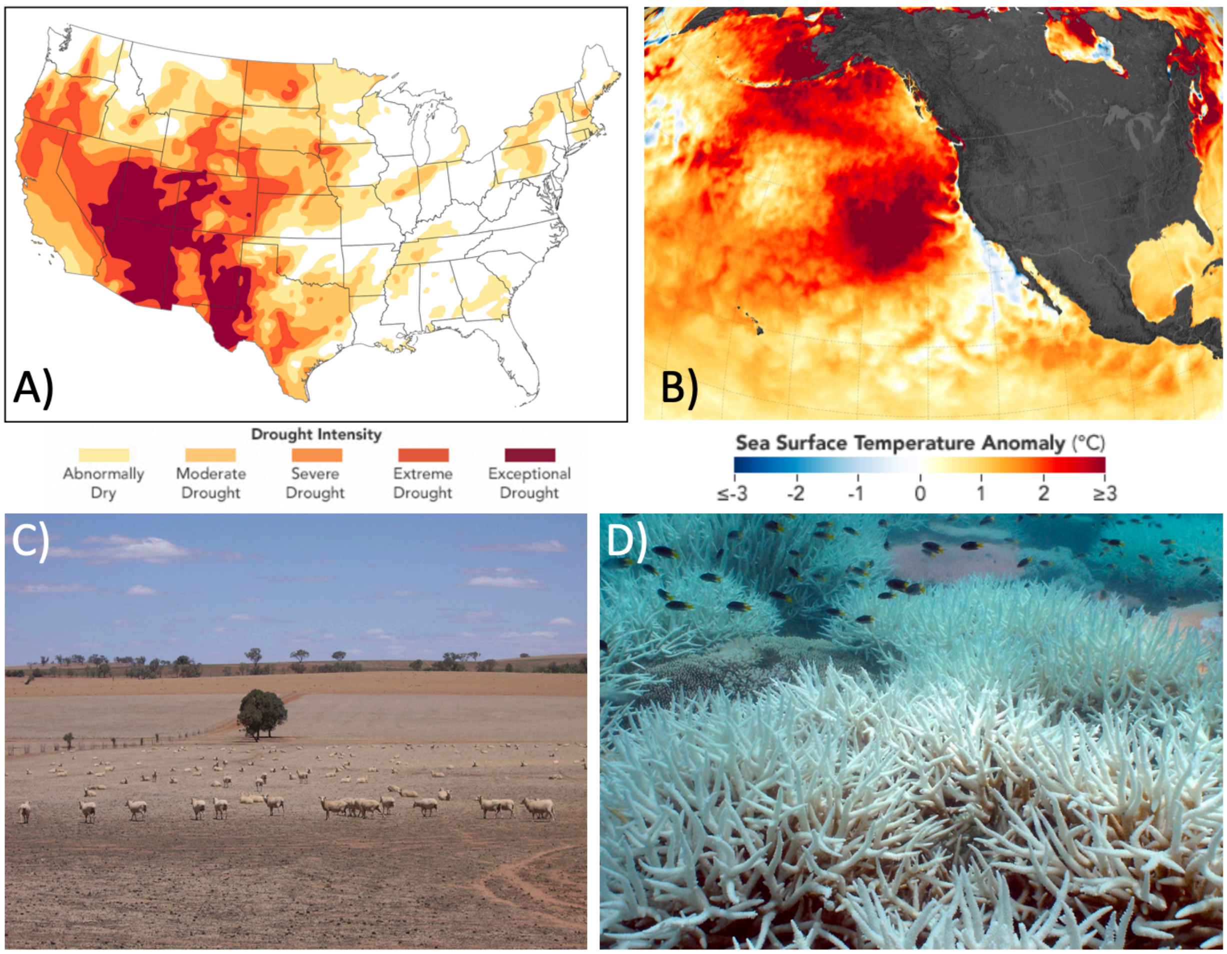


**Figure 1.** Illustration showing the parallels between climate shocks on land (A; drought) and marine climate shocks (B; marine heatwaves). For terrestrial food production systems, like agriculture and cattle systems (C) many financial tools exist (e.g., parametric insurance) that operators can buy in order to manage these climate risks. At sea, fishers, aquaculturalists and marine tourism operators depend on the biological productivity of the oceans. Marine climate shocks such as marine heatwaves can impact this productivity, for example by creating conditions where corals bleach (D). Figures A and B are from the NASA Earth Observatory; C is a photograph taken by VirtualSteve, Wikipedia; D is from Damian Thomson, CSIRO.

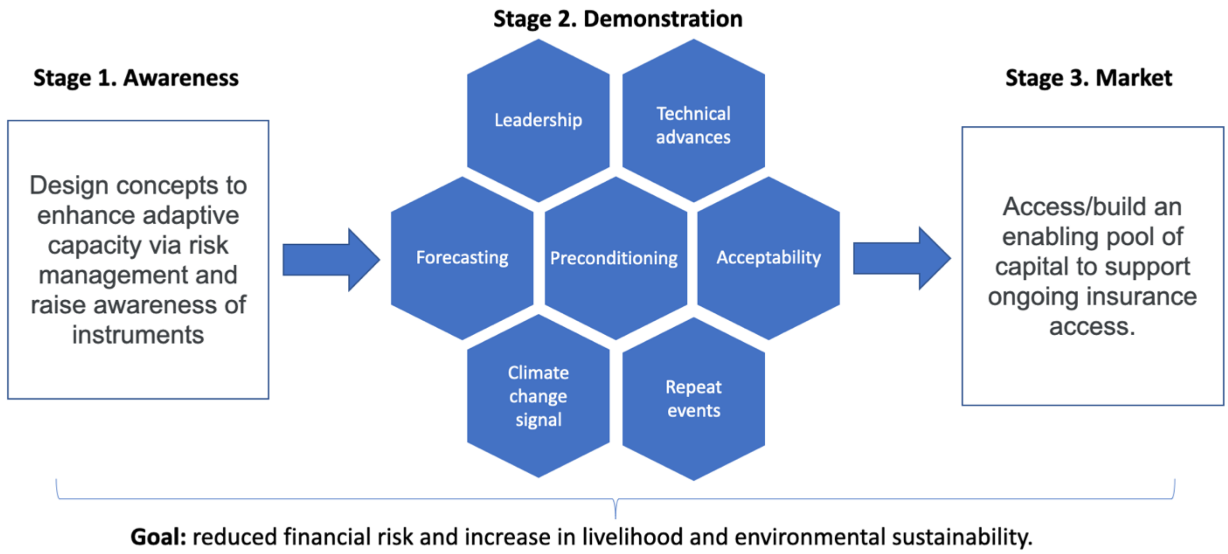


**Figure 2.** Proposed stages to implementing an insurance-based risk reduction approach for marine resource users exposed to climate shocks such as marine heatwaves, hypoxic events, harmful algal blooms and others. See the "Implementation" section for a longer description.