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Climate Change Adaptation and Fisheries

Title/Author	**Biodiversity redistribution under climate change: Impacts on ecosystems and human well-being / Pecl, G. T., Araújo, M. B., Bell, J. D., Blanchard, J., Bonebrake, T. C., Chen, I. C., Clark, T. D., Colwell, R. K., Danielsen, F., Evengård, B., Falconi, L., Ferrier, S., Frusher, S., Garcia, R. A., Griffis, R. B., Hobday, A. J., Janion-Scheepers, C., Jarzyna, M. A., Jennings, S., ... Williams, S. E.**
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Title/Author	**Managing consequences of climate-driven species redistribution requires integration of ecology, conservation and social science / Bonebrake, T. C., Brown, C. J., Bell, J. D., Blanchard, J. L., Chauvenet, A., Champion, C., Chen, I. C., Clark, T. D., Colwell, R. K., Danielsen, F., Dell, A. I., Donelson, J. M., Evengård, B., Ferrier, S., Frusher, S., Garcia, R. A., Griffis, R. B., Hobday, A. J., Jarzyna, M. A., ... Pecl, G. T.**
Source	**Biological Reviews February 2018, Volume 93 (1), Pages 284–305 https://doi.org/10.1111/brv.12344 (Database : Wiley Online Library)**

Title/Author	**Integrating climate adaptation and biodiversity conservation in the global ocean / Tittensor, D. P., Beger, M., Boerder, K., Boyce, D. G., Cavanagh, R. D., Cosandey-Godin, A., Crespo, G. O., Dunn, D. C., Ghiffary, W., Grant, S. M., Hannah, L., Halpin, P. N., Harfoot, M., Heaslip, S. G., Jeffery, N. W., Kingston, N., Lotze, H. K., McGowan, J., McLeod, E., ... Worm, B**
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Source	Land Nov 2021, Volume 10 (11), Pages 1271 https://doi.org/10.3390/land10111271 (Database : MDPI)

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Title/Author	**Climate change adaptation in aquaculture / Galappaththi, E. K., Ichien, S. T., Hyman, A. A., Aubrac, C. J., & Ford, J. D.**
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Title/Author	**Biodiversity redistribution under climate change: Impacts on ecosystems and human well-being / Pecl, G. T., Araújo, M. B., Bell, J. D., Blanchard, J., Bonebrake, T. C., Chen, I. C., Clark, T. D., Colwell, R. K., Danielsen, F., Evengård, B., Falconi, L., Ferrier, S., Frusher, S., Garcia, R. A., Griffis, R. B., Hobday, A. J., Janion-Scheepers, C., Jarzyna, M. A., Jennings, S., ... Williams, S. E.**
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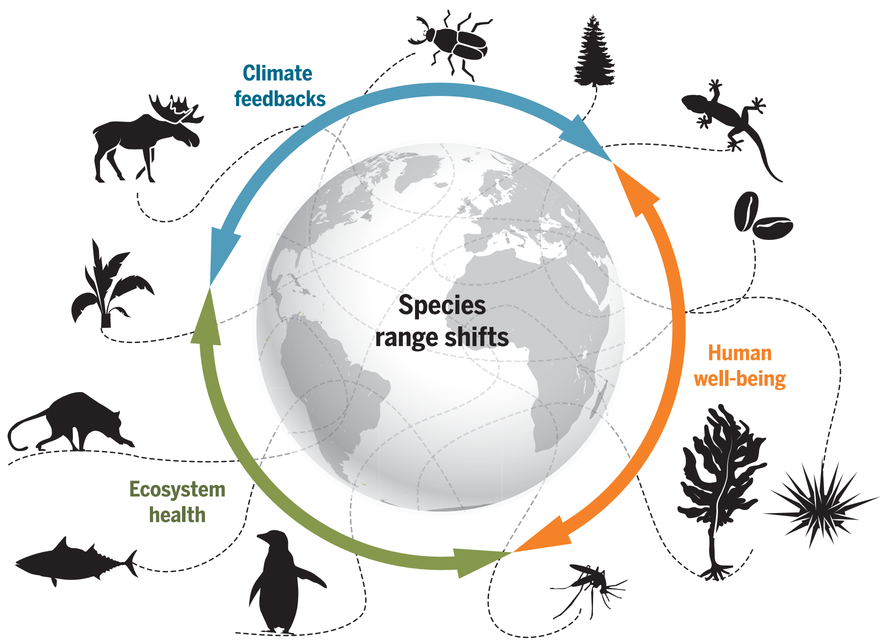
REVIEW SUMMARY

CLIMATE CHANGE

Biodiversity redistribution under climate change: Impacts on ecosystems and human well-being

Gretta T. Pecl,* Miguel B. Araújo,† Johann D. Bell, Julia Blanchard, Timothy C. Bonebrake, I-Ching Chen, Timothy D. Clark, Robert K. Colwell, Finn Danielsen, Birgitta Evengård, Lorena Falconi, Simon Ferrier, Stewart Frusher, Raquel A. Garcia, Roger B. Griffis, Alistair J. Hobday, Charlene Janion-Scheepers, Marta A. Jarzyna, Sarah Jennings, Jonathan Lenoir, Hlif I. Linnetved, Victoria Y. Martin, Phillipa C. McCormack, Jan McDonald, Nicola J. Mitchell, Tero Mustonen, John M. Pandolfi, Nathalie Pettorelli, Ekaterina Popova, Sharon A. Robinson, Brett R. Scheffers, Justine D. Shaw, Cascade J. B. Sorte, Jan M. Strugnell, Jennifer M. Sunday, Mao-Ning Tuanmu, Adriana Vergés, Cecilia Villanueva, Thomas Wernberg, Erik Wapstra, Stephen E. Williams

BACKGROUND: The success of human societies depends intimately on the living components of natural and managed systems. Although the geographical range limits of species are dynamic and fluctuate over time, climate change is impelling a universal redistribution of life on Earth. For marine, freshwater, and terrestrial species alike, the first response to changing climate is often a shift in location, to stay within preferred environmental conditions. At the cooler extremes of their distributions, species are moving poleward, whereas range limits are contracting at the warmer range edge, where temperatures are no longer tolerable. On land, species are also moving to cooler, higher elevations; in the ocean, they are moving to colder water at greater depths. Because different species respond at different rates and to varying degrees, key interactions among species are often disrupted, and new interactions develop. These idiosyncrasies can result in novel biotic communities and rapid changes in ecosystem functioning, with pervasive and sometimes unexpected consequences that propagate through and affect both biological and human communities.



As the global climate changes, human well-being, ecosystem function, and even climate itself are increasingly affected by the shifting geography of life. Climate-driven changes in species distributions, or range shifts, affect human well-being both directly (for example, through emerging diseases and changes in food supply) and indirectly (by degrading ecosystem health). Some range shifts even create feedbacks (positive or negative) on the climate system, altering the pace of climate change.

ADVANCES: At a time when the world is anticipating unprecedented increases in human population growth and demands, the ability of natural ecosystems to deliver ecosystem services is being challenged by the largest climate-driven global redistribution of species since the Last Glacial Maximum. We demonstrate the serious consequences of this species redistribution for economic development, livelihoods, food security, human health, and culture, and we document feedbacks on climate itself. As with other impacts of climate change, species range shifts will leave "winners" and "losers" in their wake, radically reshaping the pattern of human well-being between regions and different sectors and potentially leading to substantial conflict. The pervasive impacts of changes in species distribution transcend single systems or dimensions, with feedbacks and linkages between multiple interacting scales and through whole ecosystems, inclusive of humans. We argue that the negative effects of climate change cannot be adequately anticipated or prepared for unless species responses are explicitly included in decision-making and global strategic frameworks.

OUTLOOK: Despite mounting evidence for the pervasive and substantial impacts of a climate-driven redistribution of Earth's species, current global goals, policies, and international agreements fail to account for these effects. With the predicted intensification of species movements and their diverse societal and environmental impacts, awareness of species "on the move" should be incorporated into local, regional, and global assessments as standard practice. This will raise hope that future targets—whether they be global sustainability goals, plans for regional biodiversity maintenance, or local fishing or forestry harvest strategies—can be achievable and that society is prepared for a world of universal ecological change. Human society has yet to appreciate the implications of unprecedented species redistribution for life on Earth, including for human lives. Even if greenhouse gas emissions stopped today, the responses required in human systems to adapt to the most serious effects of climate-driven species redistribution would be massive. Meeting these challenges requires governance that can anticipate and adapt to changing conditions, as well as minimize negative consequences. ■

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REVIEW

CLIMATE CHANGE

Biodiversity redistribution under climate change: Impacts on ecosystems and human well-being

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Distributions of Earth's species are changing at accelerating rates, increasingly driven by human-mediated climate change. Such changes are already altering the composition of ecological communities, but beyond conservation of natural systems, how and why does this matter? We review evidence that climate-driven species redistribution at regional to global scales affects ecosystem functioning, human well-being, and the dynamics of climate change itself. Production of natural resources required for food security, patterns of disease transmission, and processes of carbon sequestration are all altered by changes in species distribution. Consideration of these effects of biodiversity redistribution is critical yet lacking in most mitigation and adaptation strategies, including the United Nation's Sustainable Development Goals.

The history of life on Earth is closely associated with environmental change on multiple spatial and temporal scales (*1*). A critical component of this association is the capacity for species to shift their distributions in response to tectonic, oceanographic, or climatic events (*2*). Observed and projected climatic changes for the 21st century, most notably global warming, are comparable in magnitude to the largest global changes in the past 65 million years (*3*, *4*). The combined rate and magnitude of climate change is already resulting in a global-scale biological response. Marine, freshwater, and terrestrial organisms are altering distributions to stay within their preferred environmental conditions (*5*–*8*), and species are likely changing distributions more rapidly than they have in the past (*9*). Unlike the introduction of non-native species, which tends to be idiosyncratic and usually depends on human-mediated transport, climate-driven redistribution is ubiquitous, follows repeated patterns, and is poised to influence a greater proportion of Earth's biota. This redistribution of the planet's living organisms is a substantial challenge for human society.

Despite agreements to curb greenhouse gas emissions, the climate will continue to change for at least the next several hundred years, given the inertia of the oceanic and atmospheric circulation systems (*10*), and species will continue to respond, often with unpredictable consequences. Since 1880, there has been an average warming of 0.85°C globally (*10*), resulting in well-documented shifts in species distributions with far-reaching implications for human societies, yet governments have agreed to accept more than double this amount of warming in the future (e.g., the 2°C target from the Paris Conference of Parties 21). Moreover, current global commitments will only limit warming to 2.7° to 3.7°C, more than three to four times the warming already experienced (*11*). To date, all key international discussions and agreements regarding climate change have focused on the direct socioeconomic implications of emissions reduction and on funding mechanisms; shifting natural ecosystems have not yet been considered in detail.

Here we review the consequences of climate-driven species redistribution for economic development and the provision of ecosystem services, including livelihoods, food security, and culture, as well as for feedbacks on the climate itself (Fig. 1 and table S1). We start by examining the impacts of climate-driven species redistribution on ecosystem health, human well-being, and the climate system, before highlighting the governance challenges these impacts individually and collectively

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create. Critically, the pervasive effects of changes in species distribution transcend single systems or dimensions, with feedbacks and linkages among multiple interacting spatial and temporal scales and through entire ecosystems, inclusive of humans (Figs. 2 and 3). We conclude by considering species redistribution in the context of Earth systems and sustainable development. Our Review suggests that the negative effects of climate change cannot be adequately mitigated or minimized unless species responses are explicitly included in decision-making and strategic frameworks.

Biological responses and ecosystem health

Species are affected by climate in many ways, including range shifts, changes in relative abundance within species ranges, and subtler changes in activity timing and microhabitat use (*12*, *13*). The geographic distribution of any species depends upon its environmental tolerance, dispersal constraints, and biological interactions with other species (*14*). As climate changes, species must either tolerate the change, move, adapt, or face extinction (*15*). Surviving species may thus have increased capacity to live in new locations or decreased ability to persist where they are currently situated (*13*).

Shifts in species distributions across latitude, elevation, and with depth in the ocean have been extensively documented (Fig. 1). Meta-analyses show that, on average, terrestrial taxa move poleward by 17 km per decade (*5*) and marine taxa by 72 km per decade (*6*, *16*). Just as terrestrial species on mountainsides are moving upslope to escape warming lowlands (*17*), some fish species are driven deeper as the sea surface warms (*18*).

The distributional responses of some species lag behind climate change (*6*, *8*). Such lags can arise from a range of factors, including species-specific physiological, behavioral, ecological, and evolutionary responses (*12*). Lack of adequate habitat connectivity and access to microhabitats and associated microclimates are expected to be critical in increasing exposure to macroclimatic warming and extreme heat events, thus delaying shifts of some species (*19*). Furthermore, distribution shifts are often heterogeneous across geographic gradients when factors other than temperature drive species redistribution. For example, precipitation changes or interspecific interactions can cause downward elevation shifts as climate warms (*20*). Although species may adapt to changing climates, either through phenotypic plasticity or natural selection (*21*), all species have limits to their capacity for adaptive response to changing environments (*12*), and these limits are unlikely to increase for species already experiencing warm temperatures close to their tolerance limits (*22*).

The idiosyncrasies of species responses to climate change can result in discordant range shifts, leading to novel biotic communities as species separate or come into contact in new ways (*23*). In turn, altered biotic interactions hinder or facilitate further range shifts, often with cascading effects (*24*). Changes in predation dynamics, herbivory, host-plant associations, competition, and mutualisms can all have substantial impacts at the community level (*16*, *25*). A case in point involves the expected effects of crabs invading the continental shelf habitat of Antarctic seafloor echinoderms and mollusks—species that have evolved in the absence

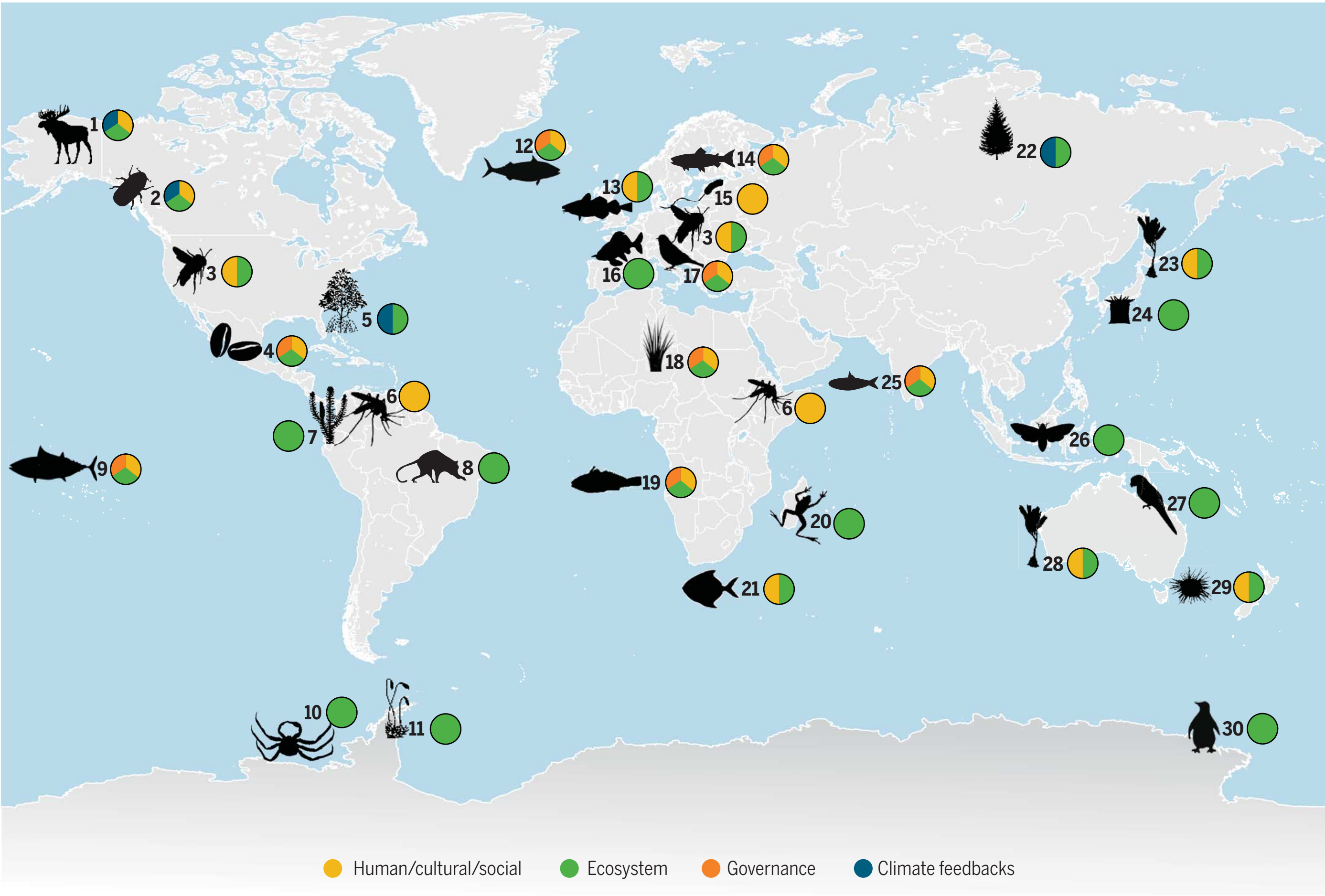

Fig. 1. Climate-driven changes in the distribution of life on Earth are affecting ecosystem health, human well-being, and the dynamics of climate change, challenging local and regional systems of governance. Examples of documented and predicted climate-driven changes in the distribution of species throughout marine, terrestrial, and freshwater systems of the globe in tropical, temperate, and polar regions are shown. Details of the impacts associated with each of these changes in distribution are provided in table S1, according to the numbered key, and the links to specific Sustainable Development Goals are given in table S2.

of skeleton-crushing predators (26). The community impacts of shifting species can be of the same or greater magnitude as the introduction of nonnative species (16), itself recognized as one of the primary drivers of biodiversity loss (27).

When species range shifts occur in foundation or habitat-forming species, they can have pervasive effects that propagate through entire communities (28). In some cases, the impacts are so severe that species redistribution alters ecosystem productivity and carbon storage. For example, climate-driven range expansion of mangroves worldwide, at the expense of saltmarsh habitat, is changing local rates of carbon sequestration (29). The loss of kelp-forest ecosystems in Australia and their replacement by seaweed turfs have been linked to increases in herbivory by the influx of tropical fishes, exacerbated by increases in water temperature beyond the kelp's physiological tolerance limits (30, 31). Diverse disruptions from the redistribution of species include effects on terrestrial productivity (32), impacts on marine community assembly (33), and threats to the health of freshwater systems from widespread cyanobacteria blooms (34).

The effects on ecosystem functioning and condition arising from species turnover and changes in the diversity of species within entire communities are less well understood. The redistribution of species may alter the community composition in space and time (beta diversity), the number of species co-occurring at any given location (alpha diversity), and/or the number of species found within a larger region (gamma diversity) (35). The diversity and composition of functional traits within communities may also change as a result of species range shifts (36), although changes in functional traits may occur through alterations in relative abundance or community composition, without changes in species richness. Increasingly, evidence indicates that species diversity, which underlies functional diversity, has a positive effect on the mean level and stability of ecosystem functioning at local and regional scales (37). It therefore appears likely that any changes in diversity resulting from the redistribution of species will have indirect consequences for ecosystem condition.

Extinction risk from climate change has been widely discussed and contested (38–40), and predictions of extinction risk for the 21st century are considerable (41). In some cases, upslope migration allows mountain-dwelling species to track suitable climate, but topography and range loss can sometimes trap species in isolated and eventually unsuitable habitats (42). The American pika (*Ochotona princeps*) has been extirpated or severely diminished in some localities, signaling climate-induced extinction or at least local extirpation (43). Complicated synergistic drivers or "extinction debt"—a process in which functional extinction precedes physical extinction—may make climate-induced extinction seem a distant threat. However, the disappearance of the Bramble Cay melomys (*Melomys rubicola*), an Australian rodent declared extinct due to sea level rise (44), shows that anthropogenic climate change has already caused irreversible species loss.

Notwithstanding the rich body of evidence from the response to climate change of species and ecosystems in the fossil record (45), understanding more recent, persistent responses to climate change usually requires several decades of data to rigorously assess pre- and postclimate change trends at the level of species and ecosystems (46). Such long-term data sets for biological systems are rare, and recent trends of declining funding undermine the viability of monitoring programs required to document and respond to climate change.

Human well-being

The well-being of human societies is tied to the capacity of natural and altered ecosystems to produce a wide range of goods and services. Human well-being, survival, and geographical distribution have always depended on the ability to respond to environmental change. The emergence of early humans was likely conditioned by a capacity to switch prey and diets as changing climatic conditions made new resources available (47). However, recent technological changes in agriculture, forestry, and fisheries have weakened the direct link between human migration and survival. Now, human societies rely more on technological and behavioral innovation to accommodate human demography, trade and economics, and food production to changing species distribution patterns. The redistributions of species are expected to affect the availability and distribution of goods and services for human well-being in a number of ways, and the relative immobility of many human societies, largely imposed by jurisdictional borders, has limited capacity to respond to environmental change by migration.

Redistributions of species are likely to drive major changes in the supply of food and other products. For example, the relative abundance of skipjack tuna in the tropical Pacific, which underpins government revenue and food security for many small island states, is expected to become progressively greater in eastern areas of the western and central Pacific Ocean, helping to offset the projected ubiquitous decline in the supply of fish from degraded coral reefs in that region (48). Conversely, it is estimated that an average of 34% of European forest lands, currently covered with valuable timber trees, such as Norway spruce, will be suitable only for Mediterranean oak forest vegetation by 2100, resulting in much lower economic returns for forest owners and the timber industry (49).

The indirect effects of climate change on food webs are also expected to compound the direct effects on crops. For example, the distribution and abundance of vertebrate species that control crop pests are predicted to decline in European states, where agriculture makes important contributions to the gross domestic product (50). Shifts in the spatial distribution of agriculture will be required to counter the impact of these combined direct and indirect effects of changing climate. Geographic shifts in natural resource endowments and in systems supporting agriculture, forestry, fisheries, and aquaculture will result in winners and losers, with many of the negative effects likely to occur in developing countries (51). A prime example is the projected effect of climate change on the supply of coffee, with principal coffee-growing regions expected to shift (52).

Species range shifts are also affecting the intrinsic and economic values of recreation and tourism, in both negative and positive ways (53). The buildup of jellyfish due to warmer temperatures in a Mediterranean lagoon has had a negative effect on local economies linked to recreation, tourism, and fishing (54). In southeast Australia, a range-extending sea urchin has overgrazed macroalgae, resulting in localized loss of up to 150 associated taxa and contributing to reduced catch limits for popular recreational fisheries species dependent on large seaweed (55). Impacts have been positive in some contexts, such as the recent emergence of highly prized species in recreational fishing areas (53).

Indirect effects from changes in species distributions that underpin society and culture can be dramatic. In the Arctic, changes in distributions of fish, wild reindeer, and caribou are affecting the food security, traditional knowledge systems, and endemic cosmologies of indigenous societies (Figs. 1 and 2) (7). In partial response, the Skolt Sámi in Finland have introduced adaptation measures to aid survival of Atlantic salmon stocks faced with warming waters and to maintain their spiritual relationship with the species. These measures include increasing the catch of pike to reduce predation pressure on salmon. In the East Siberian tundra, faced with melting permafrost, the Chukchi people are struggling to maintain their traditional nomadic reindeer-herding practices (56) (Fig. 2). Citizen-recording of climate-induced changes to complement assessments based on scientific sampling and remote sensing forms part of their strategy to maintain traditional practices.

Human health is also likely to be seriously affected by changes in the distribution and virulence of animal-borne pathogens, which already account for 70% of emerging infections (57, 58). Movement of mosquitoes in response to global warming is a threat to health in many countries through predicted increases in the number of known and potentially new diseases (Fig. 3). Malaria, the most prevalent mosquito-borne disease, has long been a risk for almost half of the world's population, with more than 200 million cases recorded in 2014 (59). Malaria is expected to reach new areas with the poleward and elevational migration of *Anopheles* mosquito vectors (60). Climate-related transmission of malaria can result in epidemics due to lack of immunity among local residents (59) and will challenge health systems at national and international scales, diverting public- and private-sector resources from other uses.

The winners and losers arising from the redistributions of species will reshape patterns of human well-being among regions and sectors of industry and communities (61). Those regions with the strongest climate drivers, with the most-sensitive species, and where humans have the least capacity to respond will be among the most affected. Developing nations, particularly those near the equator, are likely to experience greater climate-related local extinctions due to poleward and elevational range shifts (62) and will face greater economic constraints. In some cases, species redistribution will also lead to substantial conflict—the recent expansion of mackerel into Icelandic waters is a case in point (Fig. 1 and table S1). The mackerel fishery in Iceland increased from 1700 metric tons in 2006 to 120,000 metric tons in 2010, resulting in "mackerel wars" between Iceland and competing countries that have traditionally been allocated mackerel quotas (63). Likewise, with upslope shift of climate zones in the Italian Alps, intensified conflict is anticipated between recreation and biodiversity sectors. For example, climate-driven contractions in the most valuable habitat for high-elevation threatened bird species and for ski trails are predicted to increase, along with an increase in the degree of overlap between the bird habitat and the areas most suitable for future ski trail construction (64).

Climate feedbacks

Species redistributions are expected to influence climate feedbacks via changes in albedo, biologically driven sequestration of carbon from the atmosphere to the deep sea (the "biological pump"), and the release of greenhouse gases (65). For instance, terrestrial plants affect albedo via leaf area and color and regulate the global carbon cycle through CO_2 atmosphere-land exchanges. Similarly, CO_2 atmosphere-ocean exchanges are biologically modulated by CO_2-fixing photosynthetic phytoplankton and by the biological pump that exports carbon into deep ocean reservoirs (66).

The climate-driven shifts in species distributions most likely to affect biosphere feedbacks involve redistribution of vegetation on land (Figs. 2 and 4) and phytoplankton in the ocean. Decreased albedo, arising from the combined effect of earlier snowmelt and increasing shrub density at high latitudes, already contributes to increased net radiation and atmospheric heating, amplifying high-latitude warming (67). Thus, continued warming will decrease the albedo in the Arctic, not only through a decline in snow cover but also through a northward shift of coniferous trees (Fig. 2). Pearson *et al.* (68) projected that by 2050, vegetation in the Arctic will mostly shift from tundra (dominated by lichens and mosses with high albedo) to boreal forest (dominated by coniferous trees with low albedo). Additionally, the greenhouse effect may be amplified by top-of-atmosphere radiative

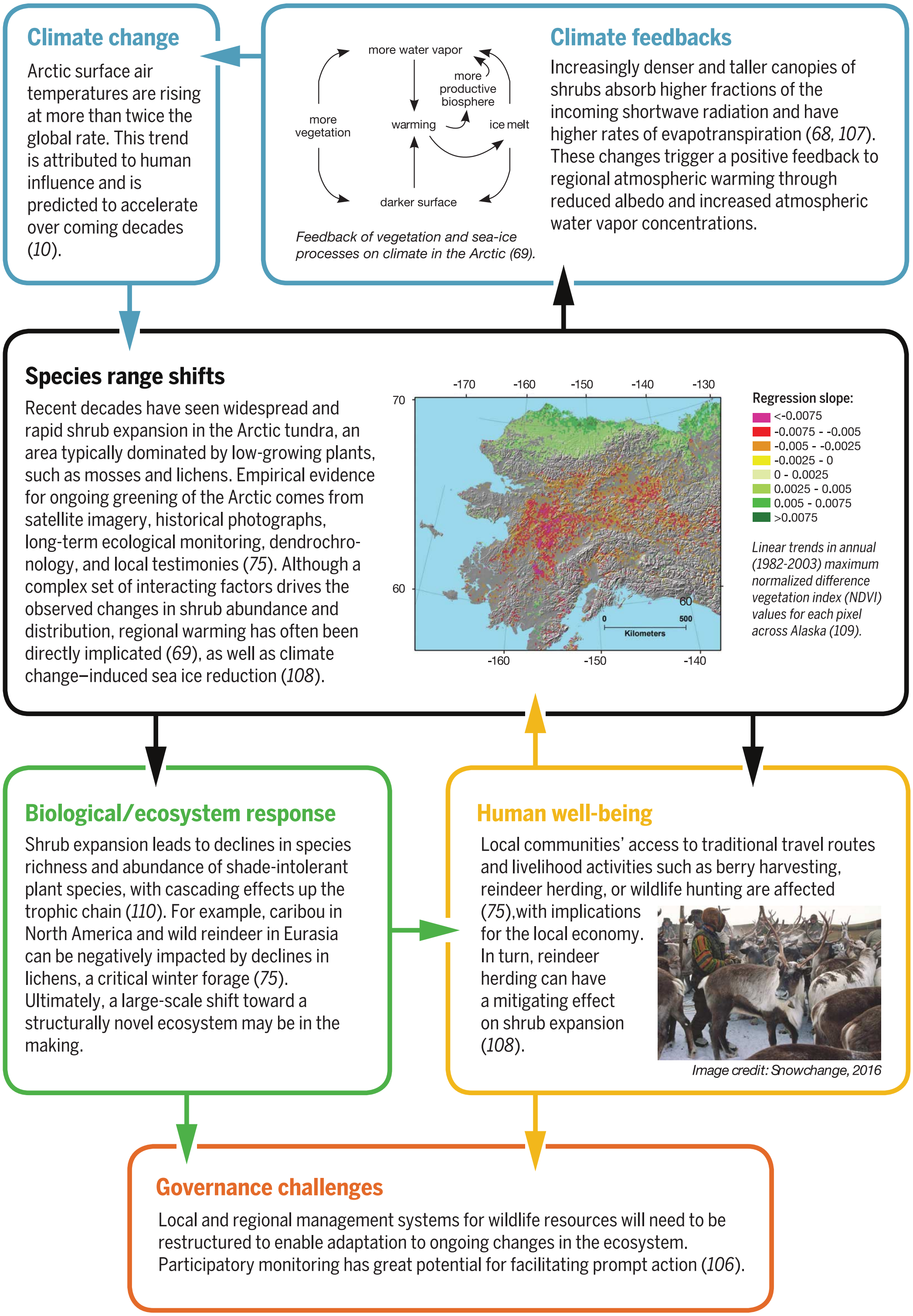

Fig. 2. Species on the move drive greening of the Arctic. Changes in species distribution can lead to climate feedbacks, changes in ecosystem services, and impacts on human societies, with feedbacks and linkages between each of these dimensions, illustrated here through climate-driven changes in Arctic vegetation. See Fig. 4 for a more comprehensive description of the direct and indirect climate feedbacks. See also (10, 68, 69, 75, 106–110).

imbalance from enhanced evapotranspiration associated with the greening of the Arctic (69). At low latitudes, ongoing plant redistribution [e.g., mangrove expansion and forest dieback (29)] potentially amplifies climate warming through carbon-cycle feedbacks (70). However, future projections in the tropics are uncertain because of a lack of close climatic analogs from which to extrapolate (71).

Species redistribution at high latitudes also affects vegetation state indirectly through pests like defoliators and bark beetles that are moving northward and upslope in boreal forests (72) (Figs. 1, 2, and 4). The combined effects of increasing temperatures and droughts increase plant stress, thus contributing to the severity of pest outbreaks and tree dieback. These processes, in turn, increase fuel loads and fire frequency (73), ultimately driving additional feedback through massive biomass burning and CO_2 release. Finally, increased shrub canopy cover at high latitudes may locally reduce soil temperatures through a buffering effect (74), slowing the release of CO_2 from permafrost degradation, thus potentially mitigating warming (75) (Fig. 2).

Redistribution of marine phytoplankton is expected to affect the ocean's biological and carbonate pumps and the production of atmospheric aerosols. The subpolar North Atlantic, which is already highly productive and stores ~25% of the ocean's anthropogenic CO_2 (76), may experience phytoplankton changes due to retreat of the Arctic sea ice and strengthening of ocean stratification. These changes are expected to lead, respectively, to northward movement of productive areas and suppression of the spring bloom, substantially altering CO_2 exchanges between the ocean and the atmosphere at high latitudes (77), although the net effect is uncertain. Rising temperatures may also lead to changes in the composition of different plankton functional groups (78). Expected changes in the relative dominance of diatoms and calcareous plankton can strongly affect the biological cycling of carbon. Such a change was a possible contributor to CO_2 differences between Pleistocene glacial and interglacial periods (79). Similarly, shifts from diatom- to flagellate-dominated systems in temperate latitudes and increased

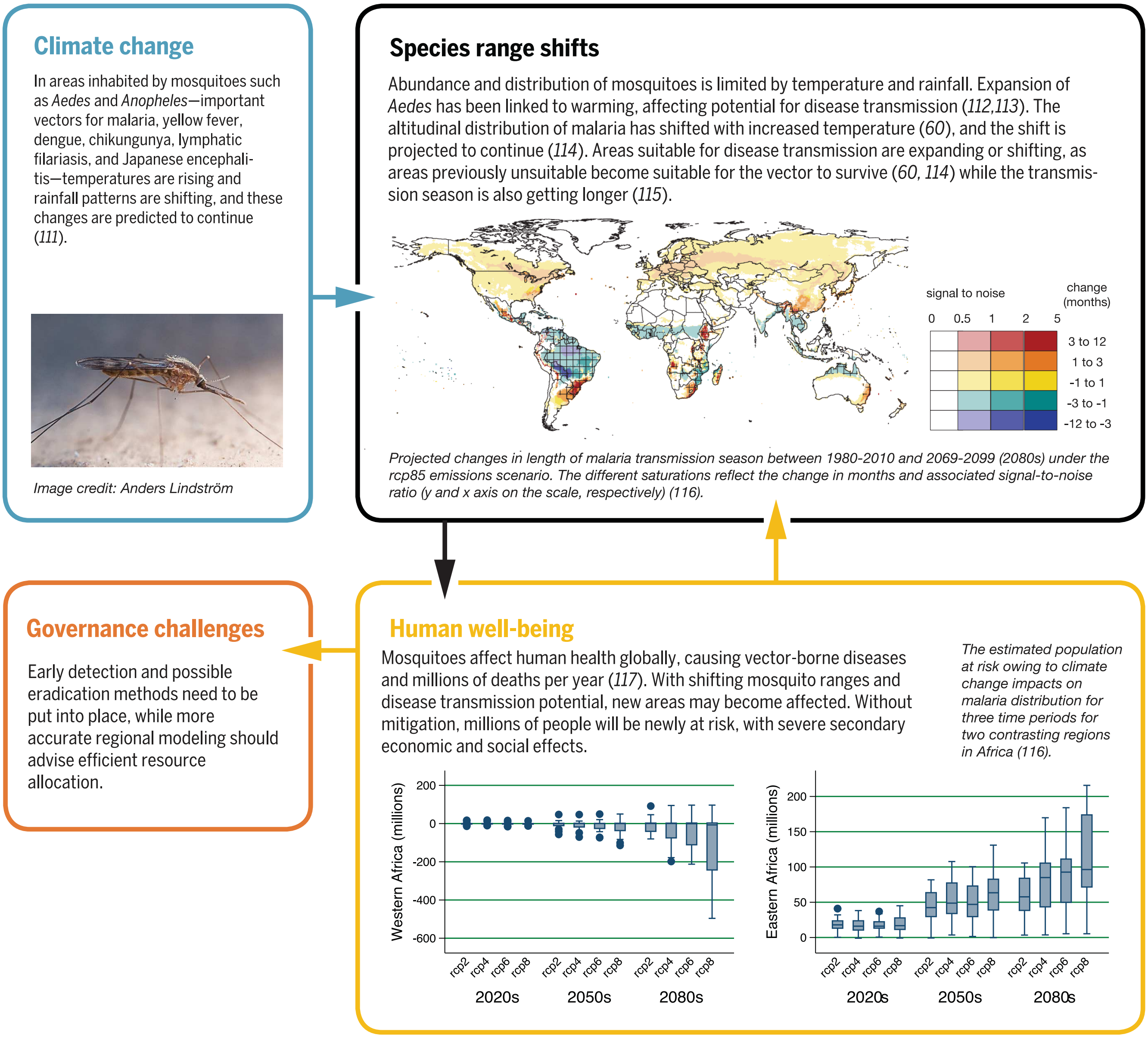

Fig. 3. Mosquito species on the move as vectors of disease. Climate change has facilitated an increase in the distribution of disease vectors, with considerable human cost and associated governance challenges. The bars in the human well-being graphs represent the minimum and maximum ranges; the boxes depict the 25th, 50th, and 75th percentiles of the distribution; and the circles represent outliers. See also (60, 111–117).

microbial remineralization, both associated with warming, are expected to reduce the efficiency of the biological pump and therefore affect atmospheric CO_2 (80).

Temperature-related changes in phytoplankton distributions will also affect production of dimethyl sulfide (DMS), which contributes sulfur particles to the atmosphere and seeds cloud formation (81). These particles are expected to decrease surface temperature, but they may also act as a greenhouse gas, so the net effect on climate warming is not yet clear. There is no simple relationship between DMS production and phytoplankton biomass, chlorophyll concentration, or primary production, which suggests a complex regulation of DMS production by the whole marine planktonic ecosystem and the physical environment controlling it. Hence, current climate models cannot give an estimate of the strength or even the direction of the phytoplankton-DMS-climate feedback.

Climate-influenced links between terrestrial and marine regions may also lead to species redistribution and climate feedbacks. For example, episodic land-atmosphere-ocean deposition of iron (e.g., pulses of Sahara dust) produces phytoplankton blooms (82) and enhances carbon export via the biological pump. Changes to the phytoplankton-driven drawdown of atmospheric CO_2 may therefore arise through changes in the spatial distribution of iron deposition, which may be affected by changes in drought conditions, agricultural practices, and large-scale atmospheric circulation (83). These complex processes—not only driven by climate-induced species redistribution but also affecting the climate system itself—need to be incorporated into climate models to improve future projections (65).

Governance challenges

The impacts of the global redistribution of species on human welfare and ecosystem services require new governance mechanisms for biodiversity conservation and management. A dynamic and multilevel legal and policy approach is needed to address the effects of species range limits moving across local, national, and international jurisdictional boundaries. The development of international guidance where laws do not yet exist will need to account for different legal regimes, resources, and national capacities.

Shifts in species distributions will require changes in the objectives of conservation law, which have traditionally emphasized in situ conservation and retention of historical conditions. Objectives should acknowledge that species will move beyond their traditional ranges, that novel ecosystems will inevitably be created and that historic ecosystems may disappear, as a consequence of such movements (84). The experience of transjurisdictional managed relocations (conservation introductions outside of historical ranges) may inform the development of risk assessment processes that must navigate the complex ethical challenges arising from novel interactions (85) and risks of collateral damage (86). Moreover, communication among relevant agencies throughout the new and former ranges of shifting species is essential to avoid investing in protecting species in locations where they are no longer viable and yet failing to manage them appropriately in their new ranges.

Legal instruments are typically slow to change and often privilege the protection of property and development rights. Although this inertia provides certainty and stability, it underscores the need for flexible approaches that can respond quickly to novel threats arising from species movement or to capitalize on new opportunities. For example, the Landscape Resilience Program of Australia's Queensland government identified priority locations for new protected areas that would maximize available habitat for range-shifting species (87). Some jurisdictions with well-developed land use and development processes have moved toward adaptive development approvals, and Australia's fisheries management regime uses decision rules that automatically trigger new arrangements when predetermined environmental conditions are reached (88). Mechanisms of this sort could be used more widely to implement adaptive management for broader conservation purposes, such as management plans with preset increases in protective strategies that are triggered, or the automatic expansion of protection for habitat outside protected areas when certain climatic indicators are observed.

The changing distribution of species within countries, between countries, and between national borders and the global commons will require increased cooperation and governance across multiple scales among new stakeholders. The European Union's Habitats Directive [European Commission (EC), 1992] and Birds Directive (EC, 1979) are early examples of a cooperative approach to identifying and protecting networks of habitat across national borders. Initiatives such as the Transfrontier Conservation Areas in Southern Africa (Southern African Development Community Protocol, 1999) also provide useful insights to guide future multiscale and cross-border initiatives. Some challenges may also be addressed by increased use of dynamic management techniques. Several countries are already implementing dynamic ocean management practices for bycatch protection (89), though equivalent applications in a terrestrial context are more limited. Collaborative initiatives with indigenous communities may also offer new opportunities for conservation of range-shifting species. Indigenous communities can provide traditional ecological knowledge that complements remote sensing and field data and provides historical context (56), and new management arrangements may incentivize conservation activities.

Earth systems and sustainable development

Human survival, for urban and rural communities, depends on other life on Earth. The biological components of natural systems are "on the move," changing local abundances and geographical distributions of species. At the same time, the

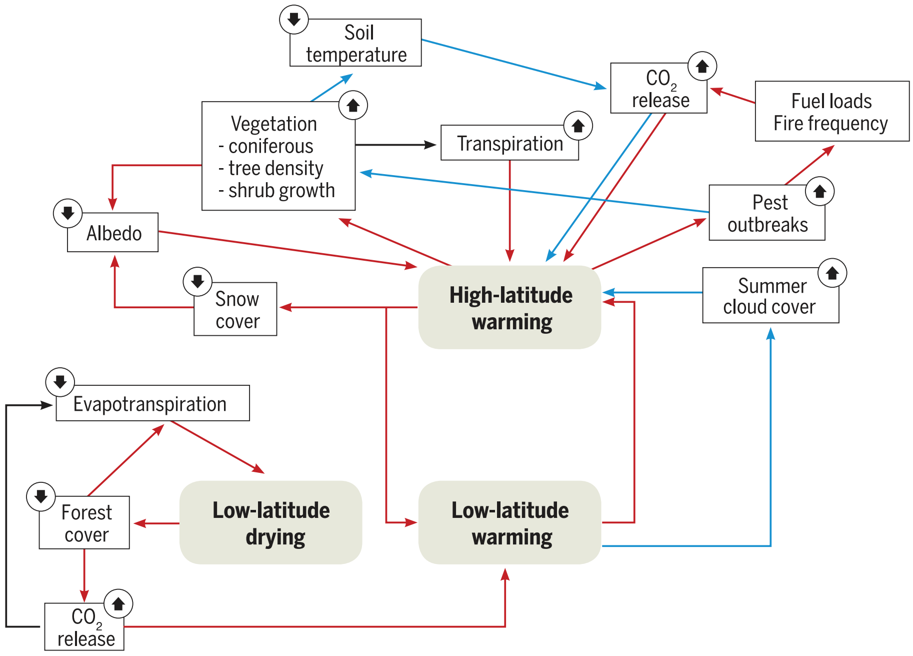

Fig. 4. Climate feedbacks and processes driven by the redistribution of plant species at high latitudes. Climate affects vegetation at high latitudes directly through climatic processes but also indirectly through pests like defoliators and bark beetles that are moving northward and upslope in boreal forests. Some processes increase warming (red arrows), whereas others may serve to decrease warming (blue arrows). Increasing shrub canopy cover in the Arctic at high latitudes may reduce soil temperatures locally through a buffering effect, potentially slowing down CO_2 carbon release due to permafrost degradation, thus acting to slow climate warming. However, greening of the Arctic also decreases albedo, which accelerates warming.

ability of people and communities to track these pervasive species redistributions and adapt to them is increasingly constrained by geopolitical boundaries, institutional rigidities, and inertias at all temporal and spatial scales.

In the coming century, all people and societies will face diverse challenges associated with development and sustainability, many of which will be exacerbated by the redistribution of species on the planet (Figs. 2 and 3). The impacts of species redistribution will intersect with at least 11 of the United Nations' Sustainable Development Goals (SDGs) (table S2) and will be particularly prominent for several of these SDGs.

SDG2 (Zero Hunger) requires feeding more than 9 billion people by 2050 (*90*). However, the ability to deliver food through agriculture will be altered via the direct effects of climate change, as the distributions and abundances of pollinators change and as plant pathogens and pests become more prevalent or emerge in new places as a result of global warming (*91*, *92*). SDG3 (Good Health and Well-Being) is made more challenging by tropical illnesses spreading to new areas (*58*) and changes in food security and the distribution of economic wealth on local, regional, and global scales. Moreover, human well-being is also related to many other facets of society and culture, including attachment to place (*56*, *93*) and the living environment found around us. The mental health of indigenous and rural communities, in particular, may be affected as species redistribution alters the capacity for traditional practices, subsistence, or local industries. The success of SDG13 (Climate Action) will depend on accounting for the direct and indirect influences of shifting organisms and associated feedbacks on our biosphere, yet these processes and feedbacks are rarely accounted for in projections of future climate. Sustainable management and the conservation of SDGs 14 and 15 (Life Below Water and Life on Land) are unlikely to be effective unless climate-driven alterations in species ranges and their profound ecosystem consequences are taken into consideration.

Managing for movement

Under extensive reshuffling of the world's biota, how should conservation goals and strategies for policy and implementation be developed to maximize long-term resilience of biodiversity and human systems? How should natural resource management across diverse, multiuse, multiscale land and seascapes be integrated to maximize resilience of both human and natural systems? How should specific threats and stressors (including their interactions) be managed while minimizing impacts on valued ecosystem assets? For the scientific community to help develop mitigation and adaptation strategies in the face of widespread change in species distribution and ecosystem functioning, a better understanding of the mechanisms underlying such changes is needed. Scientists also need access to real-time data streams, as well as to integrate this information into decision-support frameworks. Moreover, scientists and their institutions need to rapidly communicate advances and outcomes to the broader public and to policy-makers. However, the natural world responds in dynamic and unpredictable ways, and the phenomenon of species redistribution is not, nor will it ever be, fully understood or completely predictable. This uncertainty necessitates flexible and dynamic governance so adaptation to changing conditions can be rapid, maximizing opportunities and minimizing negative consequences.

Underlying biological processes

Because knowledge of the biological and ecological processes underlying resilience of organisms to predicted average and extreme environmental conditions is limited, the traits on which natural and anthropogenic selection will act are uncertain. For example, specific physiological mechanisms have been hypothesized to underlie the thermal ranges of ectothermic organisms (*94*), yet a lack of universality in the proposed mechanisms highlights a need for novel, multidisciplinary investigations (*95*). Large-scale, multigenerational experimental research programs are required to provide a robust understanding of the adaptive responses of organisms to environmental change and to determine the heritability of key traits, as recently has been achieved for sea turtles (*96*). Modeling approaches, lab and field-based experimental manipulations, and field-based monitoring programs need to be combined with more effective policy communication to understand and implement responses to species redistributions.

Monitoring programs

To best adjust to species redistributions, gaps in understanding need to be acknowledged and filled through hypothesis testing. Our understanding is weakest in poorly surveyed regions such as the tropics and Antarctica (*8*). As range shifts continue to unfold, there will be opportunities to refine our understanding of the process, but taking advantage of these opportunities requires access to consistent, high-quality, near-real-time data on a series of environmental and biological parameters (*97*).

The current absence of a global, comprehensive, coordinated biodiversity monitoring system is a major obstacle to our understanding of climate change implications for natural systems. Thus far, extensive global cooperation and progress have been achieved in terms of coordinating the collection and distribution of physical and chemical environmental monitoring data. For example, the Global Climate Observing System facilitated international agreement and a global commitment toward consistent monitoring of climate variables, ultimately supporting the development of spatiotemporally-explicit and uncertainty-explicit predictions about changes in our climate (*98*). Ongoing efforts through the Group on Earth Observation Biodiversity Observation Network and the Intergovernmental Oceanographic Commission Global Ocean Observing System are beginning to implement the use of Essential Biodiversity Variables (*41*) and ecosystem Essential Ocean Variables (*99*), respectively, but the process is slow and underresourced. A global, robust biodiversity monitoring system that successfully integrates field and remote-sensing data could substantially improve our ability to manage the changes to come while potentially driving faster mitigation measures (*100*).

Incorporating species on the move into integrated assessment models

Knowledge of underlying biological processes and access to real-time data are necessary but not sufficient for informed responses. Improved capacity to model linkages and feedbacks between species range shifts and ecosystem functioning, food security, human health, and the climate is required. Modeling is essential to reliably project the potential impacts of alternative scenarios and policy options on human well-being, as the basis for evidence-based policy and decision support (*101*). One avenue forward is to incorporate species redistribution and its associated effects into integrated assessment models (IAMs) (*102*), which are used widely within the climate science community and are now being rapidly mobilized and extended to address synergies and trade-offs between multiple SDGs (*103*). IAMs offer a promising approach for connecting processes, existing data, and scenarios of demographic, social, and economic change and governance. Although species distribution models are commonplace, advances are needed to connect species redistribution with ecosystem integrity (*104*) and feedbacks between humans and the biosphere.

Communication for public and policy

How does the scientific community engage effectively with the public on the issue of species redistribution and its far-reaching impacts? Part of the answer could be citizen science and participatory observing approaches, in which community members are directly involved in data collection and interpretation (*105*). These tools can help to address gaps in both data and communication (*100*). When properly designed and carefully tailored to local issues, such approaches can provide quality data, cost-effectively and sustainably, while simultaneously building capacity among local constituents and prompting practical and effective management interventions (*106*).

Conclusions

The breadth and complexity of the issues associated with the global redistribution of species driven by changing climate are creating profound challenges, with species movements already affecting societies and regional economies from the tropics to polar regions. Despite mounting evidence for these impacts, current global goals, policies, and international agreements do not sufficiently consider species range shifts in their formulation or targets. Enhanced awareness, supported by appropriate governance, will provide the best chance of minimizing negative consequences while maximizing opportunities arising from species movements—movements that, with or without effective emission reduction, will continue for the foreseeable future, owing to the inertia in the climate system.

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SUPPLEMENTARY MATERIALS

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Editor's Summary

Consequences of shifting species distributions

Climate change is causing geographical redistribution of plant and animal species globally. These distributional shifts are leading to new ecosystems and ecological communities, changes that will affect human society. Pecl *et al.* review these current and future impacts and assess their implications for sustainable development goals.

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Managing consequences of climate-driven species redistribution requires integration of ecology, conservation and social science

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ABSTRACT

Climate change is driving a pervasive global redistribution of the planet's species. Species redistribution poses new questions for the study of ecosystems, conservation science and human societies that require a coordinated and integrated approach. Here we review recent progress, key gaps and strategic directions in this nascent research area, emphasising emerging themes in species redistribution biology, the importance of understanding underlying drivers and the need to anticipate novel outcomes of changes in species ranges. We highlight that species redistribution has manifest implications across multiple temporal and spatial scales and from genes to ecosystems. Understanding range shifts from ecological, physiological, genetic and biogeographical perspectives is essential for informing changing paradigms in conservation science and for designing conservation strategies that incorporate changing population connectivity and advance adaptation to climate change. Species redistributions present challenges for human well-being, environmental management and sustainable development. By synthesising recent approaches, theories and tools, our review establishes an interdisciplinary foundation for the development of future research on species redistribution. Specifically, we demonstrate how ecological, conservation and social research on species redistribution can best be achieved by working across disciplinary boundaries to develop and implement solutions to climate change challenges. Future studies should therefore integrate existing and complementary scientific frameworks while incorporating social science and human-centred approaches. Finally, we emphasise that the best science will not be useful unless more scientists engage with managers, policy makers and the public to develop responsible and socially acceptable options for the global challenges arising from species redistributions.

Key words: adaptive conservation, climate change, food security, health, managed relocation, range shift, sustainable development, temperature.

CONTENTS

I. INTRODUCTION

Species across the globe, in all ecosystems, are shifting their distributions in response to recent and ongoing climate change (Parmesan & Yohe, 2003; Sorte, Williams & Carlton, 2010; Pinsky *et al.*, 2013; Alofs, Jackson & Lester, 2014; Lenoir & Svenning, 2015; Poloczanska *et al.,* 2016; Scheffers *et al.,* 2016). These shifts are faster at greater levels of warming (Chen *et al.,* 2011) and are projected to accelerate into the future with continued changes in the global climate system (Urban, 2015). Thus, there is a clear need to understand the impacts and consequences of global species redistribution for ecosystem dynamics and functioning, for conservation and for human societies (Pecl *et al.,* 2017).

Species range dynamics and climate have an intertwined history in ecological research going back centuries (Grinnell, 1917; Parmesan, 2006). However, research on species range shifts driven by contemporary climate change is relatively recent, dating back only 20 years (Southward, Hawkins & Burrows, 1995). In the past decade, research on the subject has increased dramatically (Fig. 1). While coverage is far from complete methodologically, geographically or taxonomically (Lenoir & Svenning, 2015; Brown *et al.,* 2016; Feeley, Stroud & Perez, 2017), this increased research effort highlights growing awareness that species are moving in response to climate change, worldwide (IPCC, 2014).

We believe that 'species redistribution science' has emerged as a field in its own right. However, to date the field has lacked strategic direction and an interdisciplinary consideration of research priorities. Historically, researchers have used 'species range shifts' or 'species distribution shifts' as favoured descriptive terms for climate-driven species movements. Here we use the term 'species redistribution' to encapsulate not only species movement, but also its consequences for whole ecosystems and linked social systems. Despite accumulating evidence of recent climate-driven species redistributions (Lenoir & Svenning, 2015; Poloczanska *et al.,* 2016; Scheffers *et al.,* 2016), integrated and interdisciplinary frameworks that can effectively predict the ecological, conservation and societal consequences of these changes remain uncommon [but see Williams *et al.* (2008) for a framework highlighting species vulnerability and potential management responses]. A long-term strategy for the field of species redistribution research is required to capitalise on, and respond to, the 'global experiment' of large-scale changes in our natural and managed ecosystems. What can be implemented now to build scientific and social capacity for adaptation to species redistribution over the next decade, the next century and beyond (IPCC, 2014)?

The 'Species on the Move' conference (held in Hobart, Australia, 9–12 February 2016) brought together scientists from across the physical, biological and social sciences. Here, we build on the outcomes of this conference by identifying key research directions to meet the global challenge of preparing for the impacts of climate-driven species redistribution on the biosphere and human society. We focus on directions and needs around three focal points for understanding species redistribution and its impacts: (*i*) species redistribution ecology, (*ii*) conservation actions, and (*iii*) social and economic impacts and responses. For each focal point we summarise recent trends in the field and propose priority questions for future research. We identify promising research directions and approaches for addressing these questions, placing emphasis on the potential benefits from integrating approaches across multiple disciplines and sub-disciplines. In so doing, we argue that greater interdisciplinary synthesis is fundamental to ensuring that species redistribution research continues to advance beyond simple documentation of species range shifts, to develop research programs and achieve outcomes that will inform policy and management decisions.

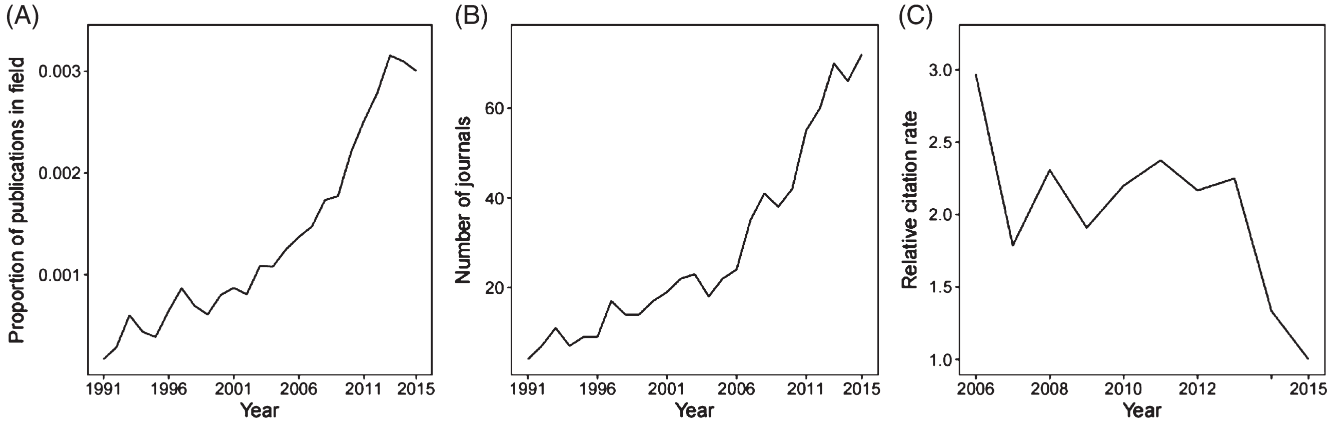

Fig. 1. Publication trends for papers on species range shifts. (A) Proportion of publications addressing species redistribution over a time, as a fraction of all papers in environmental sciences/ecology fields. (B) Number of journals publishing species redistribution papers over time. (C) Median annual citation rate of species redistribution papers decreases to the median annual citation rate of papers in the general environmental sciences/ecology field.

II. SPECIES REDISTRIBUTION AS A FIELD OF RESEARCH

To support our synthesis of future directions, we first establish how the research field of climate-driven species redistributions has evolved and quantify, bibliometrically, the prevailing research foci. To understand this history in the context of the broader scientific literature, we analysed publication trends in the peer-reviewed literature on species range shifts over the past 25 years. In total we extracted 1609 publications from Thompson Reuters *Web of Science* that contained search terms relating to distribution change or range shift (see online Appendix S1 for details).

In 2006, both the proportion of range shift publications in the 'environmental sciences' and the diversity of journals publishing research on range shifts showed a clear increase (Fig. 1). At the same time, citation rates dropped relative to the discipline's baseline heralding that publications about range shifts had shifted from a few high-profile publications to mainstream ecological science (Fig. 1).

We analysed this corpus to identify research trends in two ways. First, we identified 'trending' terms. Terms were defined based on word stems, and trending terms were those that showed a significant increase in use in titles, abstracts or key words since 1995. Second, we identified 'high-impact' terms, i.e. those associated with higher than average citation rates, once we had accounted for the confounding effect of publication year. The trends analysis indicated that range shift science has become increasingly interdisciplinary over time. Terms associated with socioeconomic approaches, such as 'ecosystem services' have also become increasingly prevalent and tend to be associated with high-impact papers (Fig. 2). Management-oriented studies, with terms including 'priority' (referring to management priorities) are also increasing in use. Both socioeconomic ('social', 'socioeconomic') and management-related terms ('complement*' referring to complementary protection) were associated with higher than average citation rates during the period 2010–2015 (Fig. 2). Thus, we find clear evidence for the emergence of a new field that is generating increasing interest, while expanding to link with other existing and emerging fields.

III. SPECIES REDISTRIBUTION ECOLOGY

Species redistribution has been widely documented (Scheffers *et al.*, 2016) and well-developed theories have been proposed to explain how and why range shifts occur (Bates *et al.*, 2014) and how future species redistribution may proceed under global climate change (Urban *et al.*, 2016). Hence, we can consider the ecology of species redistribution under two broad and complementary areas: explanatory ecology and anticipatory ecology. Explanatory ecology generally aims to evaluate models and theory to enhance scientific understanding of the processes that drive species redistribution. For detailed reviews on subject areas specific to explanatory ecology we refer the reader to Somero (2010) (physiological factors), Blois *et al.* (2013) (biotic interactions), Maguire *et al.* (2015) (historical ecology), and Garcia *et al.* (2014) (climate trends/extreme events). Anticipatory ecology, by contrast, intends to forecast future states by inferring possible trajectories or behaviours of the system, based on parameters likely to be impacted by anthropogenic factors, such as predicting the effects of climate change on species, communities and ecosystems. For detailed reviews of anticipatory ecology we recommend Urban *et al.* (2016) and Cabral, Valente & Hartig (2016).

In this section, we do not duplicate former reviews of the explanatory and anticipatory ecology of species redistribution. Our review focuses, instead, on gaps in explanatory and anticipatory ecology (Table 1) that need to be filled in order to predict the impacts of species redistribution on biodiversity and human well-being.

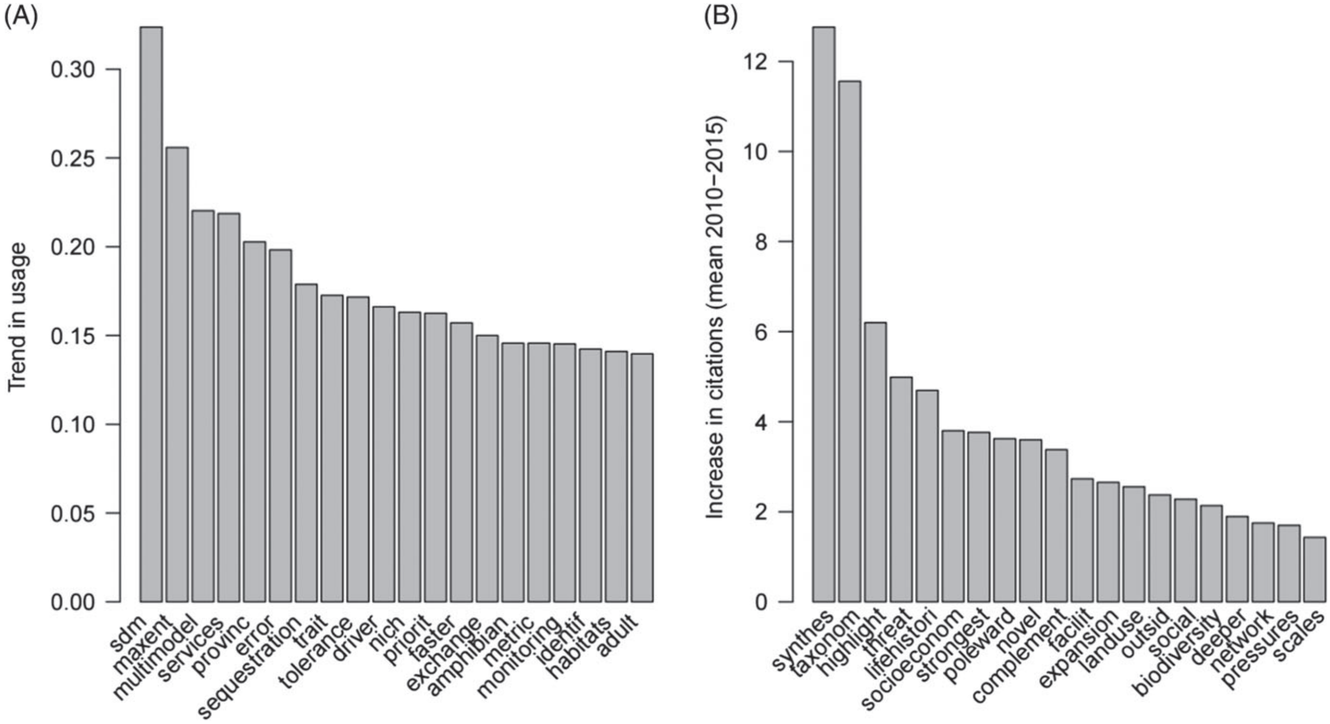

Fig. 2. Analysis of trends used within the species redistribution literature: (A) top 20 trending words that increased significantly in usage, and (B) top 20 high-impact words that correspond with increased citation rates of papers published between 2010 and 2015. See online Appendix S1. sdm, species redistribution model.

To achieve this aim, we examine multiple elements of explanatory ecology, including the physiological and ecological factors underpinning species redistribution, biotic interactions and historical ecology, as well as climate trends and extreme events. We conclude this section with a discussion of the challenges of anticipatory ecology.

(1) Physiological and ecological factors underpinning species redistribution

Climate change is causing pervasive impacts on ectothermic animals because of their reliance on environmental temperature to regulate body temperature (Deutsch *et al.*, 2008; Kearney & Porter, 2009). Thermal performance curves, which quantify how an ectotherm's body temperature affects its performance or fitness, are used to understand range shifts and to predict future distributions (Sunday, Bates & Dulvy, 2012; Sunday *et al.*, 2014). While thermal tolerance and performance patterns have been well studied for ectothermic taxa (Dell, Pawar & Savage, 2011), similar trends in large-scale patterns of climatic niche, e.g. heat tolerance conserved across lineages, are also apparent for endotherms and plants (Araújo *et al.*, 2013). The use of thermal performance curves in predicting species distributions often disregards ecological interactions (e.g. competition, predation, mutualism) that may be critical to population establishment and persistence (but see Urban, Tewksbury & Sheldon, 2012). In addition, the form of each species' performance curve has important effects on species interactions, with asymmetries in the thermal performance curves between interacting species likely having important impacts on the strength and outcome of interactions (Dell *et al.*, 2011; Dell, Pawar & Savage, 2014). Physiological plasticity (e.g. thermal acclimation), resource specialisation, competitive interactions and behavioural thermoregulation (Thomas *et al.*, 2001; Burton, Phillips & Travis, 2010; Feary *et al.*, 2014; Sunday *et al.*, 2014; Tunney *et al.*, 2014; Tedeschi *et al.*, 2016) are additional factors that can modify thermal performance curves and/or impact the nature and outcome of species range shifts.

Future research would therefore benefit from approaches that connect mechanistic processes across biological levels of organisation, from genes to ecosystems. For example, because selection acts on individual genotypes/phenotypes, an understanding of intraspecific variation in key functional traits will help in forecasting species' breadth of tolerance and capacity for range shifts (Norin, Malte & Clark, 2016). In general, both low and high variability in thermal tolerances can exist within and among populations and may vary with extrinsic factors such as environmental filtering, which causes a convergence in tolerance (i.e. heat hardening; Phillips *et al.*, 2015), or intrinsic factors such as body size or life-history stages, which might result in thermal tolerance dispersion (Ray, 1960; Angilletta, Steury & Sears, 2004; Daufresne, Lengfellner & Sommer, 2009; Cheung *et al.*, 2013; Scheffers *et al.*, 2013).

The mechanistic basis behind variability in thermal tolerance remains poorly understood (Clark, Sandblom &

Table 1. Key questions posed by attendees of the 2016 *Species on the Move* conference and additional questions developed for each research focus: Ecology, Conservation and Society. Also included for each key question are cross-cutting themes (*sensu* Kennicutt *et al.*, 2015). ECO, Ecology; CONS, Conservation; SOC, Society; SDM, species redistribution model

Key questions and topics	Approaches and interdisciplinary cross-cutting	References
Ecology		
To what extent will novel species combinations impact future change to ecological communities? **CONS/SOC**	Experimental manipulation Modelling	Urban *et al*. (2012) and Alexander *et al*. (2015)
How much do biotic interactions affect range shifts, compared to the effects on ranges from species traits, geographic context and physical rates of change? **CONS**	Incorporation of species interactions into SDMs Palaeoecological methods	Ferrier *et al.* (2007), Wisz *et al.* (2013), Blois *et al.* (2013) and Fitzpatrick *et al.* (2013)
How can we predict species responses to extreme events? Much empirical physical research is focused on extreme events, but most biological/ecological modelling evaluates slow long-term change. **CONS/SOC**	Incorporate extreme climatic events into modelling/predictions Measure key mechanistic processes	Zimmermann *et al.* (2009), Azzurro *et al.* (2014) and Briscoe *et al.* (2016)
What is the role of plasticity (physiological, behavioural) in mediating species responses within and between populations, and how does plasticity affect modelling predictions? **CONS**	Accounting for intraspecific differences in realised niche	Valladares *et al.* (2014) and Bennett *et al.* (2015)
What are the main determinants of time lags in biotic responses to climate change (the climatic debt)? **CONS**	Explaining magnitude of lags in response to climate change in addition to the magnitude of the shift	Bertrand *et al.* (2016)
How will uncertainty in climate change projections affect predictions of species redistribution? **CONS**	Multi-model ensemble averaging	Fordham *et al.* (2011)
How can co-occurring taxa/communities best be modelled under changing climates? **CONS**	Community-level models	Maguire *et al.* (2016)
Conservation		
How can we integrate uncertainty into the conservation planning process? What time frame allows for robust actions while minimising uncertainty? **SOC**	Decision science	Shoo *et al.* (2013)
How can we monitor large-scale landscapes and seascapes and complex natural and social interactions best across regions? **ECO/SOC**	Monitoring to adjust (adaptive) conservation actions continuously Interpretation of satellite remote-sensing, population surveys	Tøttrup *et al.* (2008), Pettorelli *et al.* (2014) and Kays *et al.* (2015)
What are the values and risks associated with novel communities that arise from individual species range shifts? What are the effects of invasive species on the maintenance of phylogenetic and functional diversity? **ECO**	Assessing functional and phylogenetic diversity Palaeoecological methods	Buisson *et al.* (2013) and Albouy *et al.* (2015)
How do we apply prescriptive/assisted evolution to accommodate species redistribution? **ECO**	Molecular ecology Conservation genomics	Smith *et al.* (2014) and Hoffmann *et al.* (2015)
How can we build dynamic conservation management strategies that cope with changes in species distributions? **SOC**	Sequential dynamic optimsation	Alagador *et al.* (2014)
How does climate change interact with other drivers of biodiversity change (e.g. invasive species, land use and fire) to influence outcomes for biodiversity (all species)? **ECO/SOC**	Management of local stressors Coupled population and SDMs	Russell *et al.* (2009), Bonebrake *et al.* (2014) and Jetz *et al*. (2007)
Will microrefugia allow species to persist locally as climate changes? If so, where are they? **ECO**	Climate change metrics Fine-scale grids	Keppel *et al.* (2012) and Ashcroft *et al.* (2012)
Society		
How do species redistributions impact ecosystem services through biodiversity reshuffling? **ECO**	Coupled SDM and trait-based methods	Moor *et al.* (2015)
What are the key messages we need to communicate to the public about shifting distribution of marine and terrestrial species? How do we communicate them effectively? **ECO**	Creating opportunities for respectful dialogue between scientists and the public Improving ecological and science literacy	Jordan *et al.* (2009) Groffman *et al*. (2010)

Table 1. Continued

Key questions and topics	Approaches and interdisciplinary cross-cutting	References
How can people and communities contribute further to monitoring the impacts of changes in the distributions and relative abundances of species caused by climate change? **ECO/CONS**	Community-based observation systems	Higa *et al.* (2013) and Chandler *et al.* (2016)
What is the effect of climate change on soil biodiversity, and how does climate change affect soil health and agriculture? **ECO/CONS**	SDMs and soil science	Hannah *et al.* (2013) and le Roux *et al.* (2013)
How can marine spatial planning be reorganised to reconcile biodiversity conservation and food security? **ECO/CONS**	Adaptive management Restoration	Garcia & Rosenberg (2010), Rice & Garcia (2011) and Sale *et al.* (2014)
What practical adaptations for agriculture, fisheries and aquaculture can be promoted to minimise the risks to food security and maximise the opportunities that are expected to arise from altered species distributions? **ECO/CONS**	Adaptive management Restoration	Bradley *et al.* (2012) and Bell *et al.* (2013)
How will climate change impact the redistribution of disease-associated species and influence infectious disease dynamics? **ECO**	Host and vector SDMs	Rohr *et al.* (2008) and Harrigan *et al.* (2014)
How can international environmental agreements that influence resource-management decisions incorporate local community observations and insights into their guidance and policy-making objectives? **CONS**	Evidence-based legal processes Multiple evidence-based frameworks	Tengö *et al.* (2017)

Jutfelt, 2013) but may be revealed through new genetic tools (Bentley *et al.,* 2017). Measuring genetic diversity as organisms expand their range and documenting genetic structure during and after colonisation can provide a wealth of information on evolutionary dynamics of range shifts (McInerny *et al.,* 2009; Sexton, Strauss & Rice, 2011; Duputié *et al.,* 2012), but requires new, dedicated research programs and/or careful analysis of historical museum collections. Knowledge of the genetics underpinning thermal tolerance can directly inform species conservation and ecosystem restoration through assisted evolution applications (Van Oppen *et al.,* 2015).

The magnitude of range shifts can be population, species, and ecosystem dependent, suggesting determinants or mediators of species redistribution other than climate (Rapacciuolo *et al.,* 2014; Rowe *et al.,* 2015). Species redistribution studies have commonly sought to identify ecological traits that explain species responses (see Fig. 2; McGill *et al.,* 2006; Sunday *et al.,* 2015; Pacifici *et al.,* 2015). However, trait-based studies have had mixed success at identifying predictors of range shifts, with thermal niches and climate trends remaining in general the strongest explanatory variables (Buckley & Kingsolver, 2012; Pinsky *et al.,* 2013; Sommer *et al.,* 2014; Sunday *et al.,* 2015). Key traits may include those related to dispersal and establishment (Angert *et al.,* 2011; Sunday *et al.,* 2015; Estrada *et al.,* 2016), local persistence, such as intrinsic ability to tolerate changing climate (physiological specialisation; Bertrand *et al.,* 2016), phenotypic plasticity (Valladares *et al.,* 2014), micro-evolutionary processes (genetic adaptation; Duputié *et al.,* 2012), capacity to utilise microhabitat buffering effects (Scheffers *et al.,* 2013), fossorial habits (Pacifici *et al.,* 2017), and tolerance to habitat fragmentation (Hodgson *et al.,* 2012). Determining the contexts and conditions under which different traits mediate species redistribution, and to what degree those traits determine redistribution, is an important avenue of future research.

(2) Biotic interactions

In general, biotic interactions remain under-measured in range-shift studies, yet they likely play a key role in mediating many climate-induced range shifts (Davis *et al.,* 1998; HilleRisLambers *et al.,* 2013; Ockendon *et al.,* 2014). Shifts in species interactions will occur as a result of differential responses to climate by individual species that can lead to asynchronous migrations within communities and creation of novel assemblages (Pörtner & Farrell, 2008; Hobbs, Higgs & Harris, 2009; Gilman *et al.,* 2010; Urban *et al.,* 2012; Kortsch *et al.,* 2015; Barceló *et al.,* 2016). Asynchronous shifts can also cause decoupling of trophic interactions, for example when symbiont–host interactions break down (Hoegh-Guldberg *et al.,* 2007) through mismatches in the phenology between consumers and their resources (Winder & Schindler, 2004; Durant *et al.,* 2005; Post & Forchhammer, 2008; Thackeray *et al.,* 2016) or through differential thermal sensitivity of consumers and their resources (Dell *et al.,* 2014). Conversely, climate change and species distribution shifts can create novel species interactions through range expansions, as species that have evolved in isolation from one another come into contact for the first time (Vergés *et al.,* 2014; Sánchez-Guillén *et al.,* 2015).

Some of the most dramatic impacts of community change are likely to arise through the assembly of novel species combinations following asynchronous range shifts associated with climate change (Urban *et al.,* 2012; Alexander, Diez & Levine, 2015). These predictions are supported by palaeoecological studies that show how novel species interactions resulting from past climatic changes drove profound community-level change (Blois *et al.,* 2013). The emergence of novel ecological communities will pose significant conservation and societal challenges, because most management paradigms are insufficient to cope with major reorganisation of ecosystems (Morse *et al.,* 2014; Radeloff *et al.,* 2015). Studies of the response of linked social-ecological systems to historical climatic changes are needed to inform the management of ecosystems under ongoing and future climate change (e.g. Hamilton, Brown & Rasmussen, 2003).

Contemporary observations of extreme events suggest that shifts in species interactions are particularly important when redistribution occurs in foundation (i.e. habitat-forming) or keystone species. Shifts in foundation species can initiate cascading effects on other species and act as biotic multipliers of climate change (Zarnetske, Skelly & Urban, 2012). For example, many of the greatest ecosystem impacts of climate change in marine systems have been caused by the loss of habitat-forming species such as corals, kelp forests and seagrasses (Hoegh-Guldberg & Bruno, 2010; Thomson *et al.,* 2015; Vergés *et al.,* 2016; Wernberg *et al.,* 2016).

Explanatory ecology is now shifting its focus from single species to the role of biotic interactions in mediating range shifts. A key research priority is to identify the importance of biotic interactions relative to species traits, geographic context and physical rates of change (Sunday *et al.,* 2015). A limiting factor has been the lack of multi-species 'climate change experiments' (Wernberg, Smale & Thomsen, 2012) and long time-series data that follow multiple trophic levels (Brown *et al.,* 2016). Thus, there is a need to join multiple data sets in order to understand how biotic interactions shape range shifts. Understanding the role of biotic interactions in species redistribution is important to inform conservation and societal challenges. For instance, models of three interacting invasive pests (potato tuber moths) in the Andes predicted that their redistribution would alter biotic interactions, which would in turn impact the level of crop damage (Crespo-Pérez *et al.,* 2015).

(3) Community redistribution and historical ecology

Despite species redistribution science being born of ecology, we are still a long way from understanding how species redistribution will drive changes in ecological communities (Marzloff *et al.,* 2016). Historical ecology suggests that climate change can result in dramatic alterations in community structure. For example, the equatorial dip in diversity evident in modern marine communities (Tittensor *et al.,* 2010) was most pronounced for reef corals during the warmer intervals of the last interglacial period (125 ka), indicating that both leading and trailing edges of species ranges were responding to increases in ocean temperature (Kiessling *et al.,* 2012). Pleistocene reef records suggest that species and communities are relatively robust to climate change and that ecological structure generally has persisted within reef coral communities over multiple climatic cycles (Pandolfi, 1996; Pandolfi & Jackson, 2006). By contrast, many North American tree species have shifted their individual distributions and adapted genetically to Quaternary climatic changes (Davis & Shaw, 2001). Human migrations, settlement patterns, and species use have also been linked to environmental change (Graham, Dayton & Erlandson, 2003). However, the rate of contemporary climate change, genetic constraints on rapid adaptation and dramatic land cover changes over the past century will challenge 'natural' species redistribution in the Anthropocene (Hoffmann & Sgro, 2011; Moritz & Agudo, 2013) and complicate human responses to these changes.

A key question for historical ecology is to determine the extent to which community change is driven by multiple species-specific responses to climate, *versus* shifts in key species driving cascading community change. Historical ecology can fill an important gap in our understanding, given that it focuses on systems that were, in most cases, far less influenced by humans than occur presently. Furthermore, studies in deep time allow us a glimpse into the outcome of processes similar to those that we are watching in their infancy today.

(4) Climate trends, scale mismatch and extreme events

Climate trends are a key predictor of range shifts due to the importance of climatic tolerances (or thermal performance curves) in controlling species ranges. Observational evidence of the direction of range shifts in terrestrial and aquatic environments are overwhelmingly consistent with expectations required for species to track temperature changes (Sorte *et al.,* 2010; Chen *et al.,* 2011; Comte *et al.,* 2013; Poloczanska *et al.,* 2013). Longitudinal range shifts, as well as shifts towards the tropics or lower elevations (which run counter to intuitive expectations), can be attributed to the complex mosaic of regional climate changes expected under global change that involve not only temperature but also other factors such as precipitation and land-use changes (Lenoir *et al.,* 2010; Crimmins *et al.,* 2011; McCain & Colwell, 2011; Tingley *et al.,* 2012; Pinsky *et al.,* 2013; VanDerWal *et al.,* 2013).

Multi-directional distribution shifts stem partly from the spatial arrangement of mountain ranges on land and continental shelves in the ocean, which are important physiographic features constraining (as barriers) or enhancing (as corridors) species redistribution (VanDerWal *et al.,* 2013; Burrows *et al.,* 2014). For example, the ranges of some forest plants are shifting equatorward and upward as the climate warms in France, likely due to the fact that the main mountain ranges in France are located in the south

(Alps, Massif Central and Pyrenees; Kuhn *et al.,* 2016). Such geographic features may thus represent potential climatic traps or 'cul-de-sacs' for living organisms facing climate change. The northern Mediterranean Sea, for example, will likely act as a cul-de-sac for endemic fishes under future climate change (Lasram *et al.,* 2010).

A challenge in using climate variables to explain species redistribution is that species may respond to different climate variables than those available from historical measurements, due to a spatial mismatch between the size of the studied organisms and the scale at which climate data are collected and modelled (Potter, Woods & Pincebourde, 2013). For instance, relationships between climate velocity and marine species redistribution are weak or non-existent using global sea-surface temperature data sets to calculate climate velocity (Brown *et al.,* 2016), but can be strong using locally measured temperatures that coincide with organism sampling (Pinsky *et al.,* 2013). Therefore, we consider it a research priority to find ways to reconstruct high spatial- and temporal-resolution temperature histories that are relevant to the organisms under study (Franklin *et al.,* 2013; Kearney, Isaac & Porter, 2014; Levy *et al.,* 2016). This objective requires better communication and more collaboration among climatologists, remote sensing specialists and global change biologists to produce climatic grids at spatial and temporal resolutions that match organism size and thus are more meaningful for forecasting species redistribution under anthropogenic climate change.

The study of extreme events has been instrumental to species redistribution research, because punctuating events provide distinct natural experiments for the study of biological responses to climate change. The frequency and amplitude of extreme events is increasing with climate change (IPCC, 2013), placing increasing emphasis on studying extreme events in the context of longer-term change. Impacts of climate change on biological communities are often mediated by extreme events (Fraser *et al.,* 2014; Thomson *et al.,* 2015; Wernberg *et al.,* 2016). For example, ocean temperatures along the western Australian coast increased for over 40 years, with kelp forests exhibiting little noticeable ecological change, but a marine heat wave drove a 100 km kelp forest range contraction in only 2 years (Wernberg *et al.,* 2016). The infrequent nature of extreme events means that long time series are required to document the cumulative impacts on ecosystems. For example, in Australia, severe wildfires in quick succession brought about an ecosystem regime shift in mountain ash forests (Bowman *et al.,* 2014). A research priority is therefore to extend studies that document changes arising from a short-term extreme event into longer time series that may allow us to understand the cumulative effects of changes in frequency of extreme events.

(5) Anticipating future redistributions

The urgency of responding to anthropogenic climate change has stimulated a shift towards anticipatory ecology that aims to predict future ecological change. The shift to anticipatory ecology is indicated by our literature analysis, which found an increased frequency of terms related to prediction [Fig. 2; terms 'sdm' (species distribution model) and 'maxent' (a popular tool for such modelling); Phillips & Dudík (2008)]. Approaches to predicting the consequences of climate change for biodiversity are varied and include correlative species distribution models (SDMs; Guisan & Zimmermann, 2000) as well as mechanistic and hybrid SDMs that account for physiological constraints, demographic processes or environmental forecasts (Kearney & Porter, 2009; Hartog *et al.,* 2011; Webber *et al.,* 2011; Dullinger *et al.,* 2012; Cheung *et al.,* 2015; Table 1). The emergence of the study of species redistributions during the era of rapidly increasing computing power and growing availability of climate data has also contributed to the dominance of spatial modelling techniques. The emphasis on forecasting has been paralleled by a development of predictive techniques, including machine-learning algorithms such as maxent (Phillips & Dudík, 2008).

Anticipatory models have recently been progressing on two fronts. First, mechanistic and process-based models, often including physiology, biotic interactions, and/or extreme events, are increasingly being used and developed for biogeographic prediction (Kearney & Porter, 2009; Cabral *et al.,* 2016). Bioenergetics models, for example, can overcome traditional species distribution model limitations when making predictions under novel climates, modelling extreme events and understanding the importance of timing of weather events (e.g. Briscoe *et al.,* 2016). Mechanistic models tend to be data intensive and have so far been little used in conservation planning despite significant potential (Evans, Diamond & Kelly, 2015; Mitchell *et al.,* 2016). However, prospects for process-based models integrating conservation and society are positive, as models become more flexible, accurate, and accessible (Kearney & Porter, 2009).

The second trend with predictive models has been an increasing focus on physical drivers at appropriate spatial and temporal scales (Potter *et al.,* 2013). In this regard, a key perspective in species redistribution is the velocity of climate change – which measures the geographic movement of temperature isotherms (Loarie *et al.,* 2009; Burrows *et al.,* 2011) to project changes in species ranges and community composition (Hamann *et al.,* 2015). Climate velocity trajectories (Burrows *et al.,* 2014) based on sea surface temperatures, for example, were recently combined with information on thermal tolerances and habitat preferences of more than 12000 marine species to project that range expansions will outnumber range contractions up to the year 2100. Broadened ranges, in turn, are projected to yield a net local increase in global species richness, with widespread invasions resulting in both homogenised and novel communities (Molinos *et al.,* 2015). However, velocity measures have limitations and can underestimate climate change exposure for some communities (Dobrowski & Parks, 2016). For marine systems, changes in the speed and direction of currents can potentially influence dispersal and therefore population connectivity, and may also need to be considered for a more complete understanding of the relationship between climate drivers and rates and magnitudes of range shifts (Sorte, 2013; Cetina-Heredia *et al.,* 2015). High-resolution particle-transport Lagrangian models may be useful in this context (van Gennip *et al.,* 2017). Ultimately, examining multiple climate change metrics and linking them to the threats and opportunities they represent for species could overcome the limitations of individual metrics and provide more-robust impact estimates (Garcia *et al.,* 2014).

IV. CONSERVATION ACTIONS

Faced with climate change as a novel and substantial threat, a new species-management paradigm has emerged (Stein *et al.,* 2013): to be effective, conservation strategies must account for both present and future needs and must be robust to future climate change. Such strategies will require integration of species redistribution science with consideration of the social and economic consequences (Table 1). Managers have several options for conserving species and ecosystems faced with range shifts: adapt conservation management in current landscapes and seascapes; facilitate natural species movement; manage resources to support species redistribution; and/or move species as a conservation intervention, i.e. managed relocation. Important reviews on conservation under climate change, such as Heller & Zavaleta (2009) and Mawdsley, O'Malley & Ojima (2009), provide context for adaptation strategies under warming. In this section we specifically aim to synthesise recent advances in species redistribution science and conservation actions that attempt to accommodate species redistributions, requiring the involvement of multiple stakeholders for effective implementation.

(1) Adapting management in current conservation landscapes and seascapes

Mitigating the impacts of climate change on species and ecosystems *in situ* is challenging, because it requires management decisions that are robust to future change and the development of adaptive solutions for specific populations (e.g. providing shelter or supplemental food; Correia *et al.,* 2015). Systematic conservation planning efforts are increasingly incorporating the principles of climate change adaption into the protected-area design process (Carvalho *et al.,* 2011; Groves *et al.,* 2012), ensuring that existing protected areas are resilient to climate change by maintaining and increasing the area of high-quality habitats, prioritising areas that have high environmental heterogeneity, and controlling other anthropogenic threats (Hodgson *et al.,* 2009). Habitat engineering may also be required to provide effective recovery and maintenance of populations, for example, through the installation of microclimate and microhabitat refuges or enhancement and restoration of breeding sites (Shoo *et al.,* 2011). Identification of microrefugia, small areas robust to warming impacts over long time periods, will also be key for long-term planning (Lenoir, Hattab & Pierre, 2017). In many countries, the legal and governance framework underpinning protected-area management may not yet allow for these types of active management interventions (McDonald *et al.,* 2016*a*), so legal reform may be needed.

(2) Facilitating natural species movement

As the most suitable habitat conditions for species are shifting geographically under climate change and species redistribute themselves, forward planning is increasingly essential, both temporally and spatially (Mawdsley *et al.,* 2009). Although most palaeoecological studies (e.g. Williams & Jackson, 2007) indicate that range shifts alone do not drive widespread extinction events [but see Nogués-Bravo *et al.* (2010) who did find evidence for extinctions], range-restricted species potentially face high climate-driven extinction risks (Finnegan *et al.,* 2015; Urban, 2015).

Reserve networks must consider current biodiversity, probable patterns of future biodiversity, corridors suitable for projected range shifts, and cost (Lawler *et al.,* 2015; Scriven *et al.,* 2015), anticipating the need for protected-area establishment in newly suitable areas (Carvalho *et al.,* 2011). Climate-velocity methods (Burrows *et al.,* 2014) or the analysis of fine-scaled climatic grids (Ashcroft *et al.,* 2012) can be used to identify climate refugia – places where microclimates are decoupled from macroclimatic fluctuations and are thus more stable and less likely to change quickly – as potentially good candidates for future protected areas. Information on future habitat suitability for threatened species (e.g. obtained using SDMs) can be coupled with information on climate refugia to target areas likely to maximise conservation benefits (see Hannah *et al.,* 2014; Slavich *et al.,* 2014). To assess landscape or seascape connectivity with greater realism, patterns of habitat fragmentation (McGuire *et al.,* 2016) and flow must be considered, i.e. wind and oceanic currents (Péron *et al.,* 2010; Sorte, 2013; van Gennip *et al.,* 2017).

In some cases, facilitating species redistribution can be achieved through the expansion or realignment of existing protected area boundaries. Where public conservation funding is limited, it may be necessary in some circumstances to release protection of some areas in order to secure others of higher priority (Alagador, Cerdeira & Araújo, 2014). In addition to maintaining connectivity through reserve network design, market-based instruments and public–private partnerships can be harnessed to accommodate species redistribution. Conservation easements, for example, while popular and potentially effective in environmental protection of private land, rarely consider climate change impacts or species redistribution (Rissman *et al.,* 2015). New mechanisms for private land stewardship and management, including Indigenous Protected Area (IPA) agreements, will also be needed.

Conservation interventions designed to meet contemporary environmental challenges can conflict with climate change planning objectives. For example, fences in Africa around wildlife reserves have been good for minimising human–wildlife conflict but poor for maintaining landscape connectivity (Durant *et al.*, 2015). Similarly, shifts in agriculturally suitable areas in the Albertine region of Africa, as a result of changing climate, may cause a displacement of agriculture into protected areas, significantly complicating climate-driven species redistribution impacts on conservation plans for the region (Watson & Segan, 2013).

(3) Resource-management systems for species redistribution

Some existing resource-management systems can be extended for adaptive management of species on the move. For example, a real-time management system is used in eastern Australia to predict the distribution of a tuna species over the cycle of a fishing season (Hobday & Hartmann, 2006; Hobday *et al.*, 2011). The changing distribution of the fish requires dynamic responses to zones that restrict fishing activity. While this example of species redistribution is on a seasonal timescale, the management system can also respond to long-term species redistribution, based on regular updates of the management zones. Such real-time management responses to changing species distributions are relatively advanced in marine systems and are being formalised in the field of dynamic ocean management (Hobday *et al.*, 2014; Lewison *et al.*, 2015; Maxwell *et al.*, 2015).

Conservation strategies for mobile and range-shifting species can also utilise innovative market-based instruments and develop new partnerships involving private landholders. A promising example is The Nature Conservancy's California pop-up wetland initiative, which involves seasonal land 'rentals', in which farmers agree to flood their fields to facilitate water bird migration (McColl *et al.*, 2016). Predictive habitat modelling of bird migration is used to earmark different land parcels, and landholders submit bids to participate in each year's habitat creation program. As in this example, local and regional conservation planning for multiple uses requires good-quality data, plus resources for monitoring and implementation. Researchers also need to understand what information land-owners, planners and policy makers actually need to aid decision-making, which requires considerable engagement and knowledge exchange (Cvitanovic *et al.*, 2015).

As part of this engagement, structured decision-making processes can inject both values and scientific data into the development of management strategies for ecosystem-based marine management, as proposed for development of high seas protected areas (Maxwell, Ban & Morgan, 2014). Options for managers and policy makers can be evaluated with quantitative modelling tools, such as models of intermediate complexity (Plagányi *et al.*, 2014), while management strategy evaluation (Bunnefeld, Hoshino & Milner-Gulland, 2011) can be used to test climate-smart management strategies that include socio-ecological criteria. In addition to novel dynamic management approaches, existing tools in development and conservation law, such as biodiversity offsets, will need to be modified to promote adaptive conservation planning for species redistribution (McDonald, McCormack & Foerster, 2016*b*) and to allow management responses on appropriate timescales (Hobday *et al.*, 2014).

(4) Managed relocation

Given numerous decision frameworks for managed relocation, the science required to inform any decision to relocate a species is defined by knowledge gaps in local species ecology and management (e.g. Richardson *et al.*, 2009; McDonald-Madden *et al.*, 2011; Rout *et al.*, 2013 and see Article 9 in Glowka *et al.*, 1994). Trial introductions of the critically endangered western swamp turtle (*Pseudemydura umbrina*) to the south-western corner of Australia (300 km south of its native range), in 2016, serve as a useful example. For the turtle, persistence in the wild is constrained by severe habitat loss and fragmentation and by a rapid reduction in winter rainfall. Correlative SDMs based on coarse-grained climatic data have created a challenge for translocation planning, as the turtle historically occupies just two wetlands 5 km apart (Mitchell *et al.*, 2013). The solution has been to build mechanistic SDMs that are based on detailed knowledge of the turtle's physiological limits, behaviour, and the ecohydrology of their ephemeral wetland habitats (Mitchell *et al.*, 2013, 2016). Forcing these process-based SDMs with future drier and warmer climates has illustrated where suitable habitat might exist into the future, and when complemented with spatially explicit multiple criteria analysis (Dade, Pauli & Mitchell, 2014) has identified candidate wetlands for future attempts to establish outside-of-range populations.

The primary challenge for practicing managed relocation is identifying ways to overcome any social barriers to relocation. Relocating species for conservation can challenge deeply held values and beliefs about human intervention in nature, and what constitutes appropriate and desirable environmental stewardship. Particular challenges may arise for Indigenous peoples, for whom connection to landscapes and historically, culturally and spiritually significant species is of great importance. Formal mechanisms for engaging with local communities and stakeholders, including consideration of the cultural effects and drivers of proactive conservation management under climate change, will be critical. Issues include cultural nuances, such as the terminology used in management proposals and policy. For example the term 'assisted colonisation', adopted in the guidelines of the International Union for Conservation of Nature (IUCN) for species introductions outside of the known range to prevent extinction, has historical and colonial connotations with the word 'colonisation' that may create barriers to participation. In this case, an alternative, culturally considerate phrase to encourage broader inclusion might be 'managed relocation' (see Schwartz *et al.*, 2012).

The IUCN guidelines for conservation translocations (IUCN/SSC, 2013) provide a complete framework to assess the need for managed relocation, including the risks associated with translocations for the species of interest and for the ecosystem that receives the new species. Potential damage to the ecosystem from managed relocation is the worst-case scenario, and this issue forces decision-makers to ask themselves what they value most. Is the survival of a particular species that is threatened by human actions sometimes worth the risk of profound change to the recipient ecosystem? If we aim for a species to thrive, when does it become invasive? These are questions that will need to be answered as managed relocation for conservation becomes more frequent. Legislative reform is also required to change the regional and domestic laws and policies that guide practical implementation of managed relocations. Many jurisdictions around the world have no explicit legal mechanisms for relocating species across jurisdictional borders, a regulatory gap that is likely to become more problematic under rapid climate change (Schwartz *et al.,* 2012). Law and policy should incorporate collaborative mechanisms for cross-tenure, local, regional and international species relocations, and should facilitate species relocation to support broader ecological processes, not just to preserve charismatic threatened species.

V. SOCIAL AND ECONOMIC IMPACTS OF SPECIES REDISTRIBUTION

Changing distributions of economically and socially important species under climate change are affecting a wide range of peoples and communities. Understanding the ecology of species on the move and the development of conservation tools for species redistribution responses will, together, contribute to an integrated approach to managing social impacts (Table 1). Consequences will likely include exacerbated food security issues; challenges for Indigenous and local livelihoods, governance and cultures; and human health problems. Facing these challenges will require an interdisciplinary, participatory approach (O'Brien, Marzano & White, 2013) that will include not only scientists and professionals from different fields but also managers, governments and communities.

(1) Food security

Since the spike in food prices in 2008, much thought has gone into how to feed nine billion people by 2050 (World Bank, 2008; Evans, 2009; Royal Society of London, 2009). A key to producing 70–100% more food by 2050 will be filling the yield gap for agriculture (Godfray *et al.,* 2010), i.e. the difference between potential and actual yields. For fisheries and aquaculture, the challenge is to provide an additional 75 Mt of fish by 2050 to supply 20% of the dietary protein needed by the human population (Rice & Garcia, 2011). Given that yields from capture fisheries have already plateaued, most of the additional fish will need to come from aquaculture (FAO, 2014).

The challenges of enhancing agricultural and fisheries productivity to meet global food demand (Godfray *et al.,* 2010; FAO, 2014) are exacerbated by species redistribution. Increased agricultural productivity will depend in part on keeping weeds, diseases and pests in check where they increase in abundance and disperse to new areas. As fish species migrate in search of optimal thermal conditions, the locations of productive fisheries will change (Cheung *et al.,* 2010), resulting in gains for some communities and losses for others (Bell *et al.,* 2013). Changes in the distributions and relative abundances of harmful marine algae, pathogens and pests, will also create new hurdles for fisheries and aquaculture (Bell *et al.,* 2016).

A key short-term priority for food-security research is the development of new global models of fishery production that account for climate change. Several models are now being used to inform large-scale policy on global change in marine fishery production (e.g. Cheung *et al.,* 2010; Barange *et al.,* 2014). However, a single approach (Cheung *et al.,* 2010) has been dominant in representing species redistributions. While this model has been repeatedly updated (Cheung & Reygondeau, 2016; Cheung *et al.,* 2016), considerable structural uncertainty remains in our ability to predict change in fishery production, as production depends critically on uncertain future fishery-management arrangements (Brander, 2015). The extent to which structural uncertainty afflicts global production estimates needs to be evaluated with alternative modelling approaches. These issues are beginning to be addressed by model ensemble initiatives such as through the Inter-sectoral Model Intercomparison Project (https://www.isimip.org/) and through the inclusion of more detailed bio-economic processes (Galbraith, Carozza & Bianchi, 2017).

(2) Indigenous livelihoods, governance and cultures

The distributions and relative abundances of species within their historic ranges have been central to the knowledge of Indigenous peoples, including not only sedentary communities, but also mobile communities such as nomads, pastoralists, shifting agriculturalists and hunter-gatherers (Kawagley, 2006; Sheridan & Longboat, 2006; Arctic Council, 2013; Mustonen & Lehtinen, 2013). Maintaining relatively intact ecosystems is crucial to the preservation of livelihoods, cosmologies, cultures and languages of these groups, and many have developed governance systems for their biological resources based on holistic observations and checks-and-balances to prevent overharvesting (Huntington, 2011; Mustonen, 2015; Mustonen & Mustonen, 2016). Alterations in species ranges and relative abundances due to climate change will have profound consequences for these governance systems.

Leaders of these societies also recognise that changes in relative abundances of species are caused by other drivers, such as extraction of natural resources and development of infrastructure (Arctic Council, 2013), and have called for a paradigm shift in governance to address the profound changes underway (Kawagley, 2006; Huntington, 2011).

This paradigm shift requires partnership approaches with non-Indigenous institutions to respond to the scale and significance of impacts on livelihoods (Huntington, 2011). Culturally safe and respectful language spoken by scientists, and teaching of science for Indigenous, traditional and mobile peoples are an essential part of this approach. Otherwise, opportunities to effectively integrate the often deep and diverse knowledge of these people into strategies to cope with change will be lost (Lee *et al.*, 2016).

(3) Human health

The risk of increases in infectious diseases due to species redistributions, potentially exacerbated by food insecurity crises, is also a significant concern (Altizer *et al.*, 2013) and a key research challenge. History is full of examples of climate-driven species movements and human distribution shifts, resulting in infectious disease outbreaks (McMichael, 2012). For example, bubonic plague outbreaks caused by the bacterium *Yersinia pestis* during the Black Death – the great pandemic originating in Asia and spreading throughout Europe between 1347 and 1353 – have been shown to occur roughly 15 years after a warmer and wetter period (Schmid *et al.*, 2015). Even the contemporary dynamics of bubonic plague, which still occurs in Central Asia, have been clearly linked to climate change (Stenseth *et al.*, 2006).

In the Arctic, many interconnected factors such as climate, wildlife populations, and health have triggered infectious disease outbreaks. Although the health of Indigenous peoples of the circumpolar region has improved over the last 50 years, certain zoonotic and parasitic infections remain higher in Arctic Indigenous populations compared to respective national population rates (Parkinson & Evengård, 2009). Evidence for associations between climate and infectious disease in the Arctic is clear, but the relationship between climate change and vector-borne disease rates is poorly explored, owing to the small number of studies on the subject (Hedlund, Blomstedt & Schumann, 2014). However, the case of increasing incidence of tick-borne encephalitis in Sweden since the 1980s is instructive: mild winters have increased tick population densities in the country, leading to increased disease incidence (Lindgren & Gustafson, 2001). A key component of prevention and control of climate-mediated infectious diseases is surveillance.

(4) Need for monitoring

More modelling is needed to understand the cascading effects of climatic changes on the species that we rely on for food and livelihoods and those whose spread can adversely affect human health. Such modelling will help identify practical adaptations and the policies needed to support them.

Collection of the information needed to validate these models can be enhanced by community-based monitoring and citizen science, engaging the agriculture, fishing and aquaculture industries and Indigenous and local communities (Mayer, 2010; Johnson *et al.*, 2015; Robinson *et al.*, 2015). These groups are well placed to monitor changes in the relative abundance and distribution of species that they rely on or regularly interact with. For many Indigenous and local communities, monitoring is central to the preservation of their sea- and land-use patterns and sustainable development (Sheridan & Longboat, 2006; Mustonen, 2015). Moreover, rapidly developing tools and networks in citizen science may enhance large-scale monitoring (Chandler *et al.*, 2016). For example, citizen science has already contributed approximately half of what we know about migratory birds and climate change (Cooper, Shirk & Zuckerberg, 2014). Broad stakeholder engagement has the added benefit of increasing awareness of the effects of climate change on human well-being, while empowering communities to effect changes in environmental behaviour and policies.

Involving local stakeholders in monitoring also enhances management responses at the local spatial scale, and increases the speed of decision-making to tackle environmental challenges at operational levels of resource management (Danielsen *et al.*, 2010). The promptness of decision-making in community-based monitoring and the focus of the decisions at the operational level of species and resource management make community-based monitoring approaches particularly suitable when species are rapidly shifting ranges. Community-based monitoring is also likely to provide information about crucial new interactions between species (Alexander *et al.*, 2011; Huntington, 2011). One potential challenge to community-based monitoring is that, in situations in which constraints or demands on resources may condition quotas or financial payments to communities, the local stakeholders might have an incentive to report false positive trends in those natural resources so they can continue to harvest the resources or continue to be paid, even though the resources may actually be declining (Danielsen *et al.*, 2014). Systems ensuring triangulation and periodic review of the community-based monitoring results will therefore be required, whether the monitoring is implemented by communities, governments or the private sector.

Increased monitoring may also increase understanding of the spatial and temporal impacts on human societies posed by changes in the distribution and abundance of species. The effects of climate change on species needs to be mainstreamed into routine food-production assessments so that society is prepared and can adapt to predicted changes. Technological improvements have increased the potential for citizen scientists to engage in the necessary monitoring (Brammer *et al.*, 2016) and for industries to capture essential data as part of routine field operations (Ewing & Frusher, 2015). On a broader scale, co-ordination of monitoring to obtain data that can be compared across diverse regions is needed. Identification of hotspots, where range changes and impacts are expected to be seen earlier (Hobday & Pecl, 2014; Pecl *et al.*, 2014), can aid in the early development of broad-based practical adaptive strategies. Moreover, technological advances are making it possible to not just monitor the location of organisms, but understand the physiological and behavioural processes underlying their movement patterns (Block *et al.*, 2001; Clark *et al.*, 2008, 2010). An integrated understanding of the drivers of species movement will greatly strengthen our capacity to plan for species redistributions in the future.

VI. INTERDISCIPLINARY APPROACHES TO ADDRESS SPECIES REDISTRIBUTION CHALLENGES

Species redistribution is a complex phenomenon dependent upon multiple and interacting multiscale climatic variation, as well as social and ecological/evolutionary processes (Fig. 3). The formation of novel species assemblages as a consequence of this redistribution brings significant new challenges for governments, resource users and communities, particularly when dependence on natural resources is high or where present or future species ranges cross jurisdictional boundaries (Pecl *et al.*, 2011). Identifying the mechanisms and processes driving species redistributions is critically important for improving our capacity to predict future biological change, managing proactively for changes in resource-based human livelihoods and addressing conservation objectives (Pinsky & Fogarty, 2012).

In recent years, the scientific study of climate-driven species redistribution has matured significantly (Fig. 1). Although research continues to focus on modelling and prediction of distribution shifts, researchers have increasingly incorporated management and socio-economic considerations explicitly (Fig. 2). As this review has highlighted, biological studies and management and social science research on species redistribution have provided a wealth of insights into global change, and have supported several innovative management responses (i.e. managed relocation, real-time management systems). Nevertheless, many challenges and key questions require answers (Table 1). Further integrated development will require working across disciplines to find innovative solutions (Bjurström & Polk, 2011).

Long-term interdisciplinary research programs that integrate the natural and social sciences are needed to study, understand and model the impact of climate-driven species redistribution on ecosystem functioning. More specifically, interdisciplinary research is needed on changes to multiple ecosystem services (e.g. food) and disservices (e.g. diseases) delivered to society, as climate changes, particularly as interdisciplinary approaches are not well represented in climate research (Bjurström & Polk, 2011). Simultaneous socio-ecological time series often reveal that people respond to ecosystem change in surprising ways. For example, a climate regime shift around 1960–1990 drove declines of a cod fishery, but opened up opportunities for a new shrimp fishery off Greenland (Hamilton *et al.*, 2003). However, only communities with sufficient capital to invest in new fishing gear, and entrepreneurial individuals who were willing to invest in a new fishery were able to adapt to the ecosystem change. Thus, societal responses to species redistributions can be highly dependent on a few individuals, and human responses and natural changes must be considered in combination (Pinsky & Fogarty, 2012).

Many challenges must be overcome to execute a successful long-term interdisciplinary research program. Even within fields such as ecology, disciplinary barriers threaten to limit advances in species redistribution research. For example, communication and collaboration between marine and terrestrial researchers (Webb, 2012) has the potential to spark key developments. Unfortunately, research proposals with the highest degree of interdisciplinarity currently have the lowest probability of being funded (Bromham, Dinnage & Hua, 2016). Although long-term monitoring programs provide the essential foundation for tracking and understanding the causes and consequences of species redistributions, they also encounter funding difficulties due to the long time span of funding required and a bias in grant agencies away from studies perceived as simply observational research and towards hypothesis-driven research (Lovett *et al.*, 2007). Institutional change in funding agencies and an emphasis on prioritising interdisciplinary and long-term projects could lead to important, high-impact climate change research (Green *et al.*, 2017). In the meantime, global change scientists also need to explore multiple options to support long-term and interdisciplinary studies, such as harnessing citizen science and engaging in large-scale collaborative efforts.

In fact, citizen science may help to fill the knowledge gap in long-term and spatially extensive studies (Breed, Stichter & Crone, 2013). Citizen science approaches typically involve recruiting observers to be part of a formal program, a method for recording meaningful data, and a means of making those data accessible and discoverable for later use. In addition, successful programs often include data-vetting and data-management practices to ensure the integrity and long-term availability of data, providing data products to contributors and other interested parties, and interpreting the results of these efforts to tell a story of environmental functioning or change to larger audiences. Further work is needed, however, to find suitable ways to connect citizen science and community-based monitoring programs with international biodiversity data repositories (Chandler *et al.*, 2016).

Growing recognition of the important role of Indigenous, traditional and mobile peoples in protected area management is one positive change in recent years. The creation of a fourth type of governance (in addition to government, shared and private governance) in the IUCN's Protected Area Guidelines specifically addresses IPAs and Indigenous peoples' and Community-Conserved territories and Areas (ICCAs). In this case, the nature–culture binary is being dismantled to incorporate a range of worldviews that promote sustainable development, governance vitality and management devolution (delegation of power) (Borrini-Feyerabend *et al.*, 2013; Lee, 2016). Acknowledging the legitimacy of traditional knowledge

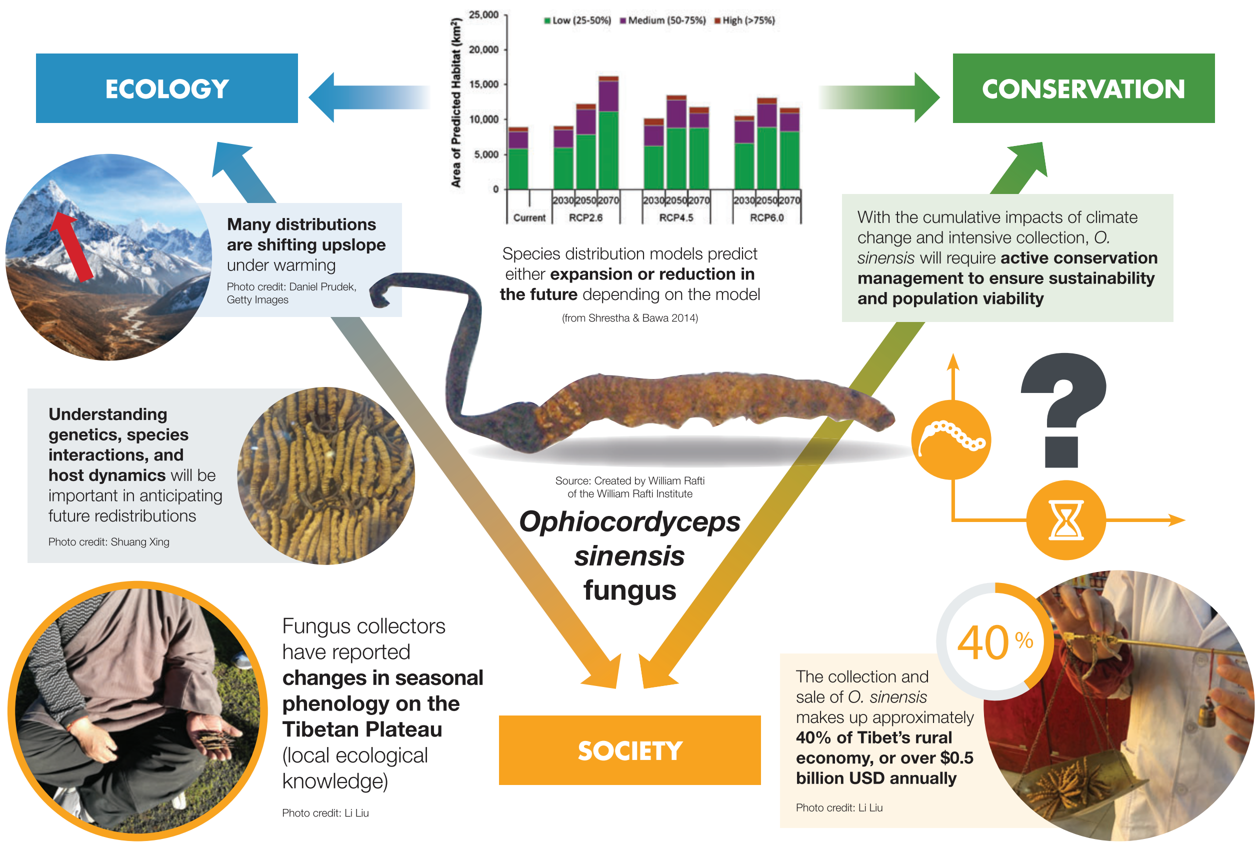

Fig. 3. *Ophiocordyceps sinensis*, a caterpillar-feeding fungus of the Tibetan plateau, presents a useful case study for the importance of an integrated and interdisciplinary approach to species redistribution. The species is widely consumed throughout China, largely for medicinal purposes. Distribution shifts of the species in recent decades have been observed, but models under future climates have yielded divergent outcomes (both range expansion and reduction) based on different sets of data and approaches (Shrestha & Bawa (2014); Yan *et al.*, 2017). Open questions remain about the physiology of the species and, particularly critical in this case, how interactions with the host caterpillar species might change under warming. *O. sinensis* is a critical part of the Tibetan economy (Winkler, 2008) but is also vulnerable to extinction given intensive collecting pressure and possible climate change impacts (Yan *et al.*, 2017). Greater understanding of the ecology of the species will assist in addressing economic and conservation challenges. But, equally importantly, the Indigenous populations that depend upon *O. sinensis* for income can also provide invaluable insights into complex ecological systems and how climate change might be changing these systems (Klein *et al.*, 2014).

systems can be instrumental in understanding species redistribution and provides a mechanism by which local communities can monitor and manage impacts (Eicken *et al.*, 2014; Tengö *et al.*, 2017).

Examples of on-ground management responses to shifting species are few, to date, and those that have been reported are based on seasonal or short-term responses to changes in species distribution (Hobday *et al.*, 2011, 2014; McColl *et al.*, 2016). These few examples do illustrate how long-term change might be accommodated, but such approaches may not support management responses for the transformational level of change that may be needed in some regions. In these cases, development of long-term adaptive pathways (sensu Wise *et al.*, 2014) for species on the move is required. These pathways can include decision points at which switching of strategies is required, for example defining at what point a habitat-creation strategy should be changed to a translocation strategy.

VII. CONCLUSIONS

(1) Until recently, species redistribution was seen as something that would happen in the future rather than an immediate issue. However, it is happening now, with serious ecological and societal implications and impacts already being observed.

(2) The cross-cutting nature of species redistribution calls for the integration of multiple scientific disciplines, from climate science to ecology, palaeoecology, physiology, macroecology, and more. We further suggest that research on contemporary species redistribution needs to span process-based studies, observational networks by both scientists and community members, historical data synthesis and modelling over a variety of scales.

(3) Species redistribution defies conservation paradigms that focus on restoring systems to a baseline and challenges environmental management strategies, which are often static

and based on human-dictated boundaries drawn in the past. Climate-driven species redistribution therefore presents both fundamental philosophical questions and urgent issues relevant to conservation and society.

(4) For species redistribution research to support development of relevant adaptive strategies and policy decisions adequately, studies need to take an interdisciplinary approach and must recognise and value stakeholders. Involving stakeholders in monitoring and collection of data offers an opportunity to help guide effective adaptation actions across sectors.

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X. SUPPORTING INFORMATION

Additional supporting information may be found in the online version of this article.

Appendix S1. Details of extraction and analysis of research foci in the field of species redistribution.

Table S1. List of 109 'trending' terms defined as word stems that significantly increased in annual frequency of appearance in publications on species redistribution since 1995.

Table S2. List of 49 'high-impact' terms defined as word stems associated with higher than average citation rates, accounting for publication year.

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SCIENCE POLICY

Integrating climate adaptation and biodiversity conservation in the global ocean

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The impacts of climate change and the socioecological challenges they present are ubiquitous and increasingly severe. Practical efforts to operationalize climate-responsive design and management in the global network of marine protected areas (MPAs) are required to ensure long-term effectiveness for safeguarding marine biodiversity and ecosystem services. Here, we review progress in integrating climate change adaptation into MPA design and management and provide eight recommendations to expedite this process. Climate-smart management objectives should become the default for all protected areas, and made into an explicit international policy target. Furthermore, incentives to use more dynamic management tools would increase the climate change responsiveness of the MPA network as a whole. Given ongoing negotiations on international conservation targets, now is the ideal time to proactively reform management of the global seascape for the dynamic climate-biodiversity reality.

INTRODUCTION

Climate change and biodiversity loss present two increasingly important challenges for modern civilization (*1*, *2*). They are also interlinked, with bidirectional feedback mechanisms and the potential for tipping points that may destabilize the Earth system, leading to unprecedented consequences for human societies (*3*). This connection has led to recognition that the climate- and biodiversity-focused policy agendas must become intertwined to better reflect the critical role the natural world plays in climate regulation, mitigation, and adaptation. Protected areas (PAs), crucial components of the biodiversity conservation toolbox, were originally conceived before awareness of the global, rapid, and enduring impacts of anthropogenic climate change. As a result, the global network of PAs does not consistently account for climate change in design and management (*2*), despite recognition of its importance (*4*) and notable conceptual advances in underlying design principles (*5*, *6*). Although its impacts are not geographically uniform, climate change will likely reduce PA effectiveness (*4*, *7*, *8*), here defined as the ability to meet stated biodiversity and conservation goals now and into the future.

Ocean ecosystems are particularly vulnerable to climate change (*9*–*11*). While marine PAs (MPAs) cannot halt the effects of climate change and are not a panacea, they are part of a larger portfolio of tools that can help with managing ecosystems and biodiversity in response. There is a clear and urgent need to move toward actively integrating climate change as a core consideration of MPA planning and implementation. Conceptual approaches and decision support tools for integrating climate change into MPA site and network design have existed for over a decade (*6*, *12*). However, the uptake of these measures into management and policy appears limited and globally uncoordinated. Climate change adaptation is also important in non-MPA spatial conservation and management tools, such as "other effective area-based conservation measures" (OECMs), which are not part of the legally designated PA network but conserve biodiversity regardless of their primary objective. OECMs are newer in definition and climate change is mentioned in their guiding principles, although acknowledgement of climate change in their design and management is not required (*13*).

Here, we explore the integration of climate change considerations into the global protected seascape. First, we review the evidence for integration in current MPA design and operation. We then examine the global distribution of past and future climate trajectories for MPAs and discuss explicitly embedding climate adaptation objectives into MPA networks. Last, we assess how a protected seascape that integrates dynamic management tools may look in practice, and then recommend policy options to help to advance this process. Policy incentives have helped spur international action and national frameworks on PA coverage (*14*) and may fulfill the same role for climate-smart network design. For each section, we finish with a practical recommendation, with the overall goal of accelerating the uptake of climate resilience as a fundamental component of the global protected seascape.

THE THEORY-PRACTICE GAP IN INTEGRATING CLIMATE CHANGE INTO MPA DESIGN AND OPERATION

Numerous organizations and governance bodies including nongovernmental organizations (NGOs) and government authorities are working to integrate climate change considerations into MPAs. Yet,

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it is difficult to develop a comprehensive global overview of the extent to which climate change is integrated into the objectives and design of existing MPA networks, as a result of the lack of a coherent centralized repository that amalgamates this information. The recently released Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) Global Assessment indicates that there are "few protected areas whose objectives and management take climate change into account" but suggests that only limited studies exist with no comprehensive synthesis (*2*).

To assess this, we reviewed the scientific literature on climate change adaptation in the design and operation of MPAs and MPA networks (see the Supplementary Materials). Of the 98 relevant papers identified, only 6 reported concrete on-the-ground implementation (Fig. 1). Of the remaining 92 papers, 29 were unimplemented examples of how to incorporate climate change considerations into specific existing or new MPA and/or network designs, and 63 consisted of theoretical reviews or planning frameworks not tied to specific MPAs or networks (Fig. 1, table S1, and refer to the text in the Supplementary Materials). Of the six examples with on-the-ground implementation, only one (the Greater Farallones National Marine Sanctuary in California) explicitly considered climate change in its management plan (table S3) (*15*). The "Climate Adaptation Plan" includes a vulnerability assessment of the sanctuary, climate change recommendations, and an implementation plan (https://farallones.noaa.gov/manage/climate/adaptation.html).

The other five examples are of MPA networks rather than single MPAs. Australian Marine Parks (MPAs designated and managed by the federal government) include design principles that identify the need to incorporate increased resilience and adaptation to climate change as far as practicable (*16*, *17*). For the remaining four examples, all concentrated in and around the Coral Triangle (table S3), MPA network design and management were informed by explicit climate resilience principles (*6*, *18*). The Kubulau MPA network in Fiji, for example, was redesigned by selecting critical coral reef areas that have shown resilience to bleaching events, maintenance of connectivity between individual MPAs, and protection of larger MPAs that include the full range of marine habitats. Resilience principles were also incorporated into management, for example with recommendations for fishing restrictions to maintain ecosystem function.

A literature review only captures part of ongoing efforts at climate change adaptation because initiatives implemented by governments or NGOs may not be captured in the scientific literature and are also difficult to synthesize (*19*); for example, the MPA-ADAPT project in the Mediterranean (https://mpa-adapt.interreg-med.eu/), the Californian Channel Islands National Marine Sanctuary, Primeiras

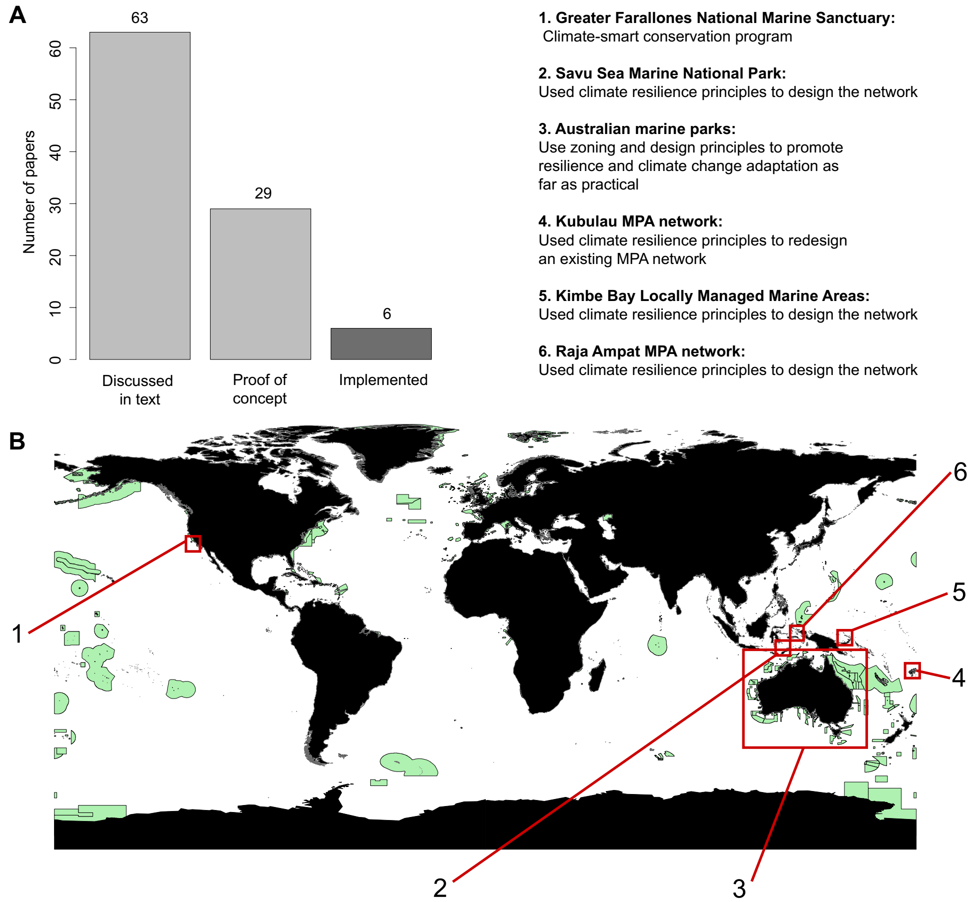

Fig. 1. Literature review of climate change consideration in MPA design. (**A**) Number of studies from the review where MPA climate change adaptation strategies were broadly discussed, presented as a proof of concept, or implemented in practice, respectively. (**B**) Location and brief description of the six implemented examples. Green areas represent MPA locations from the World Database on Protected Areas (*79*). See main text for further discussion, including search limitations, and text and tables in the Supplementary Materials for full methodological details and results.

and Segundas Environmental Protected Area in Mozambique, and the Bahamian, Palau's, and the Federated States of Micronesia's MPA networks.

Efforts to integrate climate change adaptation and biodiversity conservation may be more advanced for coral reef MPAs, perhaps as a result of the disruptive nature of bleaching impacts (*20*), although this is challenging to quantify. Furthermore, managers working in reefs and other coastal systems will face additional impacts (e.g., nutrient runoff) and specific constraints from land-based activities in comparison to offshore management regimes. Given this, design, management, and monitoring of coastal MPA networks should explicitly consider terrestrial impacts through integrated terrestrial-marine planning and modeling (*21*) and through assessment of how climate change impacts in proximal terrestrial environments may influence adjacent marine systems (*22*, *23*).

A further challenge is that the evidence base for MPAs conferring resilience to climate change is limited, largely based on coral reef ecosystems, and the effectiveness of MPAs as tools for climate-change resilience remains a matter of ongoing debate (*24*, *25*). The managed-resilience paradigm posits that MPAs, by reducing other stressors, will improve reef recovery after bleaching, but the limited data available are not sufficient to confirm this hypothesis. A solid empirical basis demonstrating the benefits of MPAs for climate resilience is required. This limited evidence base remains difficult to resolve, given the fact that most MPAs are currently not explicitly sited, designed, and/or managed for climate resilience. Controlled studies of the potential benefits of climate-smart MPAs across multiple ecosystem types are required to resolve this issue.

Our results (Fig. 1) highlight a crucial gap between theory and practice, which limits mobilization of research on the benefits of climate-smart implementation for MPAs and MPA networks (*26*, *27*). Several factors may explain this gap. First, the limited availability of spatially explicit climate and ecosystem forecasts at the MPA site scale may hamper efforts to operationalize climate change strategies. The uncertainty associated with climate models and their outputs is a challenge for managers, and a limited integration between ecology and climate science may inhibit understanding of how climate projections can be used at appropriate ecological scales (*28*–*30*).

Second, access to effective, readily implementable management strategies is predicated on information about tested practices and management interventions. Much of the literature has focused on integrating climate change considerations into MPA design through general design principles (*6*, *18*). However, more specific and scale-appropriate guidance is needed to account for local climate patterns and impacts, to help managers readily translate design principles into management strategy (*31*).

Last, in most cases, MPAs have been sited and networks have been developed to maximize conservation (and other) values while minimizing conflict with users (*32*). Including climate change in this complex negotiation may be difficult, particularly where climate adaptation pays no immediate benefit and may impose an additional burden on managers. Managers may also not have the resources to consider climate change, and hence respond instead to more immediate challenges and goals. If the benefits of accounting for climate change are not realized for decades to come, then the incentive structure is stacked against including climate change in planning.

A community of practice could help build awareness of the importance of MPA climate adaptation and mitigation benefits, helping to shift the incentive structure to be more favorable. As an example of benefits, mangroves not only are characterized by long-term carbon burial rates averaging >45 times those found in terrestrial forest ecosystems (*33*, *34*) but also provide major fisheries and coastal protection benefits as the climate changes, and can help to sustain high biodiversity elsewhere through larval and juvenile export. An important concrete first step toward a community of practice would be a means of documenting climate-smart MPA implementation experiences (see Recommendation 1).

***Recommendation 1*: Create a centralized resource to catalog whether climate change adaptation has been accounted for in the design and management of individual MPAs, OECMs, and protected seascape networks.**

- It is, at present, impossible to precisely quantify how often climate adaptation is integrated into MPA and network design/operation.
- A centralized database would enable evaluation of the uptake of climate considerations in the protected seascape and help to inform policy targets (see Recommendation 5).
- In addition to such a resource, the evidence base for MPAs conferring resilience under climate change needs to be extended through controlled studies that span multiple ecosystem types.
- The theory-practice gap for integrating climate adaptation into MPAs also needs further evaluation, and the specific local reasons for such a gap could be included with each record in the centralized resource.

ENSURING REPRESENTATION OF ALL CLIMATE TRAJECTORIES IN THE PROTECTED SEASCAPE

MPAs around the globe are already and will continue to be affected by climate change to varying degrees (*7*). Nevertheless, while it is recognized that network design needs to incorporate climate resilience (*24*), ideas differ on how to best prioritize areas to account for climate change. For example, it has been suggested that temporary climate refugia (here defined as locations with slower projected increases in future climate stress) be prioritized as part of the PA network [e.g., (*35*, *36*)]. These areas are important but are relatively rare, cannot be solely relied upon to achieve global conservation goals (*37*), and do not eliminate the need to manage for change. If we prioritize the protection of climate refugia, then we downweight vulnerable ecosystems that may require the most assistance against synergistic but abatable threats. Instead, a range of areas representing the spectrum of vulnerability, impact, and climate futures need to be included in the protected seascape to ensure that ecosystems with differing trajectories can be adequately represented and managed (Table 1) (*38*, *39*). Assessing climate futures and vulnerability for different ecosystems and MPAs (*7*) remains extremely challenging as a result of the large variation in biological responses, uncertainty around climate signals, and the difficulties in linking protection to resilience (*24*, *25*). However, one way to approach this is by analyzing the distribution of MPAs against future (*7*) and historical thermal conditions (Fig. 2). Globally, and within each MPA, we calculated the historical thermal variability (1900–2018) and the projected thermal exposure to 2100 (*7*). Almost half of the MPA area assessed (46%) is characterized by low historical environmental variability, but with novel and unprecedented thermal conditions already occurring or projected within several decades. An even larger proportion (49%) also has had low historical thermal variability, but novel thermal conditions are not projected until the mid- to late century. A very small area of MPAs (<5%) has experienced high historical variability (Fig. 2)

Table 1. Examples of climate change adaption objectives and possible actions.

Objective with climate change	Example actions to operationalize
Early detection of climate change impacts	Enhanced multisensor monitoring
	Citizen science observer networks
	Use of sentinel species as indicators
Protecting species or habitats that move	Support migration of climate-displaced species or habitats with flexible design features or other management measures and protect from other stressors
Enabling reorganization of ecosystems to retain functions and services under climate change	Manage for resilience under a changing climate rather than assuming static features and outcomes
	Reassess and revise zoning and management plans to account for ecosystem and species shifts
	Specify climate mitigation into MPA network design and management objectives
Maintaining representative MPA networks in a changing climate	Include areas of high and low predicted climate resilience, future change, and adaptation potential in representative network design
Use both static and dynamic features to better conserve ecosystems	Better integrate conservation and fisheries management measures to augment one another
	Focus network around anchor-point static areas but integrate multiple tools including more dynamic and responsive approaches (see Table 2)
Adapting to unforeseen conservation challenges and opportunities as climate change reconfigures ecosystems	Move toward dynamic conservation objectives
	Update management plans and objectives a based on observed changes
	Collect stakeholder observations and feedback

While the distribution across novel climate futures is relatively balanced, the current global MPA network is heavily skewed toward areas that have experienced relatively low historical variability in temperature (Fig. 2). However, this distribution closely reflects the proportion of these areas in the global ocean (clockwise from top left: <1, <2, 47, and 50%). Deviations from the background distribution may reflect prioritization with respect to climate variability and change, and conversely, a network distribution that closely matches that of the global ocean may represent climate-agnostic planning. It may be prudent to place more MPAs in locations with high historical variability, although the hypothesis that this may translate to greater climate resilience requires more explicit and context-dependent testing (*40*, *41*).

The idea of true representation of ocean futures means accepting the dynamic reality of climate change. While permanent refugia do not exist, sites with a longer time until novel climatic conditions emerge (i.e., temporary refugia) may prove important. However, all types of climatic trajectories should be integrated into the protected seascape, because they will all need management assistance to navigate the novel climate of the future. The resilience, adaptability, and evolutionary potential of organisms may also be influenced by their historical experience (*41*), so accounting for this in the protected seascape may add further robustness.

***Recommendation 2*: Create networks of MPAs and OECMs that span the range of past and future climate space along multiple axes of change (e.g., temperature, oxygen, and acidification) to ensure inclusion of all climate trajectories.**
- While recognizing that refugia are important, all types of climate futures should be represented, as ecosystems experiencing more rapid change may require more active management and protection from synergistic human stressors.
- Accounting for differing historical trajectories may add further robustness.

SETTING EXPLICIT CLIMATE ADAPTATION OBJECTIVES FOR MPAs

Climate change is reconfiguring marine ecosystems globally (*42*). Yet, in contrast to other potentially abatable human impacts such as fishing, it is impossible to immediately limit the in situ effects of climate change, some of which are already inescapable. Therefore, as society works to reduce greenhouse gas emissions (*24*, *25*), we also need to accept the present reality of ecosystem change and transition. Ensuring that the protected seascape achieves its conservation objectives requires much tighter integration between biodiversity conservation and climate change agendas.

This integration will require concrete MPA objectives relating to the direct and indirect impacts of climate change (see examples in Table 1). The fundamental notion of conserving habitats and ecosystems "as is," or restoring them to a previous baseline, has been replaced by the realization that climate change will cause rearrangements of marine systems on scales much larger than those of individual MPAs. Thus, objectives need to shift toward a more dynamic set of goals and actions at both the network and individual MPA level to explicitly acknowledge ongoing climate change. This shift may require embracing difficult realities of limited capacity. Dynamic responses to climate change must be spatially prioritized with clear adaptation objectives, which should result in more efficient global and regional networks. Indirectly dealing with climate change through previously established MPA network design principles (such as replication, representation, and connectivity) is important yet does not take ongoing dynamic impacts into account. Climate change needs to be explicitly incorporated into both the design phase (by optimizing siting choices) and management (operationalizing objectives that acknowledge climate change) (*24*, *43*).

The uncertainty inherent in climate change projections, scenarios, and ecological responses does not justify inaction. Climate change is unfolding, biological systems are responding, and the effectiveness of MPAs designed for today will be reduced in the future (*7*). Explicitly integrating climate adaptation objectives into MPA design and management provides a concrete step toward adaptation to climate

Table 2. Climate design principles for the protected seascape. Different tools perform complementary functions within a climate-resilient conserved seascape.

Management tool		Objectives/characteristics	Examples
Static tools	Static MPAs (anchor points)	Conservation of assemblages associated with static geomorphological features and other sites of present and future conservation importance	Great Barrier Reef Marine Park (Australia)
		Maintaining long-term monitoring (control/baseline) sites where climate impacts can be assessed in the absence of other stressors	Galapagos Marine Reserve (Ecuador)
		Creating networks for meta-populations and fixed migration corridors	Marianas Trench National Monument (USA)
	Static OECMs	Effective conservation of key ecological features and biodiversity from a single or several threats (regardless of primary objective of OECM)	Rockall Haddock Box High Seas Trawl Closure (North East Atlantic Fisheries Commission)
		Act as long-term monitoring sites for climate impacts with single or multiple additional uses and/or stressors superimposed	
		Creating networks for meta-populations and fixed migration corridors	
Dynamic tools	Dynamic ocean management areas*	Respond to rapid shifts in species distribution and threats	Dynamic fisheries closures to protect North Atlantic right whales (Canada)
		Provide short-term/seasonal corridors or stepping stones	
		Provide quicker deployment (and removal) than MPAs	
		Not fully multisectoral; often single-sectoral	
		Unlikely to be considered OECMs under the present definition, unless they remain in place for an extended period (see Table 3)	
	Climate-responsive biodiversity closures (CRBCs)	A hybrid of MPAs (multisectoral) with shorter-term closures (ability to relocate and react to climate-driven changes)	Currently conceptual—see main text
		Respond to climate-driven biological responses by moving boundaries to track shifting habitats or ecosystems	
		Focus on shifts due to climate signal rather than other fluctuations	
		Unlikely to be considered OECMs under the present definition, unless they remain in place for an extended period (see Table 3)	

*Also known as dynamic conservation features and/or short-term closures.

change. Rather than waiting and letting the effectiveness of the global protected seascape deteriorate, we need to embrace uncertainty and move forward with an ambitious coupled climate-biodiversity response, actualized through explicit climate adaptation objectives for every MPA and network.

***Recommendation 3*: Ensure that climate adaptation objectives are explicitly included in all MPA (and network) management plans.**

• This can be evaluated by setting a target for the proportion of MPAs that do so (see Recommendation 5), which can be facilitated by creating a database of this climate change integration (see Recommendation 1).

DEVELOPING CLIMATE-RESPONSIVE CONSERVATION NETWORKS IN THE OCEAN

A crucial contradiction of climate-smart MPA network design is that climate impacts and ecological responses are dynamic, yet PAs and OECMs are, by definition, spatially static (*44*–*46*). Designing the global protected seascape by combining multiple static and dynamic tools may help overcome this contradiction. Yet, while conceptual approaches have been developed to integrate static and dynamic tools in PA networks (*44*, *46*, *47*), it remains unclear how a climate-responsive seascape conservation network would look in practice.

It could be argued that climate change will erode the value of static protection. However, while changes will occur throughout the

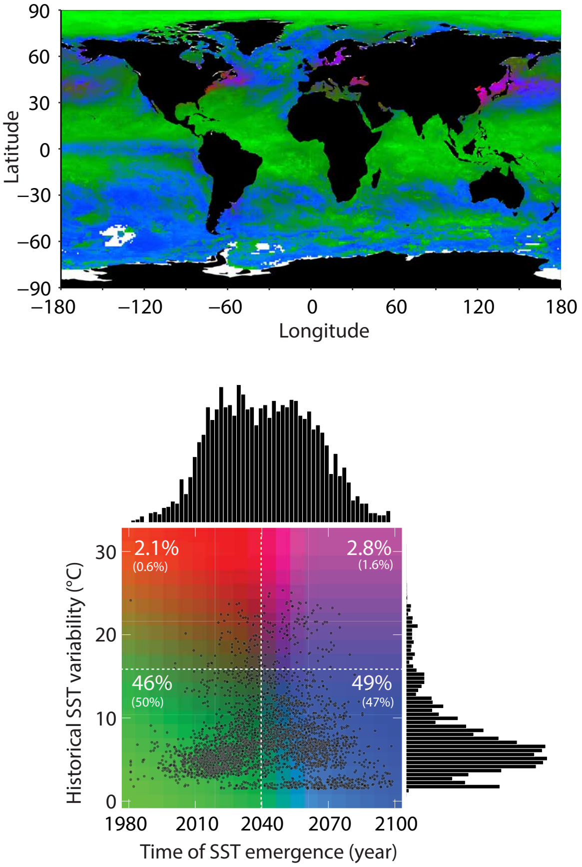

Fig. 2. Vulnerability of the existing global MPA network to climate change. (**A**) Bivariate map of the time of emergence and historical variability for the global ocean [see (B) for color axes] under a business-as-usual emissions scenario [Representative Concentration Pathway (RCP) 8.5]. Time of emergence refers to the year when projected mean sea surface temperature (SST) at a given location exceeds the bounds of preindustrial conditions. Historical variability is the total thermal range calculated from a detrended 1900 to 2018 SST time series. (**B**) Quadrant plot of MPA position in climate emergence and historical variability space. Black points represent 1° × 1° grid cells within MPAs, with larger MPAs having more points based on overlap with SST data (see text in the Supplementary Materials for full methodological details). Histograms provide the distribution of MPAs along each axis. Percentage values indicate the proportion of MPA area (grid cells) in each quadrant; percentages in brackets indicate the proportion of the global ocean in each quadrant. Color scale is based on background distribution in global ocean.

ocean, considerable evidence points to the ecological benefits of well-managed and enforced static conservation areas (*48*). Fixed MPAs, covering both the seabed and overlying water column (*49*), play a vital role in building ecological resilience to anthropogenic pressures, through long-term ecosystem-focused protection that addresses human activities across multiple sectors, and facilitating cumulative benefits (*49*–*51*). Given the strength of the evidence, fixed "anchor-point" MPAs should help to offer long-term support for marine life to adapt to changing conditions. Furthermore, a static protected seascape can conserve geographical features that are structurally complex (e.g., coral reefs, submarine canyons, and seamounts) and likely to remain important to marine life even in a changing world.

Nonetheless, it is clear that the ability of static features to meet conservation objectives may be undermined under climate change (*7*). Furthermore, implementing new MPAs based on projections of changing species distributions under specific scenarios at specific dates in the future risks ignores projection uncertainty and resulting in placements that wax and wane in effectiveness under climate change—it is again planning for a static future at some fixed date. This may not be a strategy that is robust over a long-term dynamic future (*52*).

This potential for climate change to undermine the effectiveness of static MPAs might be partly countered by setting objectives at a network level that evolve as the climate continues to restructure ecosystems (Table 1), although this is unlikely to fully suffice. A new paradigm would be to focus on accrued benefits to ecosystems, which may shift in geographic location, rather than on benefits to specific sites, in which the ecological composition may become altered and affect the delivery of location-specific benefits. If ecosystems, habitats, or communities move with climate change, then accruing benefits to or from an ecosystem necessitates moving or extending management measures as that ecosystem moves; otherwise, accrued benefits may begin to deteriorate as the objectives move beyond the boundaries of protection (*47*). This shift in focus can help to guide a conservation approach that includes dynamic management tools, here explicitly referring to dynamic management measures rather than dynamic zoning within existing static measures.

Safeguarding marine life under future change will require an MPA network that is based around existing (and new) static anchor-point MPAs, supplemented with dynamic (in time and space) management elements to accommodate rapid ecological changes (Table 2). These combined dynamic-static networks have been conceptually proposed (*44*, *46*), though not explicitly operationalized for the oceans. Here, we envisage how such a combined network might appear in practice.

Of existing area-based management tools, dynamic ocean management (temporary management measures in response to changes in and forecasts of shifts in the biophysical marine environment) is generally applied with a relatively short time horizon (days to months) (*53*) that may not appear to intuitively align with the longer-term implications of climate change. However, the ability of dynamic ocean management (and similar tools) to respond to threats to species and shifts in their distributions in near real time (*54*) makes it suitable to help to "fill the gaps" between other management measures and respond to rapid changes (Table 2).

One such example is the recent (2018 and 2019) management measures in reaction to the North Atlantic right whale (*Eubalaena glacialis*) shifting its distribution in response to climate-driven changes in environmental conditions and redistribution of prey (*55*). As a result of a habitat shift into the Gulf of St. Lawrence in Canada, these whales have experienced increased mortality from vessel strikes and entanglements in fishing gear. In response, the federal government created near real-time and spatially dynamic fishery closures and gear and vessel speed restrictions, designed specifically to limit seasonal mortality risks, and updated daily based on visual and acoustic tracking of the species (*56*).

These dynamic fishery closures can be rapidly implemented, potentially offer long-term protection, and, in some instances, could even develop into static OECMs. However, they may not be specifically designed to address long-term biodiversity objectives. Therefore, these closures do not provide all of the benefits of MPAs, as they typically address single or only several sectors, gears, or target species and permit other activities that might be harmful. This limitation could hypothetically be ameliorated by layering multiple dynamic single-sector management tools (e.g., for fishing, shipping, and seabed exploitation) in concert. However, this would require coordinated action across multiple agencies, communities, and legislative frameworks and may still fail to manage all stressors. A full conservation network should not be built solely around limited sectoral measures (*51*). It may be more effective to deploy rapid-response, multisectoral conservation management tools designed specifically to deal with climate-driven impacts on marine ecosystems.

These toolkits have been explored in hypothetical scenarios (*45*, *46*) but do not yet exist in practice. For dynamic spatially explicit and conservation-focused management, the ideal measure would hybridize the benefits of MPAs (multisectoral protection with a long-term biodiversity conservation objective) with those of dynamic sectoral closures (ability to be rapidly deployed and to be relocated to respond to climate impacts, based on changes in the effectiveness or efficiency of the network). They would not move frequently but could be triggered for relocation under specific conditions mapped to climate change response time scales, thus recognizing that climate change is an ongoing and continual problem. We term these measures "climate-responsive biodiversity closures" (CRBCs) (Table 2), given that they would be implemented primarily to deal with the effects of climate change on biodiversity.

CRBCs require, as above, viewing permanency of protection (and accrued benefits) from the perspective of tracking a particular ecosystem, habitat, or species, rather than protection of a fixed location in space. CRBCs could be used to protect habitats or ecosystems expected to gradually redistribute as a consequence of climate change; they may, therefore, be particularly suited to biogenic habitats (e.g., corals, kelp forests, and seagrass meadows), oceanographically complex regions, or aggregation points that will shift but continue to provide a key habitat for species assemblagees. For example, if a network design objective was to represent at least half of the range of a specific biogenic habitat, such as seagrass, which subsequently shifted as the climate changed, then CRBCs could be relocated to maintain representation (Fig. 3).

However, the implementation of these measures would need to be informed by robust science and ongoing monitoring, require intensive stakeholder engagement and potentially cross-jurisdictional partnerships, and necessitate high volumes of data. Alternatives to CRBCs could include implementing additional static MPAs (e.g., by increasing spatial targets) and then supplementing them using dynamic ocean management; the relative benefits and costs of these alternatives require further investigation. Nonetheless, multisectoral, long-term biodiversity-focused tools specifically designed to dynamically respond to climate change remain absent from the conventional conservation portfolio.

In summary, a paradigm is emerging of a climate change reality that cannot be fully addressed by purely static closures. By combining static and dynamic conservation measures, gaps in target coverage may be filled (Fig. 3), although international objectives may require greater consideration of how these measures fit within the policy landscape (Recommendation 6). There is an important trade-off in

Table 3. Assessment of whether dynamic management tools meet the CBD criteria (*13*) for being OECMs.

CBD criterion		Do dynamic management tools as envisaged meet criterion?
A: Area is not currently recognized as a PA		
	Not currently recognized as a PA	Yes
B: Area is governed and managed		
	Geographically defined space	Yes in size and area described
		No for geographically delineated boundaries
	Legitimate governance authorities	Yes
	Managed	Yes
C: Achieves sustained and effective contribution to in situ conservation of biodiversity		
	Effective	Yes (assuming biodiversity and conservation benefits, regardless of objectives)
	Sustained over the long term	Depends on definition of "long term." Some features may shift year to year but be in place for many years. Ultimately, it may be the intent; is the proposed length of management expected to be long-term, regardless of shorter-term dynamics?
	In situ conservation of biological diversity	Yes
	Information and monitoring	Yes
D: Associated ecosystem functions and services and cultural, spiritual, socioeconomic, and other locally relevant values		
	Ecosystem functions and services	Yes
	Cultural, spiritual, socioeconomic, and other locally relevant values	Yes (assuming explicitly accounted for)

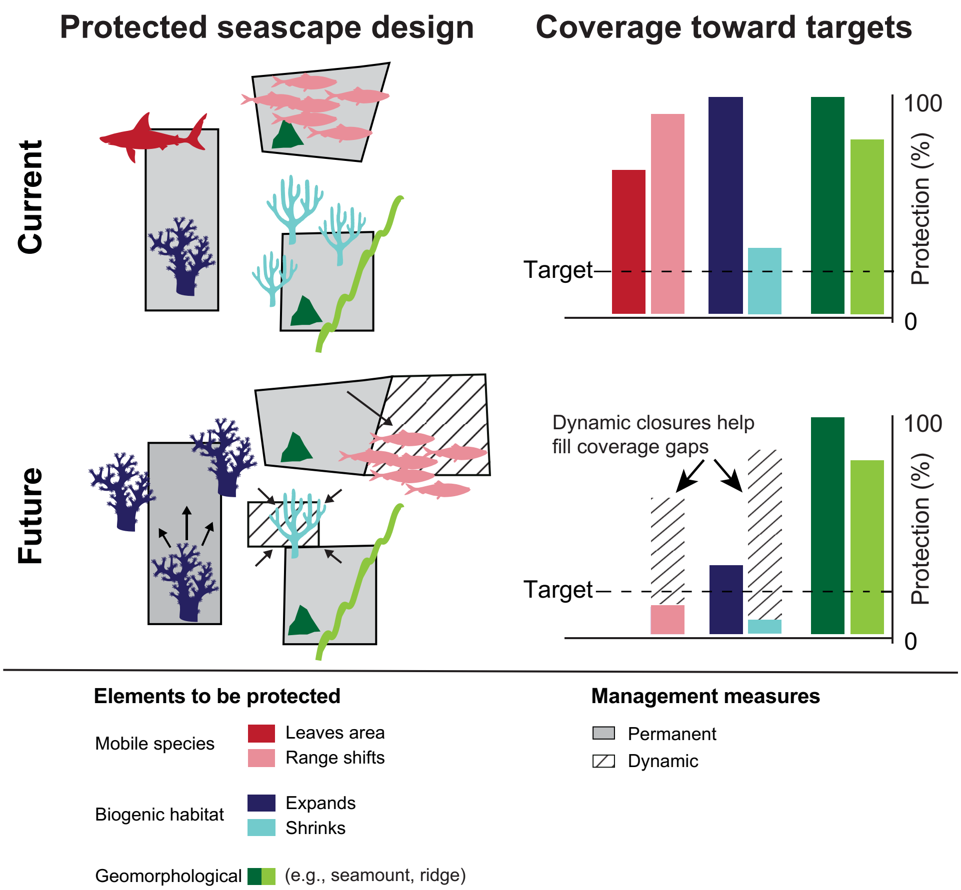

Fig. 3. The need for climate-responsive management features. Climate-driven changes in mobile species, biogenic habitat features, and static geomorphological features (e.g., seamounts and ridges), with management measures (permanent and dynamic) superimposed (left column). In this example, under the current distribution percent coverage targets (e.g., Aichi Target 11 of 10% by 2020) will be met for many species, habitats, and features (right column). However, climate-driven shifts will affect future distributions such that these targets would no longer be met, as a result of species and biogenic habitats expanding, shrinking, disappearing, or moving in relation to static protected features (although some features may get increased protection if they move into MPAs). Dynamic closures (hashed boxes, Table 2) can help to fill the protection gap in a more rapid manner than simply extending or adding new MPAs; however, these dynamic areas will not count toward international targets unless they meet OECM criteria (see Table 3).

the selection of dynamic versus static features, specifically between the cumulative ecological benefits acquired by sustained spatial protection and the declining efficiency associated with not adapting the network to changing conditions. Mobilizing new and existing tools to build dynamic climate adaption into the MPA network is feasible, if deemed of collective importance.

***Recommendation 4*: Design the global MPA network around fully protected static management measures supplemented by dynamic, climate-responsive tools.**

- A multisectoral, rapid-response spatial management tool with a long-term biodiversity conservation focus (here termed climate responsive biodiversity closures, or CRBCs), dynamically deployed to protect biodiversity under climate change, is missing from the conservation portfolio.
- Evaluating the legislative, technical, and practical feasibility of these tools, as well as their benefits and trade-offs versus other options (e.g., overlaying single-sector measures), remains an operational gap.
- Case studies of these measures could be developed and disseminated, as well as funding and capacity transfer for their implementation, if they are demonstrated to be effective.

POLICY INCENTIVES TO ENABLE A CLIMATE-BIODIVERSITY SYNTHESIS IN GLOBAL SEASCAPE MANAGEMENT

Setting explicit climate change objectives for conserved seascape management measures (Recommendation 3) and integrating static anchor points, dynamic conservation features, and other management tools (Recommendation 4) will contribute toward building a climate-resilient network. However, to enable this ambition in practice and build flexibility into management instruments, appropriate policy incentives are needed. The lack of these incentives may help explain why the uptake and adoption of climate principles into MPA design and operation have been relatively slow (Fig. 1). New international biodiversity or conservation targets could provide one such incentive.

The implementation of the global network of MPAs has been accelerating, which may, in part, be explained by Parties to the Convention on Biological Diversity (CBD) attempting to meet Aichi Target 11 that requires 10% areal protection for coastal and marine areas (*57*). Percentage targets, however, are not a panacea; they can promote perverse outcomes and cause PAs to be established at sites with relatively low biodiversity value (*58*). PAs can also vary considerably in their effectiveness, depending on capacity, management, and enforcement (*59*). Nonetheless, the steady progress toward

Aichi Target 11 in terms of percentage area covered suggests that having such specific and measurable targets may result in improvements (*60*). Certainly, specific proposals for the post-2020 biodiversity agenda have provision for increased percentage targets for global PA coverage (*61*). Ideally, these targets should be combined with others on biodiversity state or ecosystem services rather than management responses (*58*). However, in practical terms, percentage area targets for PA coverage are very likely to be a component of any post-2020 biodiversity agreement. Given this, and their effectiveness at driving global action, additional and specific measurable targets for climate-related conservation would accelerate tackling climate change impacts in the world's oceans.

CREATING TARGETS FOR THE PROPORTION OF MPAs AND OECMs THAT EXPLICITLY SET CLIMATE OBJECTIVES

To fully embrace the links between climate and biodiversity, every MPA should explicitly and proactively integrate climate change considerations into their management plans and operation, and all new areas should be designed with climate change in mind (Recommendation 3). Developing a new measurable target (or target component) that these climate-focused objectives could count toward would be an incentive that helps to raise the level of climate integration in the wider network. One promising starting point would be to promote a quantifiable target for the proportion of MPAs that explicitly incorporate climate change into their management plans and/or design.

For example, such a target could read "All marine protected areas integrate climate change into their management plans," with the associated indicator simply being the percentage of these sites that actually do so. This target has the advantage of being explicitly tied to a measurable indicator, a feature that many of the Aichi Targets lack (*57*) and that has been shown to be important for driving international action (*62*). As an additional benefit, this process may help to further explicitly integrate recognition of ecosystem-based approaches to climate mitigation, as per the CBD decision on climate and biodiversity change (*63*). Additional targets or target components could also apply to other conservation measures (e.g., "all OECMs integrate climate change into their management plans") or apply at the network level.

***Recommendation 5*: Develop a specific target for the post-2020 global biodiversity framework that measures the proportion of MPAs and marine OECMs that explicitly integrate climate change adaptation in their management plans.**

- The target should be that 100% of MPAs and OECMs include climate change adaptation into their management plans.
- A climate adaptation catalog (Recommendation 1) could provide the data to develop an indicator to measure this.
- Climate-smart management at the network level should also be incentivized.

RECOGNIZING DYNAMIC CONSERVATION FEATURES AS CONTRIBUTORS TOWARD COVERAGE TARGETS

Given that the increase in PA coverage has, in part, been driven by international targets, it seems likely that to promote the integration of dynamic conservation measures into the protected seascape, measurable post-2020 international targets will be important. The most straightforward way of enabling this would be to recognize, where appropriate, such features as OECMs and hence contributors to percentage targets for areal protection under the CBD post-2020 framework or, alternatively, and perhaps more appositely, to establish a new category for dynamic features. For example, if a 30% target for area protected by 2030 is agreed, then enabling some dynamic measures, depending on their intent, to contribute toward this would likely enhance their uptake, as would the alternative of having a separate 5% (for example) dynamic measures target on top. While the core component of any network should still be anchored around fixed multisectoral protection (*51*), dynamic features, as described above, can help to build climate responsiveness.

By their very nature, these tools (Table 2) include aspects of impermanence, which challenges whether they constitute OECMs. As with more traditional static OECMs, these assessments will vary on a case-to-case basis and may continue to do so even over time as individual features evolve. Short-term or temporary dynamic ocean management is unlikely to count, for example, while longer-term dynamic closures (for instance, shorter-term regulatory instruments renewed annually or seasonal measures as part of a long-term overall management regime) and CRBCs may be closer to OECM intentions. The most direct way of evaluating this is to compare individual dynamic elements against the CBD OECM definition (Table 3). From this definition (*13*), some dynamic features as currently conceived match the intended goals of OECMs because, regardless of objectives, they are likely to achieve ancillary positive outcomes for biodiversity conservation by reducing one or more stressors. However, we note that dynamic management may not always entail broader conservation benefits and may be narrowly focused on single species or stocks.

The primary uncertainties revolve around two requirements: that areas are "geographically defined space" (specifically "boundaries are geographically delineated") and "sustained over the long term" (Table 3). For the former, while dynamic features always have a specific geographic delineation, the location, instantiation, and size of this boundary vary over time.

With regard to being sustained over the long term, it is important to separate the permanency of intent versus the permanency of specific instantiation. The underlying intent of a dynamic feature may be to contribute to the preservation of a species, habitat, or biodiversity over a long period—in fact, it may track that biological feature to ensure its continued preservation—regardless of the fact that it can be designated, reevaluated, and redesignated at shorter time scales. Truly ephemeral or seasonal features should not qualify toward coverage targets. However, when a management feature, despite being temporally dynamic, is sustained over the long term with a defined spatial intent and application, and with a strong probability of the conservation outcome being achieved, then it may adhere more closely to the spirit of the OECM definitions.

These issues could greatly benefit from further debate and from clarification and guidelines from the Subsidiary Body on Scientific, Technical, and Technological Advice of the CBD. The challenging task of developing precise definitions and agreement on intent is needed to ensure that dynamic features fulfill their potential of improving the ability of the MPA network to respond to climate change. We recommend that serious consideration be given to further clarification of the specific role and formulation of dynamic features under the OECM definition or through the formulation of a new OECM-like definition, perhaps through an expert workshop on integrating climate considerations into network design.

Crucially, the implementation of dynamic features should not detract from the importance of a growing static anchor network of protection. Dynamic features are a supplement that can be added to ensure continued efficiency and may be particularly useful under resource limitations, especially given their rapidity of deployment. Naturally, the need for dynamic climate-conservation elements will vary depending on the local context, rate of change, and climate vulnerability (Fig. 2). There is a gain-loss proposition that must always be balanced and carefully articulated, of cumulative benefits versus sustained protection in a dynamic environment.

***Recommendation 6*: Provide explicit policy incentives, such as counting toward national fulfillment of international targets, to accelerate the uptake of dynamic features as a supplement to the global protected seascape.**

- Specifically, evaluate whether dynamic features (where appropriate in intent and execution) should either (i) count under the OECM definition or (ii) comprise a new climate-responsive category that can contribute toward existing or new global coverage targets.
- Any such contributions should not undermine but instead supplement the total coverage of fully PAs (i.e., static MPAs).

DEVELOPING LEGISLATIVE TOOLS

Legislative hurdles may also help explain why CRBCs have not yet moved from theory (*45*, *46*) to practice. It is not clear that legislation exists within national jurisdictions to allow the operationalization of these features. There may be ways of approximating this with existing tools. For example, fisheries closures and vessel speed restrictions can be made dynamic to help respond to climate-driven challenges (*56*). The protection of biodiversity across multiple sectors can only be implemented through MPAs, but the regulatory process is often time consuming and can require coordination and cooperation between multiple jurisdictions. OECMs or dynamic measures are highly variable in scope and purpose but have the potential to be quicker to implement with fewer sectoral regulatory considerations (*53*, *64*). While there is considerable variability among countries, we know of no legislative or policy framework that combines the comprehensive protection through multisectoral activity restrictions in MPAs with the potential for speed and flexibility in OECM implementation and the dynamic ability to be relocated to enable a rapid response to climate-driven ecosystem impacts. Working within the existing legal framework, the layering of protection measures through existing single-sectoral management (in a process such as marine spatial planning) remains the only approach to approximate rapid and dynamic multisectoral climate protection for ecosystems.

***Recommendation 7*: Develop legislative tools to enable rapid-response, multisectoral dynamic ocean management features with a biodiversity conservation objective to be deployed specifically in response to climate change.**

- This legislation will need to consider the relative trade-offs involved, which need to be specifically and carefully evaluated (see Recommendation 4).

SOCIAL AND EQUITY CHALLENGES

Complementing the inherent uncertainty around anticipated climate impacts on a regional and global scale, and the policy context, is the inherent social and equity challenge of implementation. Trade-offs between human well-being and the health of the ecosystems upon which we depend have been a long-term consideration in conservation science (*65*, *66*). Although biodiversity loss and climate change present global problems, they affect states to varying degrees. Low-income nations, indigenous peoples, and small island states are frequently most affected by both of these challenges (*67*, *68*). Individual states have varying financial and social capacities to mitigate and respond. To this end, ensuring that the burden of any climate-responsive marine conservation initiatives does not disproportionately fall on low-income countries is of vital importance (*69*).

Ultimately, creating an MPA system robust to climate change will incur short-term costs and yield long-term intergenerational benefit. Unless resources are available to balance these, and overcome resource iniquities (*70*), conservation efforts will not be as successful, and benefits will go unrealized. The long-term advantage of maintaining the development and conservation benefits of MPAs in the face of rapid climate change will likely be sacrificed for short-term economic gain as discussed in the broader climate change context (*71*, *72*). Providing resources to offset at least the added costs not only of establishment of systems robust to climate change but also of ongoing monitoring and addressing short-term opportunity costs (for instance, reduced fisheries catches) will help. These requirements can also be enshrined in international targets, such as Aichi Target 20, on the mobilization of financial resources. Furthermore, funding bodies and foundations may also make explicit consideration of climate change objectives a requirement when funding MPA network design or operation.

Mirroring the biodiversity observed in their underwater counterparts, there is high socioeconomic and cultural heterogeneity in coastal human communities around the world—conditions that often play a decisive role in the outcome of conservation planning (*73*). Strong local leadership and social capital play a critical role in realizing fisheries local co-management objectives at a global scale (*74*). Improved compliance with regulations (e.g., adhering to defined fishing areas and limits) occurs—even when monitoring and enforcement are lacking—if there is sufficient understanding of local norms and beliefs, and management approaches designed with these in mind (*75*). Thus, in addition to ensuring that sufficient resources are available, consultation and direct involvement in planning with affected sectors are vital for building trust between stakeholders and, ultimately, for ensuring that conservation objectives are implemented and retained (*76*, *77*).

***Recommendation 8*: Center climate-smart conservation and management around principles of stakeholder inclusiveness and capacity transfer.**

- This can be realized by funding choices and integrating principles in specific policy targets.
- The need is especially acute as new tools are developed and deployed to address ongoing change and potential loss in effectiveness of the existing MPA network.

CONCLUSIONS

Climate and biodiversity are inextricably linked and, in combination, have formed the conditions for human civilization to flourish, as evidenced by their prominence in the United Nations Sustainable Development Goals. Climate change adaptation and biodiversity conservation should form the combined basis of marine management and seascape protection. While this has long been recognized, implementation has lagged.

To drive implementation, we need to measure the uptake of climate adaptation principles into MPA (and OECM) design and management (Recommendation 1). This uptake should come through the explicit integration of these principles into MPA distribution (Recommendation 2) and objectives (Recommendation 3) to maintain network effectiveness as the ocean changes. Building climate change objectives into post-2020 targets and indicators (Recommendation 5) would expedite this process. In addition to static anchor MPAs, dynamic conservation tools need to be deployed (Recommendation 4), recognizing their strengths in terms of responding to climate change while acknowledging potential drawbacks, so as to augment ongoing efforts to increase coverage of highly PAs. The post-2020 biodiversity agenda should consider whether dynamic measures, where appropriate in terms of intent, longevity, and execution, should contribute toward global protection targets; ensuring that parties to any international biodiversity agreement are appropriately recognized for implementing new tools will help to promote their use (Recommendation 6). Furthermore, individual states may want to consider developing new multisectoral legislation to help bring new and dynamic climate-smart conservation planning tools into existence (Recommendation 7). Considerations of equity in the conservation burden, stakeholder involvement, and societal impacts need to be at the forefront when implementing a climate-resilient protected seascape (Recommendation 8).

At a high level, many of these recommendations may equally apply to terrestrial systems, although the challenges and specifics may differ. However, implementing climate-resilient biodiversity protection measures across all ecosystems is a critical and global need.

Climate change can overwhelm even strong management measures (*20*), and we should not imagine that this management is a substitute for the reduction of greenhouse gas emissions (*24*, *25*, *50*). Nonetheless, we must face the current climate change reality. Unless accounted for, it will erode the effectiveness of MPA networks through changes in the phenology, distribution, and composition of marine ecosystems. Climate change impacts on human communities can also result in adverse ecological effects, and recognizing the variation in adaptive capacity of human communities remains a key part of climate-smart decision-making (*12*, *78*). We need to anticipate and prepare for these socioecological effects with new incentives and solutions. Our shared paradigm should recognize that climate change is ongoing and will continue to affect our marine ecosystems and that the future spatial management must embrace and operationalize such dynamism.

Expanding the global protected seascape with climate resilience in mind, to meet stated biodiversity and conservation objectives in a changing world, should be a key focus for the post-2020 biodiversity framework. Addressing the crucial challenges of climate change and biodiversity loss underpins efforts to improve human well-being. To meet societal objectives as articulated in the United Nations Sustainable Development Goals, and beyond, these agendas need to be twinned, operationalized, and effectively integrated into global seascape conservation and management.

SUPPLEMENTARY MATERIALS

Supplementary material for this article is available at http://advances.sciencemag.org/cgi/content/full/5/11/eaay9969/DC1
Section S1. Methods for review of climate change adaptation in MPAs
Section S2. Methods for derivation assessing MPA vulnerability (see Fig. 2)
Table S1. References for the marine specific papers that incorporated climate change adaptation in MPA design or management presented in Fig. 1.
Table S2. Google scholar search term results for April 2019.
Table S3. Examples where climate change adaptation has been implemented in the design or management of an MPA.
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Executive summary

The *Lancet* Countdown is an international collaboration established to provide an independent, global monitoring system dedicated to tracking the emerging health profile of the changing climate.

The 2020 report presents 43 indicators across five sections: climate change impacts, exposures, and vulnerabilities; adaptation, planning, and resilience for health; mitigation actions and health co-benefits; economics and finance; and public and political engagement. This report represents the findings and consensus of the 35 leading academic institutions and UN agencies that make up the *Lancet* Countdown, and draws on the expertise of climate scientists, geographers, engineers, experts in energy, food, and transport, economists, social, and political scientists, data scientists, public health professionals, and doctors.

The emerging health profile of the changing climate

5 years ago, countries committed to limit global warming to "well below 2°C" as part of the landmark Paris Agreement. 5 years on, global carbon dioxide (CO_2) emissions continue to rise steadily, with no convincing or sustained abatement, resulting in a rise in the global average temperature of 1·2°C. Indeed, the five hottest years on record have occurred since 2015.

The changing climate has already produced considerable shifts in the underlying social and environmental determinants of health at the global level. Indicators in all domains of section 1 (climate change impacts, exposures, and vulnerabilities) are worsening. Concerning, and often accelerating, trends were seen for each of the human symptoms of climate change monitored, with the 2020 indicators presenting the most worrying outlook reported since the *Lancet* Countdown was first established.

These effects are often unequal, disproportionately impacting populations who have contributed the least to the problem. This fact reveals a deeper question of justice, whereby climate change interacts with existing social and economic inequalities and exacerbates longstanding trends within and between countries. An examination of the causes of climate change revealed similar issues, and many carbon-intensive practices and policies lead to poor air quality, poor food quality, and poor housing quality, which disproportionately harm the health of disadvantaged populations.

Vulnerable populations were exposed to an additional 475 million heatwave events globally in 2019, which was, in turn, reflected in excess morbidity and mortality (indicator 1.1.2). During the past 20 years, there has been a 53·7% increase in heat-related mortality in people older than 65 years, reaching a total of 296 000 deaths in 2018 (indicator 1.1.3). The high cost in terms of human lives and suffering is associated with effects on economic output, with 302 billion h of potential labour capacity lost in 2019 (indicator 1.1.4). India and Indonesia were among the worst affected countries, seeing losses of potential labour capacity equivalent to 4–6% of their annual gross domestic product (indicator 4.1.3). In Europe in 2018, the monetised cost of heat-related mortality was equivalent to 1·2% of regional gross national income, or the average income of 11 million European citizens (indicator 4.1.2).

Turning to extremes of weather, advancements in climate science allow for greater accuracy and certainty in attribution; studies from 2015 to 2020 have shown the fingerprints of climate change in 76 floods, droughts, storms, and temperature anomalies (indicator 1.2.3). Furthermore, there was an increase in the number of days people were exposed to a very high or extremely high risk of wildfire between 2001–04 and 2016–19 in 114 countries (indicator 1.2.1). Correspondingly, 67% of global cities surveyed expected climate change to seriously compromise their public health assets and infrastructure (indicator 2.1.3).

The changing climate has downstream effects, impacting broader environmental systems, which in turn harm human health. Global food security is threatened by rising temperatures and increases in the frequency of extreme events; global yield potential for major crops declined by 1·8–5·6% between 1981 and 2019 (indicator 1.4.1). The climate suitability for infectious

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disease transmission has been growing rapidly since the 1950s, with a 15·0% increase for dengue caused by *Aedes albopictus* in 2018, and regional increases for malaria and *Vibrio* bacteria (indicator 1.3.1). Projecting forward, based on current populations, between 145 million people and 565 million people face potential inundation from rising sea levels (indicator 1.5).

Despite these clear and escalating signs, the global response to climate change has been muted and national efforts continue to fall short of the commitments made in the Paris Agreement. The carbon intensity of the global energy system has remained almost flat for 30 years, with global coal use increasing by 74% during this time (indicators 3.1.1 and 3.1.2). The reduction in global coal use that had been observed since 2013 has now reversed for the past 2 consecutive years: coal use rose by 1·7% from 2016 to 2018. The health burden is substantial—more than 1 million deaths occur every year as a result of air pollution from coal-fired power, and some 390 000 of these deaths were a result of particulate pollution in 2018 (indicator 3.3). The response in the food and agricultural sector has been similarly concerning. Emissions from livestock grew by 16% from 2000 to 2017, with 93% of emissions coming from ruminant animals (indicator 3.5.1). Likewise, increasingly unhealthy diets are becoming more common worldwide, with excess red meat consumption contributing to some 990 000 deaths in 2017 (indicator 3.5.2). 5 years on from when countries reached an agreement in Paris, a concerning number of indicators are showing an early, but sustained, reversal of previously positive trends identified in past reports (indicators 1.3.2, 3.1.2, and 4.2.3).

A growing response from health professionals

Despite little economy-wide improvement, relative gains have been made in several key sectors: from 2010 to 2017, the average annual growth rate in renewable energy capacity was 21%, and low-carbon electricity was responsible for 28% of capacity in China in 2017 (indicator 3.1.3). However, the indicators presented in the 2020 report of the *Lancet* Countdown suggest that some of the most considerable progress was seen in the growing momentum of the health profession's engagement with climate change globally. Doctors, nurses, and the broader profession have a central role in health system adaptation and mitigation, in understanding and maximising the health benefits of any intervention, and in communicating the need for an accelerated response.

In the case of adaptation in national health systems, this change is underway. Impressively, health services in 86 countries are now connected with their equivalent meteorological services to assist in health adaptation planning (indicator 2.2). At least 51 countries have developed plans for national health adaptation, and global spending in health adaptation rose to 5·3% of all adaptation spending in 2018–19, reaching US$18·4 billion in 2019 (indicators 2.1.1 and 2.4).

The health-care sector, which was responsible for 4·6% of global greenhouse gas emissions in 2017, is taking early but important steps to reduce its own emissions (indicator 3.6). In the UK, the National Health Service has declared an ambition to deliver a net-zero health service as soon as possible, building on a decade of impressive progress in reducing delivery of care emissions by 57% since 1990, and by 22% when considering the service's supply chain and broader responsibilities. Elsewhere, the Western Australian Department of Health used its 2016 *Public Health Act* to conduct Australia's first climate and health inquiry, and the German Federal Ministry of Health has established a dedicated department on health protection and sustainability responsible for climate-related matters. This progress is becoming more evenly distributed around the world, with 73% of countries making explicit references to health and wellbeing in their Nationally Determined Contributions under the Paris Agreement, and 100% of countries in the South-East Asia and Eastern Mediterranean regions doing so (indicator 5.4). Similarly, least-developed countries and small island developing states are providing increasing global leadership within the UN General Debate on the connections between health and climate change (indicator 5.4).

Individual health professionals and their associations are also responding well, with health institutions committing to divest more than $42 billion worth of assets from fossil fuels (indicator 4.2.4). In academia, the publication of original research on health and climate changed has increased by a factor of eight from 2007 to 2019 (indicator 5.3).

These shifts are being translated into the broader public discourse. From 2018 to 2019, the coverage of health and climate change in the media increased by 96% worldwide, outpacing the increased coverage of climate change overall, and reaching the highest observed point to date (indicator 5.1). Just as it did with advancements in sanitation and hygiene and with tobacco control, growing and sustained engagement from the health profession during the past 5 years is now beginning to fill a crucial gap in the global response to climate change.

The next 5 years: a joint response to two public health crises

Dec 12, 2020, will mark the anniversary of the 2015 Paris Agreement, with countries set to update their national commitments and review these commitments every 5 years. These next 5 years will be pivotal. To reach the 1·5°C target and limit temperature rise to "well below 2°C", the 56 gigatonnes of CO_2 equivalent ($GtCO_2e$) currently emitted annually will need to drop to 25 $GtCO_2e$ within only 10 years (by 2030). In effect, this decrease will require a 7·6% reduction every year, representing an increase in current levels of national government ambition of a factor of five. Without further intervention during the next 5 years, the reductions required to achieve this target increase to 15·4% every year, moving the 1·5°C target out of reach.

The need for accelerated efforts to tackle climate change during the next 5 years will be contextualised by the impacts of, and the global response to, the COVID-19 pandemic. With the loss of life from the pandemic and from climate change measured in the hundreds of thousands, the potential economic costs measured in the trillions, and the broader consequences expected to continue for years to come, the measures taken to address both of these public health crises must be carefully examined and closely linked. Health professionals are well placed to act as a bridge between the two issues, and analogically considering the clinical approach to managing a patient with COVID-19 might be useful in understanding the ways in which these two public health crises should be jointly addressed.

First, in an acute setting, a high priority is placed on rapidly diagnosing and comprehensively assessing the situation. Likewise, further work is required to understand the problem, including: which populations are vulnerable to both the pandemic and to climate change; how global and national economies have reacted and adapted, and the health and environmental consequences of these actions; and which aspects of these shifts should be retained to support longer term, sustainable development. Second, appropriate resuscitation and treatment options are reviewed and administered, with careful consideration of any potential side-effects, the goals of care, and the life-long health of the patient. Economic recovery packages that prioritise outdated forms of energy and transport that are fossil fuel intensive will have unintended side-effects, unnecessarily adding to the 7 million people that die every year from air pollution. Instead, investments in health imperatives, such as renewable energy and clean air, active travel infrastructure and physical activity, and resilient and climate-smart health care, will ultimately be more effective than these outdated methods.

Finally, attention turns to secondary prevention and long-term recovery, seeking to minimise the permanent effects of the disease and prevent recurrence. Many of the steps taken to prepare for unexpected shocks, such as a pandemic, are similar to those required to adapt to the extremes of weather and new threats expected from climate change. These steps include the need to identify vulnerable populations, assess the capacity of public health systems, develop and invest in preparedness measures, and emphasise community resilience and equity. Indeed, without considering the current and future impacts of climate change, efforts to prepare for future pandemics are likely to be undermined.

At every step and in both cases, acting with a level of urgency proportionate to the scale of the threat, adhering to the best available science, and practising clear and consistent communications, are paramount. The consequences of the pandemic will contextualise the economic, social, and environmental policies of governments during the next 5 years, a period that is crucial in determining whether temperatures will remain "well below 2°C". Unless the global COVID-19 recovery is aligned with the response to climate change, the world will fail to meet the target laid out in the Paris Agreement, damaging public health in the short term and long term.

Introduction

The world has already warmed by more than 1·2°C compared with preindustrial levels, resulting in profound, immediate, and rapidly worsening health effects, and moving dangerously close to the agreed limit of maintaining temperatures "well below 2°C".[1–4] These health impacts are seen on every continent, with the ongoing spread of dengue virus across South America, the cardiovascular and respiratory effects of record heatwaves and wildfires in Australia, western North America, and western Europe, and the undernutrition and mental health effects of floods and droughts in China, Bangladesh, Ethiopia, and South Africa.[5–8] In the long term, climate change threatens the very foundations of human health and wellbeing, with the *Global Risks Report*[9] registering climate change as one of the five most damaging or probable global risks every year for the past decade.

It is clear that human and environmental systems are inextricably linked, and that any response to climate change must harness, rather than damage, these connections.[10] Indeed, a response commensurate to the size of the challenge, which prioritises strengthening health-care systems, invests in local communities, and ensures clean air, safe drinking water, and nourishing food, will provide the foundations for future generations to not only survive, but to thrive.[11] Evidence suggests that being more ambitious than current climate policies by limiting warming to 1·5°C by 2100 would generate a net global benefit of US$264–610 trillion.[12] The economic case of expanding ambition is further strengthened when the benefits of a healthier workforce and reduced health-care costs are considered.[13–15]

The present day effects of climate change will continue to worsen without meaningful intervention. These tangible, if less visible, impacts on public health have so far resulted in a delayed and inadequate policy response. By contrast, and on a considerably shorter timescale, COVID-19, the disease caused by severe acute respiratory syndrome coronavirus 2, has rapidly developed into a global public health emergency. Since COVID-19 was first detected in December, 2019, the loss of life and livelihoods has occurred with staggering speed. However, as for climate change, much of the impact is expected to unfold over the coming months and years, and is likely to disproportionately affect vulnerable populations as both the direct effects of the virus, and the indirect effects of the response to the virus, are felt throughout the world. Several lessons and parallels between climate change and COVID-19 are discussed in panel 1, focusing on the response to, and the recovery from, the two health crises.

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For **Peter Byass' obituary** see **Obituary** *Lancet* 2020; **396:** 752

Panel 1: Health, climate change, and COVID-19

As of Nov 9, 2020, the COVID-19 pandemic has spread to 190 countries, with more than 50 493 000 cases confirmed and more than 1 257 700 deaths recorded.[16] The scale and extent of the suffering, and the social and economic toll, will continue to evolve over the coming months, with the effects of the pandemic likely to be felt for years to come.[17] The relationship between the spread of existing and novel infectious diseases, worsening environmental degradation, deforestation, and change in land use, and animal ill health has long been analysed and described. Equally, both climate change and COVID-19 act to exacerbate existing inequalities within and between countries.[18–20]

As a direct consequence of the pandemic, an 8% reduction in greenhouse gas emissions is projected for 2020, which would be the most rapid 1-year decline on record.[21] Crucially, these reductions do not represent the decarbonisation of the economy required to respond to climate change, but simply the freezing of economic activity. Equally, the 1·4% reduction in greenhouse gas emissions that followed the 2008 global financial crisis was proceeded by a rebound, with emissions rising by 5·9% in 2010. Likewise, it is unlikely that the current fall in emissions will be sustained, with any reductions being potentially outweighed by a shift away from otherwise ambitious policies for climate change mitigation. However, this route need not be taken.[21] Over the next 5 years, considerable financial, social, and political investment will be required to continue to protect populations and health systems from the worst effects of COVID-19, to safely restart and restructure national and local economies, and to rebuild in a way that prepares for future economic and public health shocks. Harnessing the health co-benefits of climate change mitigation and adaptation will ensure the economic, social, and environmental sustainability of these efforts, while providing a framework that encourages investment in local communities and health systems and synergises with existing health challenges.[22]

Multiple, ready-to-go examples of such alignment are available, such as commonalities between future pandemic preparedness and effective health adaptation to climate-related impacts.[23] In climate-related health adaptation, decision making under deep uncertainty necessitates the use of the principles of flexibility, robustness, economic low regrets, and equity to guide decisions.[24] At the broader level, reducing poverty and strengthening health systems will both stimulate and restructure economies, and are among the most effective measures to enhance community resilience to climate change.[3]

Turning to mitigation, at a time when more and more countries are closing down the last of their coal-fired power plants and oil prices are reaching record lows, the fossil fuel sector is expected to be more affected than is the renewable energy sector.[21] If done with care and adequate protection for workers, government stimulus packages are well placed to prioritise investment in healthier, cleaner forms of energy. The response to COVID-19 has encouraged a rethinking of the scale and pace of ambition. Health systems have restructured services practically overnight to conduct millions of primary care and specialist appointments online, and a sudden switch to online work and virtual conferencing has shifted investment towards communications infrastructure instead of aviation and road transport.[25,26] A number of these changes should be reviewed, improved on, and retained over the coming years.

It is clear that a growing body of literature and rhetoric will be inadequate to respond to climate change, and this work must take advantage of the moment to combine public health and climate change policies in a way that addresses inequality directly. The UN Framework Convention on Climate Change's 26th Conference of the Parties, which is postponed to 2021 and is set to be in Glasgow, UK, presents an immediate opportunity to ensure the long-term effectiveness of the response to COVID-19 by linking the recovery to countries' revised commitments (Nationally Determined Contributions) under the Paris Agreement. The solution to one economic and public health crisis must not exacerbate another, and, in the long term, the response to COVID-19 and climate change will be the most successful when they are closely aligned.

The *Lancet* Countdown exists as an independent, multidisciplinary collaboration dedicated to tracking the links between public health and climate change. It brings together 35 academic institutions and UN agencies from every continent, and structures its work across five key sections: climate change impacts, exposures, and vulnerabilities; adaptation, planning, and resilience for health; mitigation actions and health co-benefits; economics and finance; and public and political engagement (panel 2). The 43 indicators and conclusions presented in this report are the cumulative result of the past 8 years of collaboration, and represent the consensus of climate scientists, geographers, engineers, experts in energy, food, and transport, economists, social and political scientists, public health professionals, and doctors.

Where the COVID-19 pandemic has direct implications for an indicator being reported (and where accurate data exists to allow meaningful commentary), these implications are discussed in-text. Beyond this deviation, the 2020 report of the *Lancet* Countdown maintains focus on the connections between public health and climate change, and the collaboration worked hard to ensure the continued high quality of its indicators, with only minor amendments and omissions resulting from the ongoing disruptions.

Expanding and strengthening a global monitoring system for health and climate change

the *Lancet* Countdown's work draws on decades of underlying scientific progress and data, with the initial

Panel 2: The indicators of the 2020 report of The *Lancet* Countdown

Climate change impacts, exposures, and vulnerabilities
- 1.1: health and heat
  - 1.1.1: vulnerability to the extremes of heat
  - 1.1.2: exposure of vulnerable populations to heatwaves
  - 1.1.3: heat-related mortality
  - 1.1.4: change in labour capacity
- 1.2: health and extreme weather events
  - 1.2.1: wildfires
  - 1.2.2: flood and drought
  - 1.2.3: lethality of extreme weather events
- 1.3: climate-sensitive infectious diseases
  - 1.3.1: climate suitability for infectious disease transmission
  - 1.3.2: vulnerability to mosquito-borne diseases
- 1.4: food security and undernutrition
  - 1.4.1: terrestrial food security and undernutrition
  - 1.4.2: marine food security and undernutrition
- 1.5: migration, displacement, and rising sea levels

Adaptation, planning, and resilience for health
- 2.1: adaptation planning and assessment
  - 2.1.1: national adaptation plans for health
  - 2.1.2: national assessments of climate change impacts, vulnerability, and adaptation for health
  - 2.1.3: city-level climate change risk assessments
- 2.2: climate information services for health
- 2.3: adaptation delivery and implementation
  - 2.3.1: detection, preparedness, and response to health emergencies
  - 2.3.2: air conditioning: benefits and harms
  - 2.3.3: urban green space
- 2.4: spending on adaptation for health and health-related activities

Mitigation actions and health co-benefits
- 3.1: energy system and health
  - 3.1.1: carbon intensity of the energy system
  - 3.1.2: coal phase-out
  - 3.1.3: zero-carbon emission electricity
- 3.2: clean household energy
- 3.3: premature mortality from ambient air pollution by sector
- 3.4: sustainable and healthy transport
- 3.5: food, agriculture, and health
  - 3.5.1: emissions from agricultural production and consumption
  - 3.5.2: diet and health co-benefits
- 3.6: mitigation in the health-care sector

Economics and finance
- 4.1: the health and economic costs of climate change and benefits from mitigation
  - 4.1.1: economic losses due to climate-related extreme events
  - 4.1.2: costs of heat-related mortality
  - 4.1.3: loss of earnings from heat-related reduction in labour capacity
  - 4.1.4: costs of the health impacts of air pollution
- 4.2: the economics of the transition to zero-carbon economies
  - 4.2.1: investment in new coal capacity
  - 4.2.2: investments in zero-carbon energy and energy efficiency
  - 4.2.3: employment in low-carbon and high-carbon industries
  - 4.2.4: funds divested from fossil fuels
  - 4.2.5: net value of fossil fuel subsidies and carbon prices

Public and political engagement
- 5.1: media coverage of health and climate change
- 5.2: individual engagement in health and climate change
- 5.3: coverage of health and climate change in scientific journals
- 5.4: government engagement in health and climate change
- 5.5: corporate sector engagement in health and climate change

indicator set selected as part of an open, global consultation that sought to identify which of the connections between health and climate change could be meaningfully tracked.[27] Proposals for indicators were considered and adopted on the basis of numerous criteria, including the existence of a credible underlying link between climate change and health that was well described in the scientific literature; the availability of reliable and regularly updated data across expanded geographical and temporal scales; the presence of acceptable methods for monitoring; and the relevance to policy and availability of actionable interventions.

An iterative and adaptive approach has substantively improved most of these initial indicators and resulted in the development of several additional indicators. Given this approach, and the rapidly evolving nature of the scientific and data landscape, each annual update replaces the analysis from previous years. The methods, sources of data, and improvements for each indicator are described in full in the appendix, which is an essential companion to the main report.

See Online for appendix

The 2020 report of the *Lancet* Countdown reflects an enormous amount of work done during the past 12 months to refine and improve these indicators, including the annual update of the data. Several key developments have occurred.

Methods and datasets have been strengthened and standardised for indicators that capture heat and heatwaves, floods and droughts, wildfires, the climate suitability for infectious disease transmission, food security and undernutrition, health adaptation spending, food and agriculture, low-carbon health care, the economics of air pollution, and engagement in health and climate change from the media, the scientific community, and individuals.

Geographical or temporal coverage have been improved or expanded for indicators that track heat and heatwaves, labour capacity loss, floods and droughts, the climate suitability for infectious disease transmission, climate change risk assessments in cities, the use of clean household energy, and household air pollution.

New indicators have been developed to explore heat-related mortality, migration and population displacement, access to urban green space, the health benefits of low-carbon diets, the economic costs of extremes of heat and of labour capacity loss, net carbon pricing, and the extent to which the UN Framework Convention on Climate Change's (UNFCCC) Nationally Determined Contributions (NDCs) engage with public health.

This continued progress has been supported by the *Lancet* Countdown's scientific advisory group and the creation of a new, independent, quality improvement process, which provided independent expert input on the indicators before the formal peer review process, adding rigour and transparency to the collaboration's research. In every case, the most up-to-date data available are presented, with the precise nature and timing of these updates varying depending on the data source. This presentation of data has occurred despite the impact of COVID-19, which has only affected the production of a small subset of indicators for this report.

The *Lancet* Countdown has also taken several steps to ensure that it has the expertise, data, and representation required to build a global monitoring system. Partnering with Tsinghua University, Beijing, China, and Universidad Peruana Cayetano Heredia, Lima, Peru, the collaboration launched two new regional offices for South America (in Lima), and for Asia (in Beijing), and developed a new partnership to build capacity in west Africa. This expansion is coupled with ongoing work to develop national and regional *Lancet* Countdown reports in Australia (in partnership with the *Medical Journal of Australia*), the EU (in partnership with the European Environment Agency), China, and the USA. At the same time, a new data visualisation platform has been launched, allowing health professionals and policy makers to investigate the indicators in this report.

For more on the **data visualisation platform** see lancetcountdown.org/data-platform

Future work will concentrate on supporting these regional and national efforts, building capacity for communications and engagement, developing new indicators (with a particular interest in developing indicators related to mental health and gender), and further improving existing indicators. To this end, the continued growth of the *Lancet* Countdown depends on the dedication of each of its composite experts and partners, continued support from the Wellcome Trust, and ongoing input and offers of support from new academic institutions willing to build on the analysis published in this report.

Section 1: climate change impacts, exposures, and vulnerabilities

A changing climate threatens to undermine the past 50 years of gains in public health, disrupting the well-being of communities and the foundations on which health systems are built.[28] The effects of climate change are pervasive and impact the food, air, water, and shelter that society depend on, extending across every region of the world and every income group. These effects act to exacerbate existing inequities, with vulnerable populations within and between countries affected more frequently and with a more lasting impact.[3]

Section 1 of the 2020 report tracks the links between climate change and human health along several exposure pathways, from the climate signal through to the resulting health outcome. This section begins by examining several dimensions of the effects of heat and heatwaves, ranging from exposure and vulnerability through to labour capacity and mortality (indicators 1.1.1–1.1.4). The indicator on heat-related mortality has been developed for the 2020 report, and, although ongoing work will strengthen these findings in subsequent years, this indicator complements existing indicators on exposure and vulnerability to heat and represents an important step forward.

Indicators 1.2.1–1.2.3 navigate the effects of extreme weather events, tracking wildfires, floods and droughts, and the lethality of extreme weather events. The wildfire indicator now tracks the risk of, and the exposure to, wildfires, the classification of drought has been updated to better align with climate change trends, and the attribution of the health effects of extreme weather events to climate change is presented. The climate suitability for the transmission of infectious diseases and the vulnerability of populations to infectious diseases were monitored, and so too were the evolving impacts of climate change on terrestrial and marine food security (indicators 1.3.1–1.4.2). The consideration of regional variation provided robust estimates of the effects of rising temperatures on crop yield potential. Indicator 1.5, which tracks exposure to rising sea levels in the context of migration and displacement, the resulting health effects, and policy responses, closes this section.

Indicator 1.1: health and heat

Exposure to high temperatures and heatwaves results in a range of negative health impacts, from morbidity and mortality due to heat stress and heatstroke to exacerbations of cardiovascular and respiratory disease.[29,30] The worst affected are those older than 65 years, those with disabilities or pre-existing medical conditions, those working outdoors or in non-cooled environments, and those living in regions already at the limits for human habitation.[31] The following indicators track the vulnerabilities, exposures, and impacts of heat and heatwaves in every region of the world.

Indicator 1.1.1: vulnerability to the extremes of heat—headline finding: vulnerability to the extremes of heat continues to increase in every region of the world, led by populations in Europe, with the Western Pacific region, South-East Asia region, and the African region all seeing an increase of more than 10% since 1990

This indicator re-examines the index results presented in the 2019 report,[28] which combines data on the proportion of the population older than 65 years; the prevalence of chronic respiratory disease, cardiovascular disease, and diabetes in this population, and the proportion of the total population living in urban areas. It also introduces a more comprehensive index of heat vulnerability, combining these aforementioned factors with heatwave exposure data and the International Health Regulations capacity score.

Since 1990, as a result of ageing populations, the high prevalence of chronic disease, and rising levels of urbanisation, populations in the European and Eastern Mediterranean regions have been the most vulnerable to the extremes of heat of all the WHO regions. In 2017, vulnerability was 40·6% in the European region and 38·7% in the Eastern Mediterranean region. However, no WHO region is immune and vulnerability has worsened everywhere. From 1990 to 2017, vulnerability increased in the African region (28·4% to 31·3%), the South-East Asia region (28·3% to 31·3%), and the Western Pacific region (33·2% to 36·6%). By taking into account health system strengthening and heatwave exposure across these regions, this vulnerability indicator can be usefully built into one that captures population risk, which has been done for the 2020 report (appendix pp 4–5). This new indicator shows trends similar to those aforementioned, with risk rising in every region. This index will be further developed during the course of 2020, and presented in full, alongside a broader suite of risk indicators, in future reports.

Indicator 1.1.2: exposure of vulnerable populations to heatwaves—headline finding: a record 475 million additional exposures to heatwaves affecting vulnerable populations were observed in 2019, representing some 2·9 billion additional days of heatwaves experienced

Since 2010, there has been an increase in the number of days of heatwave exposure, relative to a 1986–2005 baseline, in the population older than 65 years (figure 1). This rise has been driven by the combination of increasing heatwave occurrences and ageing populations. In 2019, there were 475 million additional exposure events. Expressed as the number of days in which a heatwave was experienced, this number breaks the previous 2016 record by an additional 160 million person-days.

Indicator 1.1.2 tracks the exposure of vulnerable populations to heatwaves and has now been updated to

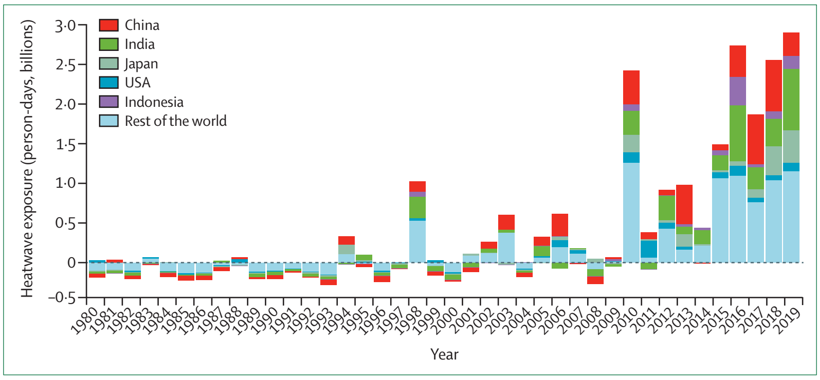

Figure 1: **Change in days of heatwave exposure relative to the 1986–2005 baseline in people older than 65 years**
The dotted line at 0 represents baseline.

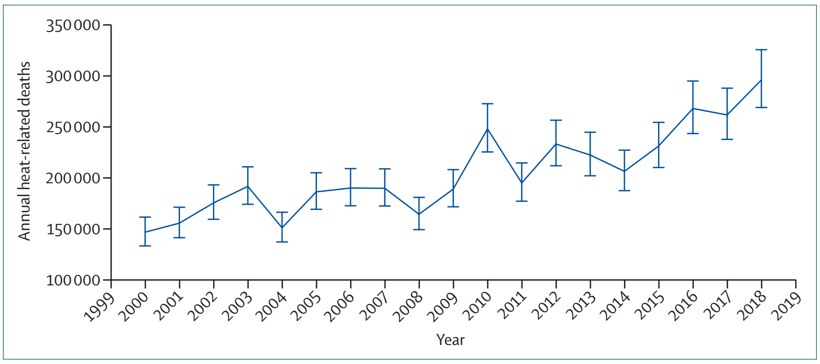

Figure 2: **Global heat-related mortality for populations older than 65 years**
The error bars were calculated on the basis of the uncertainty range of the exposure-response function, as described by Honda and colleagues.[35]

make use of the latest climate data and a hybrid population dataset.[32–34] This indicator has undergone several additional improvements to best capture heatwave exposure in every region of the world, including an improved definition of heatwave, the quantification of exposure days to capture changing frequency and duration, and improved estimates of demographic breakdown (appendix pp 6–11).

Indicator 1.1.3: heat-related mortality—headline finding: from 2000 to 2018, heat-related mortality in people older than 65 years increased by 53·7% and, in 2018, reached 296 000 deaths, the majority of which occurred in Japan, eastern China, northern India, and central Europe

This metric, newly created for the 2020 report, tracks global heat-related mortality in populations older than 65 years. By use of methods originally described by WHO, this indicator applies the exposure-response function and optimum temperature described by Honda and colleagues[35] to the daily maximum temperature exposure of the population older than 65 years to estimate the attributable fraction and thus the heat-related excess mortality.[36] As with indicator 1.1.2, data on daily maximum temperature were taken from the European Centre for

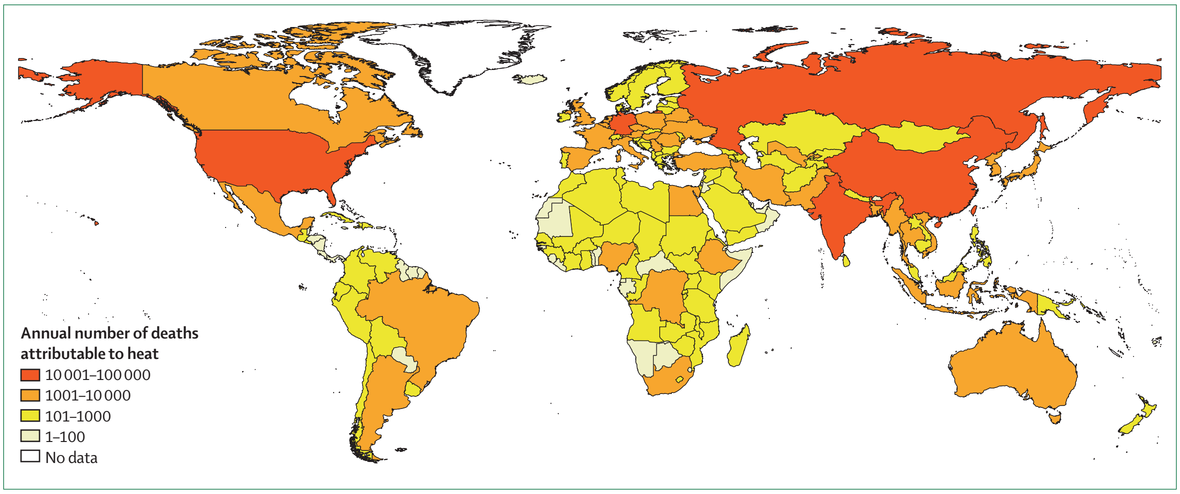

Figure 3: Annual heat-related mortality in the population older than 65 years averaged from 2014 to 2018

	Billions of work hours lost in 2000 (n=199·0)	Billions of work hours lost in 2019 (n=302·4)	Work hours lost per person in 2019
Global	199·0	302·4 (100·0%)	52·7
India	75·0	118·3 (39·1%)	111·2
China	33·4	28·3 (9·4%)	24·5
Bangladesh	13·3	18·2 (6·0%)	148·0
Pakistan	9·5	17·0 (5·6%)	116·2
Indonesia	10·7	15·0 (5·0%)	71·8
Vietnam	7·7	12·5 (4·1%)	160·3
Thailand	6·3	9·7 (3·2%)	164·4
Nigeria	4·3	9·4 (3·1%)	66·7
Philippines	3·5	5·8 (1·9%)	71·4
Brazil	2·8	4·0 (1·3%)	23·3
Cambodia	1·7	2·2 (0·7%)	202·2
USA	1·2	2·0 (0·7%)	7·1
Mexico	0·9	1·7 (0·6%)	17·4
Rest of the world	28·7	58·3 (19·3%)	27·5

Data are n or n (%). For these estimates, all agricultural and construction work was assumed to be in the shade or indoors—the lower bounds of potential work hours lost. Work hours lost per person were estimated for the population older than 15 years.

Table 1: Potential heat-related work hours lost

Medium-Range Weather Forecasts' fifth reanalysis (ERA5) and gridded population data were taken from a hybrid of the National Aeronautics and Space Administration's gridded population of the world (version four) and the Inter-Sectoral Impact Model Intercomparison Project, with full methodology described in the appendix (pp 12–13).[32–34]

This indicator estimates that the global average heat-related mortality per year in people older than 65 years has increased by 53·7% from 2000–04 to 2014–18, with a total of 296 000 deaths in 2018 (figures 2, 3). With the largest populations, China (62 000 deaths) and India (31 000 deaths) had the most deaths in 2018, followed by Germany (around 20 200 deaths), the USA (almost 19 000 deaths), Russia (18 600 deaths), and Japan (around 14 200 deaths). At more than 104 000 deaths, the European region was the most affected of the WHO regions. Importantly, the effects of temperature on mortality vary by region and are modified by local factors, including population urban green space and inequality, both within and between countries.[37,38] Work has begun to develop a future form of this indicator, which builds in more localised exposure-response functions as these functions become available.

Indicator 1.1.4: change in labour capacity—headline finding: rising temperatures were responsible for an excess of 100 billion potential work h lost globally in 2019 compared with those lost in 2000, with India's agricultural sector among the worst affected

Indicator 1.1.4 tracks the effects of heat exposure on working people, with impact expressed as potential work hours lost.[39] This indicator has been updated to capture construction, service, manufacturing, and agricultural sectors, and used climate data from the ERA5 models, with methods and data described in full previously and in the appendix (pp 13–16).[33,40–43]

Across the globe, a potential 302 billion work h were lost in 2019, which is 103 billion h more than that lost in 2000. 13 countries represented 244·1 billion (80·7%) of the 302·4 billion global work h lost in 2019 (table 1), with India having the greatest total loss and Cambodia having the highest per-capita loss of any country. In many countries in the world, agricultural workers see the worst of these effects, whereas, in high-income countries, such as the USA, the burden is often on those in the construction sector.

Indicator 1.2: health and extreme weather events

Extreme weather events, including wildfires, floods, storms, and droughts, affect human health in various

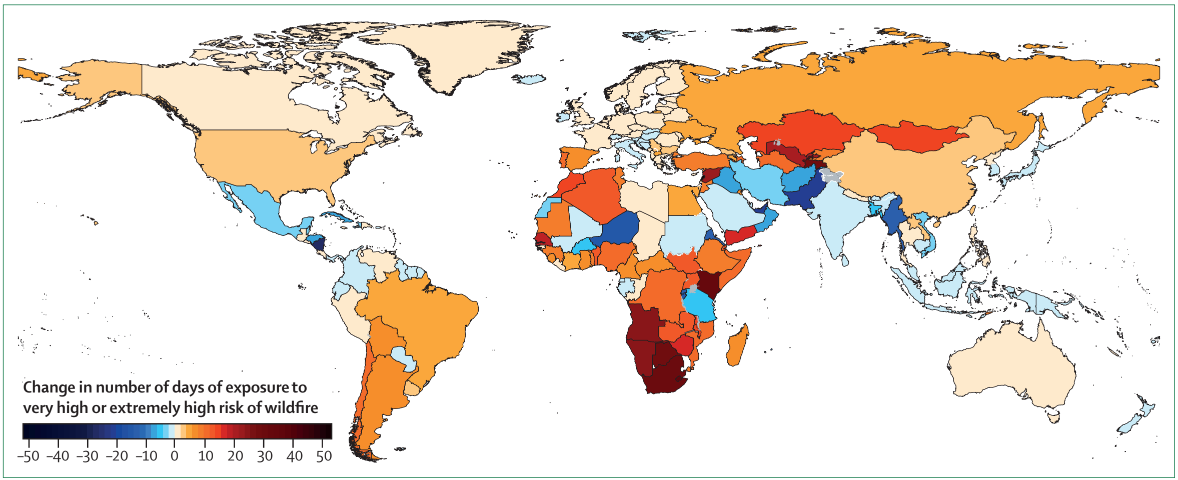

Figure 4: **Population-weighted average changes in the number of days of exposure to very high or extremely high risk of wildfire in 2016–19 compared with 2001–04**

Large urban areas with a population density of 400 people per km² or more are excluded. Wildfire risk is based on the Fire Danger Index, which rates risk on a scale from 1 to 6 (1 is very low; 2 is low; 3 is medium; 4 is high; 5 is very high; and 6 is extremely high). The higher the number, the more favourable the meteorological conditions are to trigger a wildfire.

ways, with the frequency and intensity of such events shifting as a result of climate change. Death and injury as a direct consequence of an extreme event are often compounded by effects that are mediated through the environment—eg, the exacerbation of respiratory symptoms from wildfire smoke and the spread of vector-borne and water-borne diseases following a flood or drought. Impacts are also mediated through social systems—eg, the disruption to health services and the mental ill health that can be caused by storms and fires.[3,44] The following indicators track the risk and exposure of the population to wildfires, changes in meteorological flood and drought, and the lethality of extreme weather events.

Indicator 1.2.1: wildfires—headline finding: in 114 countries, there was an increase in the number of days people were exposed to very high or extremely high risk of danger from fire in 2016–19 compared with 2001–04. This increased risk translated into an increase in population exposure to wildfires in 128 countries

For the 2020 report, analysis on the effects of wildfires has been developed to track the average number of days people are exposed to very high or extremely high risk (figure 4) of wildfire annually and the change in actual population exposure to wildfires across the globe. The indicator uses both model-based risk to wildfires and satellite-observed exposure. Climatological wildfire risk was estimated by combining daily very high or extremely high wildfire risk (a fire danger index score of 5 or 6) with climate and population data for every $0 \cdot 25° \times 0 \cdot 25°$ global grid cell.[32,45] For wildfire exposure, satellite-observed active fire spots were detected by use of the Moderate Resolution Imaging Spectroradiometer, and then aggregated and spatially joined with gridded population data on a global grid with a resolution of 10 km, with urban areas excluded.[32,46] A full description of the methodology can be found in the appendix (pp 17–18).

Compared with the period 2001–04, there was an increase in the risk of wildfire in 114 (58%) of 196 countries in 2016–19, with the largest increases occurring in Lebanon, Kenya, and South Africa (figure 4). Considering area-weighted, rather than population-weighted change, Australia, devastated by the 2019–20 fire season, had one of the largest increases in wildfire risk. During 2016–19, this increased risk translated into an additional 194 000 daily exposures to wildfires per year around the world, and an increase in population exposure to wildfires in 128 countries, compared with 2001–04. Driven by the record breaking fires in 2017 and 2018, the USA saw one of the largest increases globally, with more than 470 000 additional daily exposures to wildfires per year occurring in 2016–19 compared with 2001–04.

Indicator 1.2.2: flood and drought—headline finding: in 2018, the global land surface area affected by excess drought was more than twice that of a historical baseline

Climate change alters hydrological cycles, tending to make dry areas drier and wet areas wetter.[3] By altering rainfall patterns and increasing temperatures, climate change affects the intensity, duration, and frequency of drought events.[3,47] Drought poses multiple risks for health, threatening drinking water supplies and sanitation, and crop and livestock productivity, enhancing the risk of wildfires, and potentially leading to forced migration.[48] Additionally, altered precipitation patterns increase the risk of localised flood events, resulting in direct injury, the spread of infectious diseases, and impacts on mental health.[49]

In the 2020 report, meteorological drought is tracked by use of the standardised precipitation evapotranspiration index, which considers both precipitation and temperature, For more on the **methods and data for this analysis** see https://emdat.be/

and the effect of temperature on the loss of soil moisture. This index measures significant increases in the number of months of drought compared with an extended historical baseline (1950–2005) to account for periodic variations such as those generated by the El Niño Southern Oscillation.[50] A full explanation of the methodology and additional analysis are in the appendix (pp 19–21).

In 2018, there was a larger number of exceptional drought events affecting all populated continents and the global land surface area affected by an excess number of months in drought was more than twice that of the historical baseline. Areas that saw unusually high numbers of months with excess drought in 2018 included Europe, the Eastern Mediterranean region, and, specifically, Mongolia.

Indicator 1.2.3: lethality of extreme weather events—headline finding: from 1990 to 2019, the long-term, increasing trends in the number of weather-related disasters were accompanied by an increase in the number of people affected by these disasters in countries where health-care expenditure had reduced or had minimally increased during 2000–17

The links between climate change and the health effects of extreme weather events are presented in two ways for this indicator. The first part studies long-term trends in the occurrence of such events, along with changes in the number of people affected, and the resultant mortality. The methods and data for this analysis are similar to those used in previous reports and are described in full in the appendix (pp 22–24).[51] Recognising that an increase in the variability and intensity of these events is also expected, the second part considers the attribution of individual extreme weather events to climate change, and the effects that a selection of events have had on the health of populations (table 2, panel 3).

From 1990 to 2019, there were clear, significant, increasing trends in the number of occurrences of weather-related disasters, but no significant difference in the number of people affected per event or the number of deaths per event. Within the subset of countries that had a reduction, or a minimal increase in, health-care expenditure from 2000 to 2017, a significant increase in the number of people affected by extreme weather events was identified. By contrast, in countries with the greatest increase in health-care expenditure in 2000–17, the number of people affected by extreme weather events decreased between 1990 and 2019, despite an increasing frequency of events. One possible explanation for this finding could be the adaptive effects of health system strengthening. This

	Anthropogenic influence increased event likelihood or strength	Anthropogenic influence decreased event likelihood or strength	Anthropogenic influence not identified or uncertain
Heat (36 studies; 32 events)	Events ending in 2015 in India, Pakistan, China, Indonesia, Europe,[8,52] Egypt, Japan, southern India and Sri Lanka, Australia, and worldwide;[8,53] in 2016 in southern Africa, Thailand, Asia, and worldwide; in 2017 in Australia,[54] the USA, South Korea, western Europe,[55] China, and the Euro-Mediterranean region; in 2018 in northeast Asia, the Iberian Peninsula, and Europe; in 2019 in France[56] and western Europe;[57] and in 2020 in Australia[58]	..	Events ending in 2015–16 in India[59]
Cold and frost (nine studies; eight events)	Events ending in 2016 in Australia	Events ending in 2015 in the USA; in 2016 in China; and in 2018 in North America[60] and the UK	..
Drought and reduced precipitation (26 studies; 24 events)	Events ending in 2015 in the USA, Canada, Ethiopia, Indonesia, and Australia; in 2016 in southern Africa and Thailand; in 2017 in east Africa, the USA, and China; and in 2018 in South Africa,[61] China, and the USA	..	Events ending in 2015 in Brazil,[62] Nigeria, and Ethiopia;[63] in 2016 in Brazil, the USA, Somalia,[64] and western Europe; in 2017 in Kenya[65] and the USA; and in 2019 in Australia[58]
Wildfire (five studies; six events)	Events ending in 2015 in the USA; in 2016 in Australia and western North America; in 2018 in Australia; and in 2020 in Australia[58]	..	Events ending in 2017 in Australia
Heavy precipitation and flood (23 studies; 19 events)	Events ending in 2015 in China and the USA; in 2016 in France,[66] China, and Louisiana (USA);[67] in 2017 in Bangladesh, Peru, Uruguay, and China; and in 2018 in the USA and Japan[6,68]	Events ending in 2018 in China	Events ending in 2015 in India; in 2016 in Germany[66] and Australia; in 2017 in Bangladesh;[69] and in 2018 in Mozambique, Zimbabwe and Zambia, Australia, India,[70] and China*
Storms (eight studies; eight events)	Events ending in 2015 in the UK[71] and the western north Pacific;[72] in 2017 in the USA;[73] in 2018 in the USA;[74] and in 2019 in the USA[75]	..	Events ending in 2016 in the USA and in 2018 in western Europe[76]
Marine heat and melting sea ice (13 studies; ten events)	Events ending in 2015 in the northern hemisphere; in 2016 in the USA, Australia, the Coral Sea,[7,77] the North Pole,[7,78] the Gulf of Alaska and the Bering Sea, and the central equatorial Pacific; and in 2018 in the Tasman Sea and the Bering Sea	..	Events ending in 2015 in the central equatorial Pacific and in 2016 in the eastern equatorial Pacific
Total studies	81	6	27
Total events	76	5	28

Events have been listed according to the year in which they ended. In some countries and regions, multiple events in the same year were studied. References were gained from papers published in the *Bulletin of the American Meteorological Society*,[5–8] or otherwise are listed separately. *Anthropogenic influence had varied effects.

Table 2: **Detection and attribution studies linking extreme weather events to climate change from 2015 to 2020**

relationship will be further explored in future reports from the *Lancet* Countdown by considering variables, such as expenditure for specific health-care functions and excess deaths, in addition to the immediate event-related deaths.

Indicator 1.3: climate-sensitive infectious diseases

Indicator 1.3.1: climate suitability for infectious disease transmission—headline finding: changing climatic conditions are increasingly suitable for the transmission of numerous infectious diseases. From 1950 to 2018, the global climate suitability for the transmission of dengue increased by 8·9% for Aedes aegypti *and 15·0% for* Aedes albopictus*. In 2015–19, suitability for malaria transmission in highland areas was 38·7% higher in the African region and 149·7% higher in the Western Pacific region compared with a 1950s baseline*

Climate change is affecting the risk to humans and the distribution of many infectious diseases, including vector-borne, food-borne, and water-borne diseases.[3] By use of three different models, this indicator tracks the change in climate suitability for the transmission of infectious diseases of particular global importance: dengue, malaria, and pathogenic *Vibrio* bacteria (ie, *Vibrio parahaemolyticus*, *Vibrio vulnificus*, and non-toxigenic *Vibrio cholerae*). Temperature-driven, process-based mathematical models were used to capture the change in vectorial capacity of *A aegypti* and *A albopictus* for the transmission of dengue compared with a 1950s baseline.[94] Change in the climate suitability for *Plasmodium falciparum* malaria was modelled on the basis of empirically derived thresholds of precipitation, temperature, and relative humidity and compared with a 1950s baseline.[94] Highland areas (ie, those ≥1500 m above sea level) are highlighted in the model because increasing temperatures are eroding the effect altitude has as a barrier to malaria transmission,

For more on **climatic suitability** see https://climexp.knmi.nl/

Panel 3: Quantifying the links between climate change, human health, and extreme events

Formal statistical methods, grouped as detection and attribution studies, are already used widely in other sectors, and are increasingly deployed to quantify the extent to which climate change has had observed impacts on population health and health systems.[79–81] However, detection and attribution studies focusing on the changing likelihood and intensity of extreme events are generally limited to meteorological events in high-income and upper-middle-income countries. Further development of this body of literature offers an essential and unique way of improving understanding of current impacts and future risks of climate change on lives and livelihoods, guiding evidence-based management and adaptation. The following three case studies illustrate the linkage of detection and attribution studies of meteorological events to the resulting health impacts.

1. Reduced sea ice in the Arctic region

The Arctic region is warming two to three times faster than the global annual average, with observable impacts for Arctic communities, but limited data on the health consequences.[82] Extreme weather events, shifting migration patterns, and warmer and shorter winters now threaten food security and vital infrastructure.

The winter of 2017–18 heralded warm temperatures and an extreme low ice year in the Bering Sea.[83] The extent of sea ice was the lowest in recorded and reconstructed history: an estimated two in 1800 year event considering preindustrial climate forcing according to one study.[84] This study also suggested that climate change was responsible for 90% of the attributable risk, and that this extent of sea ice might become the mean within 20 years.[84]

This low ice year had multiple detrimental effects on communities in western Alaska, USA, although the health impacts have rarely been measured. These communities generally depend on sea ice for transportation, hunting and fishing, coastal buffering from storms, and a host of other ecosystem services. During this period of record low sea ice, a range of events occurred, including a loss of power, and damage to the water treatment plant, in Little Diomede (an Alaskan island) and a fatal accident that resulted from open waterholes along a previously frozen travel corridor on the Kuskokwim River.[85–87]

2. Northern European heatwaves in 2018 and 2019

During the summer of 2018, parts of northern Scandinavia experienced record breaking daily temperatures that were more than 5°C warmer than those in 1981–2010, an occurrence that evidence suggests was made five times more probable as a result of climate change.[88] In Sweden, the Public Health Agency estimated an excess mortality of 750 deaths between July and August, 2018, with more than 600 of these attributed to higher temperatures, when compared with the same weeks in 2017.[89]

Countries across western Europe and Scandinavia again experienced record breaking temperatures in 2019, with the temperatures in several countries exceeding 40°C for 3–4 days during June and July. Attribution studies suggest climate change was responsible for a ten times increase in the likelihood of the event occurring, and a 1·2–3·0°C increase in the temperature of these events, with almost 1500 deaths in France and 400 deaths in the Netherlands occurring because of these events.[57,90,91]

3. Japan heatwave of 2018

The summer of 2018 in Japan saw a combination of a national emergency resulting from extreme precipitation followed closely by record breaking temperatures. The event had roughly a 20% probability of occurring in today's world compared with a probability of 0% in a world without climate change.[92,93] Another attribution study compared modest and extreme heatwave days with a 1941–79 baseline, concluding that the probability of the defined heatwave event was 1·5 times higher for 1980–2018 and 7·0–8·0 times higher for 2019–50. This hot summer had large health implications. In 2018, there were an estimated 14 200 heat-related deaths in the population in Japan aged more than 65 years—more than 3000 more deaths than the previous record set in 2010, and 8100 more than the 2000–04 average (indicator 1.1.3).

which has resulted in more favourable conditions in densely populated highland areas, as seen in Ethiopia.[95] In the case of pathogenic *Vibrio* spp, which cause a range of human infections, including gastroenteritis, wound infections, sepsis, and cholera, 2019 and 2016–19 average climate suitability were compared with a 1980s global baseline and between one region each in Europe (the Baltics), the Atlantic Northeast coast of the USA, and the Pacific Northwest coast of North America.[96–98] Full descriptions of the context of these diseases, the methodology of the models, and additional analysis can be found in the appendix (pp 25–33).

Climate suitability for disease transmission increased globally for all diseases tracked. 2018 was particularly favourable for the transmission of dengue, with a global rise in vectorial capacity of 8·9% for *A aegypti* and 15·0% for *A albopictus* compared with a 1950s baseline (figure 5). Although average suitability for dengue remained low in Europe, 2018 was the most suitable year yet recorded for both vector species in this region, with a change from the 1950s baseline of 25·8% for *A aegypti* and 40·7% for *A albopictus*. There have been significant increases in the environmental suitability for the transmission of falciparum malaria in highland areas of four of the five malaria endemic regions, with an increase of 38·7% in the African region and 149·7% in the Western Pacific region in 2015–19 compared with the 1950s baseline (figure 5). The coastal area suitable for *Vibrio* infections in the past 5 years has increased at northern latitudes (40–70° N) by 50·6% compared with a 1980s baseline. Regionally, the area of coastline suitable for *Vibrio* spp has increased by 61·2% for the Baltics and 98·9% for the Atlantic Northeast. In 2019, for the second consecutive year, the entirety of the Baltic coastline was suitable for the transmission of *Vibrio* bacteria.

Indicator 1.3.2: vulnerability to mosquito-borne diseases—headline finding: following a sharp decline from 2010 to 2016, 2016–18 saw small up-ticks in national vulnerability to dengue outbreaks in four of six WHO regions; further data are required to establish a trend

As discussed, climate change is expected to facilitate the expansion of *Aedes* mosquito vectors that transmit dengue. Improvements in public health services might counteract these threats in the short-to-medium term; however, climate change will continue to make such efforts increasingly difficult and costly.[99] This indicator tracks vulnerability to mosquito-borne disease by combining data from indicator 1.3.1 on vectorial capacity for the transmission of dengue with the core capacities of countries' health-care systems, as outlined by WHO's International Health Regulations, which have been

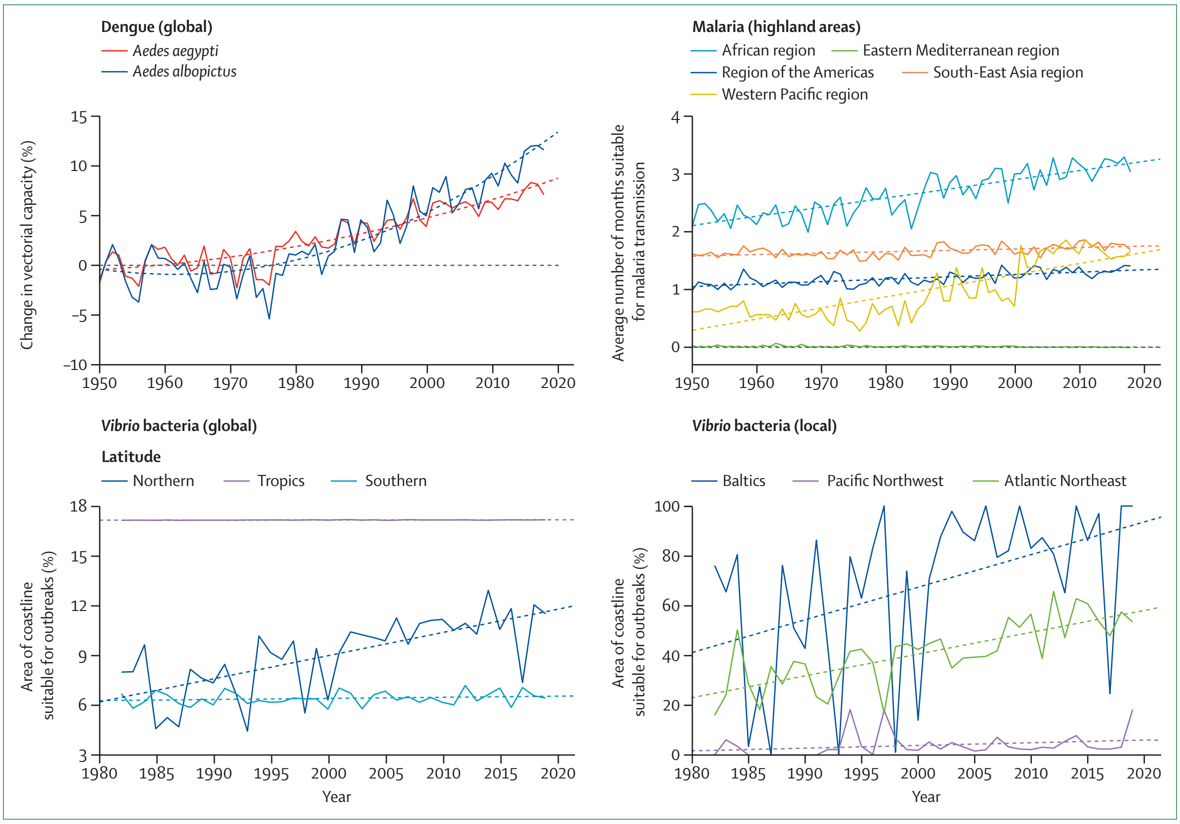

Figure 5: **Change in climate suitability for infectious diseases**
Solid lines represent the annual change. Dashed lines represent the trend since 1950 (for dengue and malaria) and 1982 (for *Vibrio* bacteria).

shown to be effective predictors of protection against disease outbreak.[100] The methods used here remain unchanged from previous reports and are described in full in the appendix (pp 33–35).[94,101]

From 2010 to 2016, vulnerability to mosquito-borne diseases declined substantially for the four most vulnerable WHO regions (the Western Pacific region, the African region, the South-East Asia region, and the region of the Americas), reflecting considerable improvements in their core health capacities. However, from 2016 to 2018, this trend began to halt, and then reversed, with further data required to confirm any long-term shift.

Indicator 1.4: food security and undernutrition

Although the global food system still produces enough to feed a growing world population, poor management and distribution has resulted in a paucity of progress on the second sustainable development goal on hunger. The global number of undernourished people is projected to increase to more than 840 million in 2030.[102]

Climate change threatens to exacerbate this crisis further, with rising temperatures, climatic shocks, and ground level ozone affecting crop yields, and sea surface temperature and coral bleaching affecting marine food security.[3] These effects will be experienced unequally, disproportionately impacting countries and populations already facing poverty and malnutrition, and exacerbating existing inequalities. The following two indicators monitor these changes, tracking the change in crop yield potential and sea surface temperature.

Indicator 1.4.1: terrestrial food security and undernutrition—headline finding: from 1981 to 2019, crop yield potential for maize, winter wheat, soybean, and rice has followed a consistently downward trend, with reductions relative to baseline of 5·6% for maize, 2·1% for winter wheat, 4·8% for soybean, and 1·8% for rice

For this indicator, crop yield potential was characterised by crop growth duration (the time taken to reach a target sum of accumulated temperatures) during the crop's growing season. If this sum is reached early, then the crop matures too quickly, and yields are lower than average. Therefore, a reduction in crop growth duration represents a reduction in crop yield potential.[103] This indicator tracks the change in crop growth duration for four key staple crops: maize, wheat, soybean, and rice at the individual country level and globally by use of a similar approach to previous reports, which has been improved to provide more accurate local estimates and now uses ERA5 data.[34]

The yield potential of maize, winter wheat, soybean, and rice continues to decline globally and for most individual countries. This indicator shows that continuing to increase or even maintain global production is increasingly difficult because of the changing climate. In 2019, the reduction in crop growth duration relative to baseline was 5·6% (7·9 days) for maize, 2·1% (4·9 days) for winter wheat, 4·8% (6·1 days) for soybean, and 1·8% (2·0 days) for rice (figure 6). For maize, most countries in the world saw a decline in crop growth duration, with large areas of South Africa, the USA, and Europe having reductions in their crop growing seasons of more than 20 days—a reduction of more than 14% of the 1981–2010 global average crop duration. This reduction compounds the current negative impacts of weather and climate shocks, made more frequent and more extreme by climate change, that are hampering localised efforts to reduce undernutrition.

Indicator 1.4.2: marine food security and undernutrition—headline finding: average sea surface temperature rose in 46 of 64 investigated territorial waters between 2003–07 and 2015–19, presenting a risk to marine food security

A large proportion of the global population, especially in low-income and middle-income countries, is highly dependent on fish sources of protein.[104] Additionally,

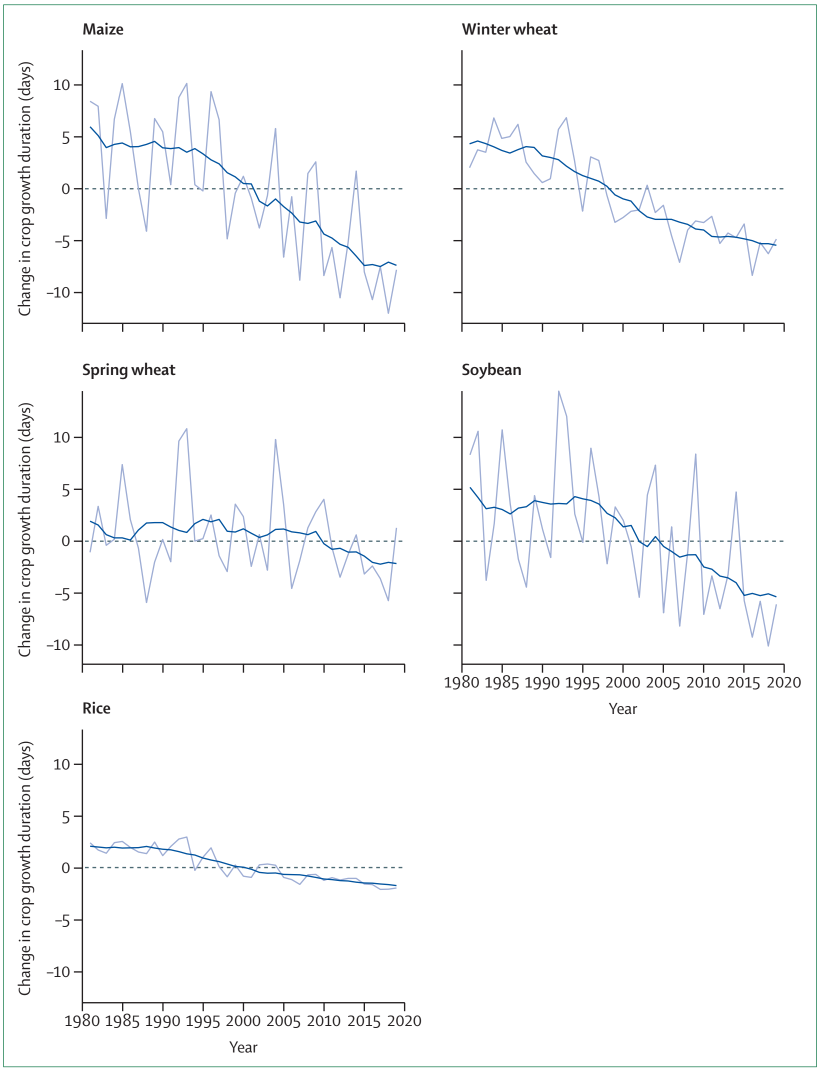

***Figure 6:* Change in crop growth duration relative to the 1981–2010 global average**

The grey line represents the annual global area-weighted change. The blue line represents the running mean over 11 years (5 years forward and 5 years backward). The dashed line represents the 1981–2010 baseline.

omega-3 is important in the prevention of cardiovascular disease; worldwide, 1·4 million deaths due to cardiovascular disease in 2017 were attributed to diets low in seafood omega-3 fatty acids.[105] Sea surface temperatures, rising as a consequence of climate change, impair marine fish capacity and capture through numerous mechanisms, including the bleaching of coral reefs and reduced oxygen content, putting populations at risk.[106] This indicator tracks sea surface temperatures in the territorial waters of 64 countries located in 16 fishing areas of the Food and Agriculture Organization of the UN.[107–109]

Comparing the time periods 2003–07 and 2015–19, average sea surface temperatures increased in 46 of the 64 investigated areas, with a maximum increase of 0·87°C observed in the territorial waters of Ecuador. Farm-based fish consumption has increased consistently during the past four decades, with a corresponding decline in capture-based fish consumption, exacerbated in part by these evolving temperature trends.[106] Between 1990 and 2017, diets low in seafood omega-3 increased by 4·7% at a global level, with more than 70% of countries seeing a rise in exposure to this risk factor, increasing the risk of mortality from cardiovascular disease.

Indicator 1.5: migration, displacement, and rising sea levels

Headline finding: without intervention, between 145 million people and 565 million people living in coastal areas today will be exposed to, and affected by, rising sea levels in the future

Through its impacts on extreme weather events, land degradation, food and water security, and rising sea levels, climate change is influencing human migration, displacement, and relocation with consequences to human health.[110,111] Left unabated, estimates for the average global sea level rise by the end of the century range from 1·0 –2·5 m, with projections rising as high as 5 m when taking into account regional and local coastal variation.[112,113] This indicator, newly introduced for the 2020 report, tracks current population exposure to future rising sea levels and provides a measure of the extent to which health or wellbeing are considered in national policies that connect climate change and human mobility.

The exposure of populations to average global sea level rises of 1 m and 5 m was measured by use of a coastal digital elevation model and current population distribution data, with a full description of this new indicator outlined in the appendix (pp 51–57).[114,115] Based on the population distributions of 2017, 145 million of the world's population could be exposed to an average global sea level rise of 1 m, a value rising to 565 million people with an average sea level rise of 5 m (figure 7). A range of health impacts related to rising sea levels are likely to occur, with changes in water and soil quality and supply, livelihood security, disease vector ecology, flooding, and saltwater intrusion.[116,117] The health consequences of these effects will depend on various factors, including the options of both in situ and migration adaptation.[118–120] These effects could be moderated if countries begin to prepare. Considering preparation for climate change-related migration, national policies that connect climate change and migration were also assessed as part of this indicator. Up to Dec 31, 2019, there were 43 national policies across 37 countries that connected climate change and migration, and 40 of these policies across 35 countries explicitly referenced health or wellbeing. The policies commonly accepted that mobility could be domestic and international, although mention of immobility was sparse.

Conclusion

The indicators that comprise section 1 of the 2020 report describe a warming world that is affecting human health both directly and indirectly and putting already vulnerable populations at a high risk. Metrics of exposure and vulnerability to extreme weather are complemented by trends of worsening global crop yield potential and increasing climate suitability for the transmission of infectious disease. Subsequent reports will continue to develop the methods and data underlying these indicators, with a particular focus on the creation of a new indicator on mental health, and the exploration of the gender dimensions of existing indicators.

Correlating climate change and mental health is challenging for several reasons, including local and global stigma and under-reporting, differences in health systems, and variations in cultural understandings of wellbeing. Partly because of this difficulty, the literature has focused on extremes of heat, with investigations reporting correlations between higher temperatures and heatwaves and the risk of violence or suicide. Proposed reasons for this association vary from the effects of disrupted sleep to short-term agitation.[121,122] Stronger evidence outlines the links between extreme weather events and mental ill health, with emerging research describing the effect of a loss of access to the environment and ecosystem services.[123]

Taken as a whole, the data described in section 1 provide a compelling justification for an accelerated response to climate change. There are clear limits to adaptation, necessitating increasingly urgent interventions to reduce greenhouse gas emissions. How communities, governments, and health systems will be able to moderate the impacts of a changing climate is discussed in section 2 and section 3.

Section 2: adaptation, planning, and resilience for health

With a growing understanding of the human costs of a warming climate, the need for adaptation measures to protect health is now more important than ever. The COVID-19 pandemic makes clear the challenges faced by health systems around the world resulting from large unexpected shifts in demand without sufficient adaptation or integration of health services across other sectors.[124] As

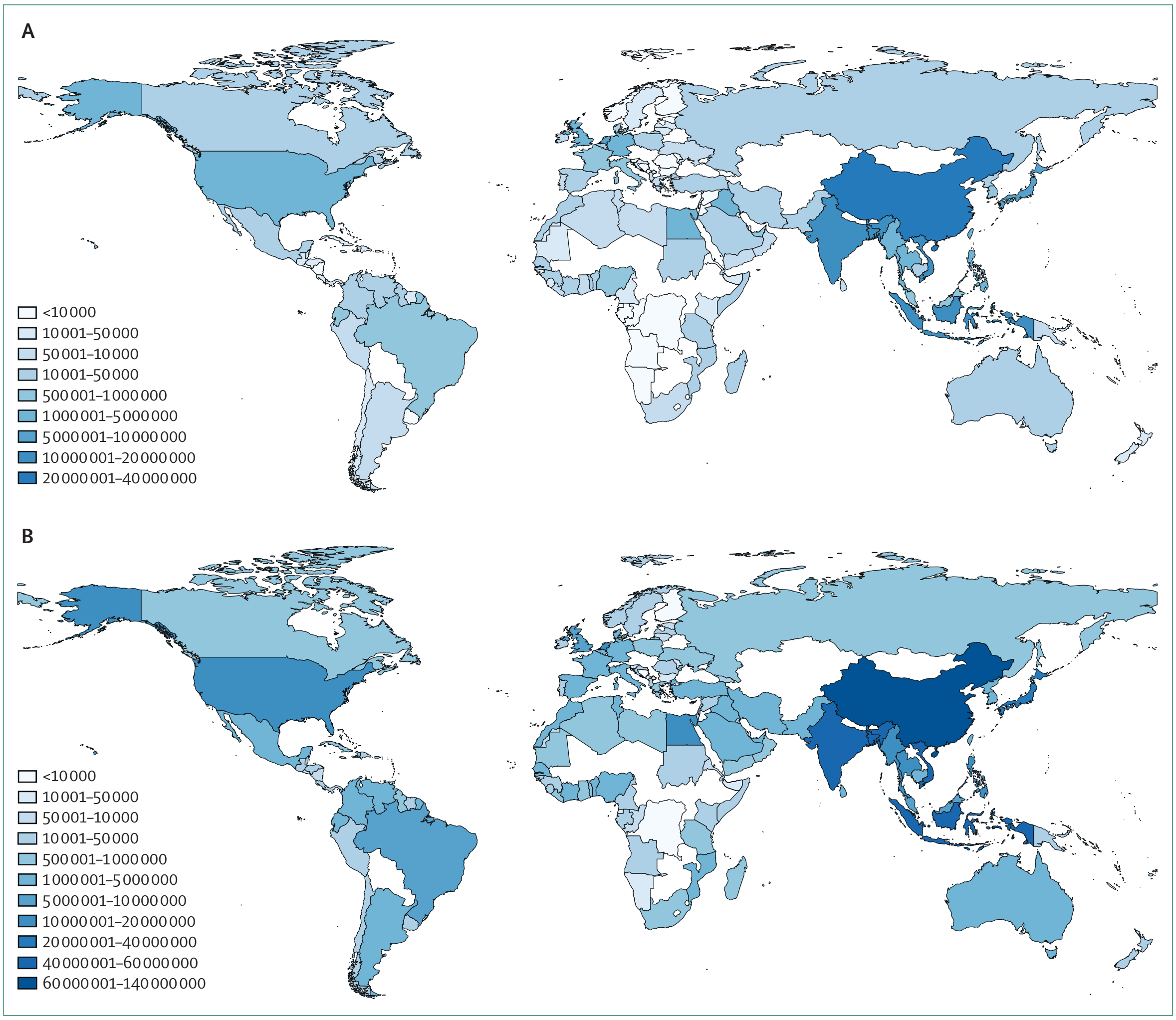

Figure 7: **Number of people exposed to 1 m and 5 m of global average sea level rise by country**
(A) 1 m. (B) 5 m.

this public health crisis continues, and is compounded by climate-attributable risks, rapid and proactive interventions are crucial to prepare for, and build resilience to, both the health threats of climate change and of pandemics.[125]

Heavily determined by regional hazards and the underlying health needs of populations, the implementation of adaptation and resiliency measures requires localised planning and intervention. National adaptation priorities must take into account subnational capacities, inequalities, and the local distribution of vulnerable populations. As health adaptation interventions are being increasingly introduced, evidence of their success often remains mixed.[126] Measuring the impact of these long-term interventions at the global scale presents particular challenges, and the indicators in this section aim to monitor the progress of health adaptation through the lens of the WHO Operational Framework for Building Climate Resilient Health Systems.[23] The adaptation indicators look beyond the health system to focus on the following domains: planning and assessment (indicators 2.1.1–2.1.3), information systems (indicator 2.2), delivery and implementation (indicators 2.3.1–2.3.3), and spending (indicator 2.4). As is often the case in adaptation, several of these indicators rely on self-reported data on adaptation plans, assessments, and services, which also presents challenges. Where possible, efforts have been made to validate these data.

Numerous indicators in this section have been further developed for the 2020 report and one new indicator is presented. The data on national health adaptation planning and assessments (indicators 2.1.1 and 2.1.2) has been presented in greater detail and calculations of the effectiveness of air conditioning as an intervention (indicator 2.3.2) have been improved by use of more recent evidence. The definition of health-related adaptation spending (indicator 2.4) has been expanded to capture activities that are closely related to health in various non-health sectors. Importantly, a new indicator, focusing on the use of urban green spaces as an adaptive measure with numerous health benefits, has been introduced in this year's report (indicator 2.3.3).

Indicator 2.1: adaptation planning and assessment

Adaptation planning and risk management is essential across all levels of government, with national strategy and coordination linked to subnational and local implementation and delivery.[3] In every case, risk assessments are an important first step of this process.

The following three indicators track adaptation plans and assessments at the national and city level by use of data from the WHO Health and Climate Change Survey and the CDP Annual Cities Survey.[127,128] Information on the data and methods for each are presented in the appendix (pp 58–61). Data from the WHO survey have not been updated for this year, and hence further qualitative analysis has been done to investigate the barriers to adaptation.

Indicator 2.1.1: national adaptation plans for health—headline finding: 50% of countries surveyed have developed national health and climate change strategies or plans. However, funding remains a key barrier to implementation of these strategies, with 9% of countries reporting to have the funds to fully implement their plans

51 (50%) of 101 countries surveyed have developed national health and climate change strategies or plans. National governments have identified financing as one of the main barriers to the implementation of these plans.[28,128] Of the 45 countries with plans and who reported on funding, only four (9%) reported having adequate national funding available to fully implement such strategies. This low proportion highlights the importance of access to international climate finance for governments from low-resource settings. Despite this importance, only 17 (49%) of 35 national health authorities from low-income and lower-middle-income countries reported having access to climate funds from bodies such as the Global Environment Facility, the Adaptation Fund, the Green Climate Fund, or other donors. The Green Climate Fund, which currently has not funded a single health sector project for the tenth year running, is now looking to align its programming to incorporate health and wellbeing co-benefits in light of, and in response to, COVID-19. Although not yet accredited to submit and implement projects, WHO became a Green Climate Fund readiness partner in 2020, giving WHO the ability to support countries in their efforts to develop health components of national adaptation plans and to strengthen health considerations related to climate change.

Another key barrier to the implementation of national health and climate strategies is a paucity of multisectoral collaboration within government. Progress on cooperation across sectors remains uneven, with 45 (45%) of 101 countries surveyed reporting the existence of a memorandum of understanding that outlines roles and responsibilities with respect to climate policy between the health sector and the water and sanitation sector. However, less than a third of the 101 countries had a similar cooperative agreement between the health sector and the agricultural (31 [31%]) or social service sectors (26 [26%]). Furthermore, only about a quarter of countries reported agreements between the health sector and the sectors for transport (25 [25%]), household energy (19 [19%]), or electricity generation (22 [22%]). These omissions represent an important missed opportunity to recognise the health implications of national climate policies and to promote activities that maximise health benefits, avoid negative health effects, and evaluate the associated health savings that might result.

Indicator 2.1.2: national assessments of climate change impacts, vulnerability, and adaptation for health—headline finding: 48 (48%) of 101 countries surveyed have assessed national vulnerability and adaptation for health, with further investment required to adequately fund these crucial components of health system resilience

Strengthening all aspects of a health system allows it to protect and promote the health of a population in the face of known and unexpected stressors and pressures. In the case of climate change, this strengthening requires a comprehensive assessment of current and projected risks and population vulnerability. This indicator focuses on vulnerability assessments at the national level and the barriers faced by national health-care systems.[128]

Similar to the scarcity of funding for health and climate change plans, vulnerability assessments for health are also under-resourced. Indeed, assessing vulnerability was among the top three adaptation priorities identified as being underfunded by national health authorities, alongside the strengthening of surveillance and early warning systems and broader research on health and climate change. This underfunding was reported to be particularly true for subnational assessments and for those designed to be particularly sensitive to the needs of vulnerable population groups.

Indicator 2.1.3: city-level climate change risk assessments—headline finding: in 2019, 605 (77%) of 789 global cities surveyed had either already completed or were currently undertaking climate change risk assessments, with 545 (67%) of 814 cities expecting climate change to seriously compromise their public health assets and services, a substantial increase from 2018

Cities are home to more than half of the world's population, produce 80% of global gross domestic product (GDP), consume two thirds of the world's energy, and represent a crucial component of the local adaptation response to climate change.[129] As such, this indicator captures cities that have undertaken a climate change risk or vulnerability assessment and expectations on the vulnerability of their public health assets. First presented in the 2017 report of the *Lancet* Countdown and since improved to include further questions specific to public health, data for this indicator are sourced from the Carbon Disclosure Project's 2019 survey of 789 global cities (a 33% increase in survey respondents from 2018).[127,130]

In 2019, 491 (62%) of 789 cities had completed an assessment of climate change risk or vulnerability, and a further 114 (28%) cities were either in the process of an assessment or will have completed one within the next 2 years. Although some selection bias probably exists, a growing number of risk assessments are being completed by cities in low-income countries (14 [64%] of 22 in 2019), highlighting the beginning of adaptation where adaptation is arguably most needed. The survey also revealed a core driving factor in these assessments—545 (67%) of 814 cities reported that their public health infrastructure would be seriously compromised by climate change.

Indicator 2.2: climate information services for health

Headline finding: the number of countries reporting that their meteorological services provide climate information to the health sector has continued to grow, increasing from 70 to 86 countries during the past 12 months

The use of meteorological services in the health sector is an essential component of adaptation. This indicator tracks the collaboration between these two parts of government by use of data reported by national meteorological and hydrological services to the World Meteorological Organization. Further detail is provided in the appendix (pp 62–64).

A total of 86 national meteorological and hydrological services of member states of the World Meteorological Organization reported providing climate services to the health sector, an increase of 16 from the 2019 report of the *Lancet* Countdown.[28] By WHO region, 19 of the countries reporting these climate services were from the African region, 16 were from the region of the Americas, seven were from the Eastern Mediterranean region, 23 were from the European region, eight were from the South-East Asia region, and 13 were from the Western Pacific region. Of the 86 positive respondents, 66 (77%) reported being highly engaged with their corresponding health service, alongside other sectors such as agriculture, water, and electricity generation. As detailed in indicator 2.1.1, multisector collaborations present governments with the opportunity to support an adaptation approach to the risks of climate change that is fully integrated.

Indicator 2.3: adaptation delivery and implementation

Indicator 2.3.1: detection, preparedness, and response to health emergencies—headline finding: in preparation for a multi-hazard public health emergency, 109 countries have reported medium-to-high implementation of a national health emergency framework

The International Health Regulations are an instrument of international law designed to aid the global community in preventing and responding to potential public health emergencies.[101] This indicator focuses on core capacity eight, which evaluates the degree to which countries have implemented a national health emergency framework by assessing levels of planning, management, and resource allocation.[101] The national health emergency framework applies to all public health events and emergencies, air pollution, extreme temperatures, droughts, floods, and storms. The core capacities of the International Health Regulations are also important components of the response to infectious disease threats, with similar capacities and functions considered when assessing preparedness to a pandemic such as the COVID-19 pandemic.[131] The results of this survey are provided in full in the appendix (pp 64–65).

In 2019, 166 (86%) of 194 WHO member states completed the assessment portion related to core capacity eight, 16 fewer than in 2018. Of these 166, 109 (66%) countries reported having medium-to-high degrees of implementation of multi-hazard preparedness and capacity, a 10% increase compared with 2018 data. The level of implementation varied by region. Medium-to-high levels were reported in 26 (90%) of 29 countries in the region of the Americas, 41 (87%) of 47 in the European region, 11 (85%) of 13 in the Western Pacific region, seven (64%) of 11 in the South-East Asia region, 12 (63%) of 19 in the Eastern Mediterranean region, and in only 12 (26%) of 47 countries in the African region. Despite these disparities, capacities have increased across all regions, and the global average increased from 59% in 2018 to 62% in 2019.

For the **country profile database by the World Meterological Organization** see https://cpdb.wmo.int/

Indicator 2.3.2: air conditioning: benefits and harms—headline finding: between 2016 and 2018, the world's air conditioning stock continued to rise, further contributing to climate change, air pollution, peak electricity demand, and urban heat islands, while also conferring protection against heat-related illness

Air conditioning represents one of numerous effective indoor cooling mechanisms for preventing heat-related illness and mortality.[132] However, in 2018, air conditioning accounted for an enormous 8·5% of total global electricity consumption, contributing to, if sourced from fossil fuels, emissions of carbon dioxide (CO_2) and fine particulate matter ($PM_{2·5}$), and ground level ozone formation, with the potential to leak hydrofluorocarbons that act as powerful greenhouse gases. On hot days, air conditioning can be responsible for more than half of peak electricity demand locally, and emits waste heat that contributes to the urban heat island effect.[133,134] Further research is needed to establish whether the overall harms of air conditioning outweigh the benefits. However, increased use of air conditioning in response to the warming climate could result in around 1000 additional deaths related to air pollution every summer in the eastern USA by 2050.[135]

International programmes and organisations, including Sustainable Energy for All, the Kigali Cooling Efficiency Program, and the International Energy Agency (IEA), are working to develop solutions to provide efficient indoor cooling that protect vulnerable populations against heat-related illness while minimising the health-associated harms. Such initiatives include designing buildings with improved insulation, energy efficiency measures, and improved ventilation, and increasing urban green space (detailed in indicator 2.3.3). Evidence suggests that simple electric fans with light water spraying could also be an effective stay-at-home measure against heatwaves in hot and humid regions during the COVID-19 pandemic.[136]

This indicator draws on data provided by the IEA and includes an improved calculation of the prevented fraction of deaths from air conditioning, making use of an updated meta-analysis that built on the previously available 2007 assessment of prognostic factors in heatwave-related deaths, with full detail described in the appendix (pp 66–69).[132,137]

Between 2016 and 2018, the world's air conditioning stock (residential and commercial) increased from 1·74 billion units to 1·90 billion units and the proportion of households with air conditioning increased from 31·1% to 33·0% (a 56·7% rise since 2000; figure 8). Correspondingly, the global prevented fraction of mortality related to heatwaves increased from 23·6% in 2016 to 25·0% in 2018. Global CO_2 emissions from electricity consumption due to air conditioning increased from 1·04 $GtCO_2$ in 2016 to 1·07 $GtCO_2$ in 2018 (2% of total global emissions), highlighting the need for sustainable cooling methods in the face of a warming climate.

Indicator 2.3.3: urban green space

Headline finding: urban green space is an important measure to reduce population exposure to heat; 9% of global urban centres had a very high or exceptionally high degree of greenness in 2019, and more than 156 million people were living in urban centres with concerningly low levels of urban green space

Access to urban green space provides benefits to human health by reducing exposure to air and noise pollution, relieving stress, providing a setting for social interaction and physical activity, and reducing all-cause mortality.[138,139] In addition, green space sequesters carbon and provides local cooling that disrupts urban heat islands, benefiting both climate change mitigation and heat adaptation. As access to green space can often disproportionately benefit the most privileged in society, it is important to consider how green spaces are designed and distributed to ensure safety and equitable access.[140,141]

This indicator, new in the 2020 report, quantifies exposure to urban green space for 2019 in the 468 urban centres of more than 1 million inhabitants, as defined by the Global Human Settlement programme of the European Commission.[142,143] Indicator 2.3.3 uses remote sensing of green vegetation through the satellite-based normalised difference vegetation index, which measures the reflectance signature of green plants in the visible red and near-infrared parts of the spectrum, providing an indication of the level of green coverage on the earth surface. The maximum normalised difference vegetation index for all seasons was used to define the average level of greenness of each urban area. A full description of the methodology can be found in the appendix (pp 70–72).

In 2019, only 42 (9%) of 468 global urban centres had very high to exceptionally high levels of greenness, notably including five capital cities—Colombo (Sri Lanka), Washington, DC (USA), Dhaka (Bangladesh), San Salvador (El Salvador), and Havana (Cuba; figure 9). Concerningly, 49 (10%) urban centres, home to more than 156 million people and including 21 capital cities, were at the opposite end of the spectrum, with very low levels of urban green space.[38]

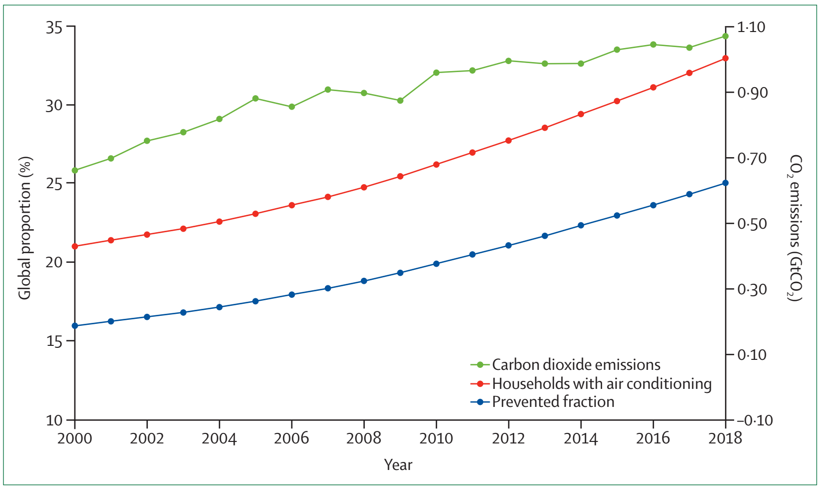

***Figure 8:* Frequency and effects of air conditioning**

Global proportion of households with air conditioning (red line), prevented fraction of heatwave-related mortality because of air conditioning (blue line), and CO_2 emissions from air conditioning (green line), from 2000 to 2018. CO_2=carbon dioxide. $GtCO_2$=gigatonnes of carbon dioxide.

Indicator 2.4: spending on adaptation for health and health-related activities

Headline finding: at $18·4 billion in 2018–19, global spending on health adaptation has increased to 5·3% of total spending on adaptation, while health-related spending has remained flat at approximately 28·4% of global adaptation spending from 2015 to 2019

As noted in the evaluation of national adaptation plans (indicator 2.1.1), inadequate financial resources pose the largest barrier to the implementation of adaptation measures. This indicator tracks spending on health and health-related adaptation within the Adaptation and Resilience to Climate Change dataset from the data research firm, kMatrix, which includes spend data from 191 countries.[144] Health-specific spending is that which occurs within the formal health-care sector. For the 2020 report, an enhanced definition of health-related spending was developed through an expert review workshop to more accurately categorise spending. The definition captures adaptation spending within other sectors (ie, agriculture and forestry, the built environment, disaster preparedness, energy,

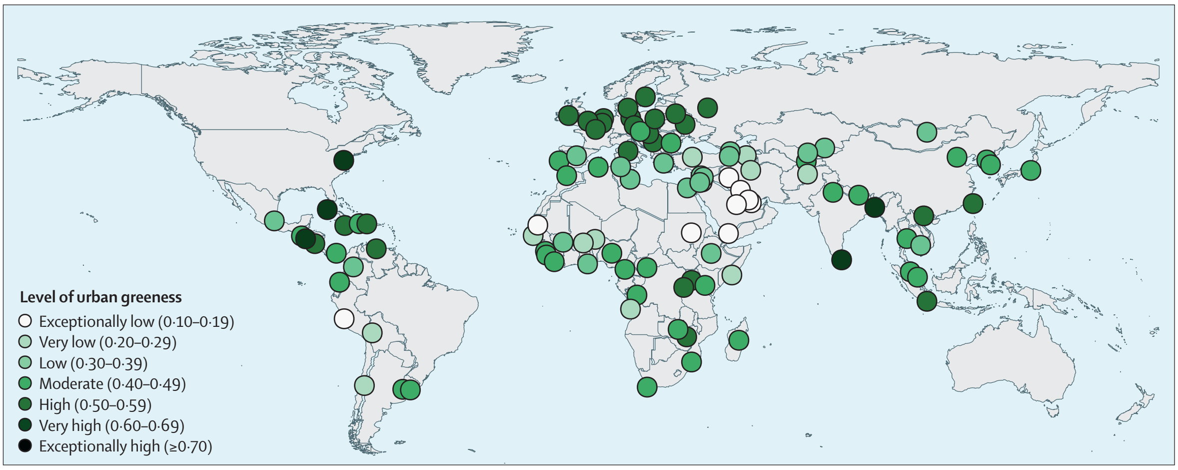

***Figure 9:* Urban greenness in capital cities with more than 1 million inhabitants in 2019**
Levels of urban greenness were quantified on the basis of the mean, population-weighted normalised difference vegetation index, which is a standard, satellite-based measurment to estimate vegetation and is on a scale of –1·0 to 1·0.

transportation, waste, and water) that have a direct impact on one or more of the basic determinants of health (ie, food, water, air, or shelter) and have been linked to health outcomes in the published literature. A full description of the methodology can be found in the appendix (pp 73–75).

Spending on climate change adaptation within the health-care sector increased by 12·7% to $18·4 billion in 2018–19 compared with data from 2017–18 (figure 10). Spending on health adaptation made up 5·3% of all adaptation spending globally in 2018–19, a share higher than 5% for the first time. The wider measure of spending on health-related adaptation increased by 7·2% to $99·9 billion from 2017–18 to 2018–19; however, as a share of global adaptation spending, spending on health-related adaptation has remained more or less constant (28·4% in 2015–16 and 28·5% in 2018–19).

Grouped by WHO region, spending for health adaptation in 2018–19 varied from $0·48 per capita in the African region to $5·92 per capita in the region of the Americas, remaining less than $1·00 per capita in the South-East Asia region. Again, looking more broadly at spending on health-related adaptation, a wider variation, ranging from $2·63 per capita in the African region to $30·82 per capita for the region of the Americas, was evident.

Conclusion

The indicators presented in this section continue to move in a positive direction, with growing recognition of the impacts of climate change within the health community. However, there is much more work to do, with a need to move from planning to implementation, and to better engage with other sectors of society in adaptation interventions (indicators 2.1.2, 2.1.2, and 2.2). The core capacity scores of the International

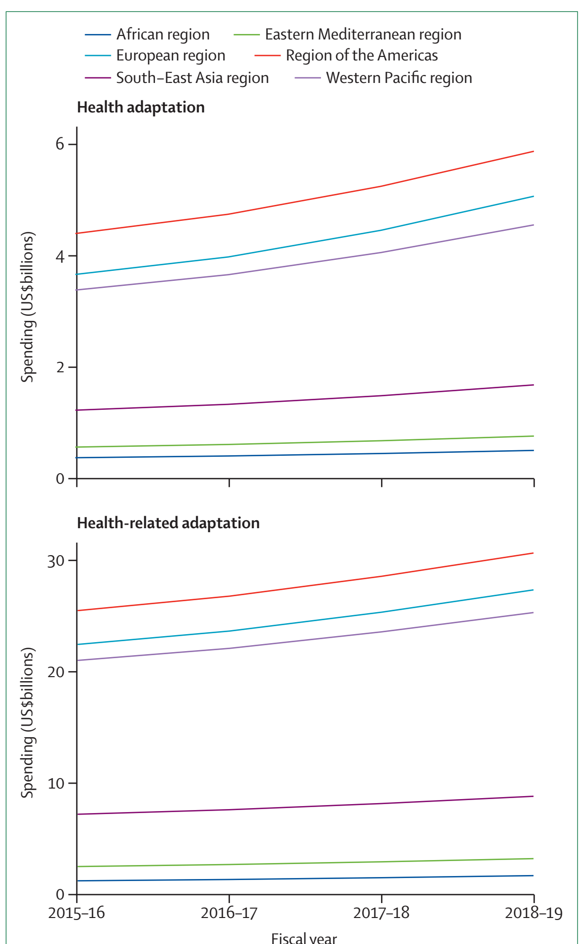

***Figure 10:* Adaptation and resilience to climate change spending by WHO Region**

Health Regulations show a need for support across many African and Eastern Mediterranean countries (indicator 2.3.1), requiring additional engagement and resources.

Global spending trends have shown promise in recent years for health and health-related adaptation (indicator 2.4); however, governments remain unable to fully implement their plans for national health adaptation (indicator 2.1.1). The findings here reiterate the need to strengthen underlying health systems and create multisectoral alignment to protect human health, particularly for the most vulnerable populations. COVID-19 has dramatically altered the pattern of health-care demand, with health systems restructuring services overnight.[145] Although the full impact of these changes is unclear, the rapid introduction of new online and telemedicine services brings many synergies with efforts to reduce the emissions of the health-care sector, and with those to increase the resilience of service delivery. As governments continue to respond to the public health and economic effects of the COVID-19 pandemic, it will be important to align these priorities and ensure that enhanced preparedness for future pandemics also confers an increased capacity to respond to climate change.

Section 3: mitigation actions and health co-benefits

In 2018, greenhouse gas emissions rose to an unprecedented 51·8 gigatonnes of CO_2 equivalent ($GtCO_2e$; 55·3 $GtCO_2e$ including land use change), with fossil fuel emissions from transport, power generation, and industry accounting for 37·5 $GtCO_2e$ (72%).[146] The vast majority of the growth in emissions, the economy, and the demand for energy occurred in low-income and middle-income countries, despite global economic headwinds.[147]

COVID-19 has had a profound effect on the global economy and on greenhouse gas emissions. Ongoing volatility makes the projections of any long-term effects challenging, although daily CO_2 emissions were 17% lower in April, 2020, than they were in April, 2019, with some countries having reductions in emissions of up to 26%.[148] Current estimates suggest that global emissions will fall by 8% in 2020 as a result of both the economic downturn and the restrictions to local and international travel.[21,148] As efforts to revitalise the economy take effect, aligning such interventions with those necessary to mitigate climate change will allow governments to generate a synergistic response, improving public health in the short term and in the long term.

If carefully planned and implemented, these interventions will yield major health benefits, underlining the importance of a “health in all policies” approach.[149,150] Highlighting this practice, the following section tracks efforts to mitigate climate change in the sectors most relevant to public health: power generation and air pollution (indicators 3.1.1–3.1.3 and 3.3); household energy and buildings (indicator 3.2); transport (indicator 3.4); diets and agriculture (indicators 3.5.1 and 3.5.2); and health care (indicator 3.6). New in the 2020 report are indicators of the national emissions from agricultural consumption (indicator 3.5.1) and the associated premature mortality from unhealthy and emissions-intensive diets (indicator 3.5.2). The methodologies of each of the existing indicators have also improved, particularly indicator 3.6, which, on the basis of feedback, has been revised to better estimate emissions from the health-care sector.

Importantly, this section must be interpreted with the understanding that enhanced ambition is urgently required, and that countries will need to increase the strength of their mitigation commitments within the Paris Agreement’s NDCs by a factor of three to limit warming to 2°C, and by a factor of five to limit warming to 1·5°C.[146]

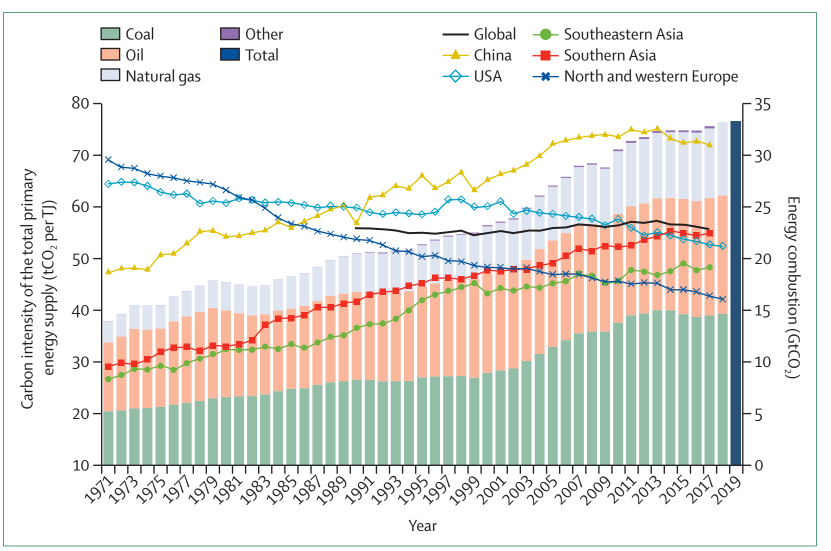

Figure 11: **Carbon intensity of the total primary energy supply for selected regions and countries and global CO_2 emissions by fuel type, 1971–2019**

Carbon intensity trends are shown by a trend line (primary axis) and global CO_2 emissions by stacked bars (secondary axis). This carbon intensity metric estimates the tCO_2 for each unit of total primary energy supplied (tCO_2 per TJ). For reference, the carbon intensity of fuels are as follows: coal, 95–100 tCO_2 per TJ; oil, 70–75 tCO_2 per TJ; and natural gas, 56 tCO_2 per TJ. CO_2=carbon dioxide. tCO_2=tonnes of carbon dioxide.

Indicator 3.1: energy system and health

Indicator 3.1.1: carbon intensity of the energy system—headline finding: the carbon intensity of the global primary energy supply has remained flat for the past three decades. Although in 2017 carbon intensity was at its lowest since 2006, it was still 0·4% higher than the levels in 1990

Because fossil fuel combustion in the energy system continues to be the biggest source of greenhouse gas emissions, mitigation in this area is key to meeting the commitments of the Paris Agreement. This indicator tracks the carbon intensity of the global energy system, expressed as the CO_2 emitted per terajoule of the total primary energy supply, with methods and data described in the appendix (p 76).[151,152]

The carbon intensity of the global energy system has barely altered in almost 30 years: in 2017, carbon intensity was 0·4% higher than that in 1990 (figure 11). Nevertheless, regional values have changed substantially. In 2018, carbon intensity was 12% lower in the USA and 20% lower in north and western Europe than the levels in 1990. China's carbon intensity remained high at 72 tonnes of CO_2 (tCO_2) per TJ in 2017; however, China's carbon intensity is decreasing, and in 2017 was 4% lower than its peak in 2013. Early statistics for 2020 suggest that global demand for all fossil fuels reduced in the first quarter because of COVID-19, and will continue to decline across the year, with resulting reductions in emissions.[21] However, without targeted intervention, emissions could rebound, as they did following the global financial crisis of 2008–09, in which a 1·4% decrease in CO_2 emissions in 2009 was offset by a 5·9% rise in 2010.[153]

Indicator 3.1.2: coal phase-out—headline finding: in 2018, global energy supply from coal was 1·2% higher than in 2017 and 74% higher than in 1990

Coal combustion continues to be the largest contributor to emissions from the energy sector and is a major contributor to premature mortality due to air pollution (indicator 3.3). The phase-out of coal-fired power is therefore an important first step in the mitigation of climate change. This indicator reports on progress towards a global phase-out, tracking the total primary energy supply from coal and coal's share of total electricity generation, with methods provided in full in the appendix (pp 77–78).[154]

Global coal use for energy increased by 1·2% from 2017 to 2018, and, although remaining below the 2014 peak, use of coal for energy has risen by 74% overall since 1990. China, responsible for 52% of global coal consumption, has driven the rise, counteracting a 2017–18 reduction in coal use from other major economies such as Germany (–6·0%), the USA (–4·2%), Australia (–3·3%), and Japan (–1·2%). However, the share of electricity generation from coal in China is falling rapidly, decreasing from 80% in 2007 to 66% in 2018, as China moves to other power sources to meet the rising demand for electricity (figure 12). Likewise, northern and western Europe have seen falls in their share of electricity generation from coal, decreasing from 21% in 2013 to 13% in 2018.

As a result of the COVID-19 pandemic, cheap oil, and continued growth in renewables, global demand for coal fell by almost 8% in the first quarter of 2020 and is expected to remain at this level throughout the year.[21] Additionally, Austria and Sweden closed their last coal-fired power plants in April, 2020, with other countries soon to follow.[155]

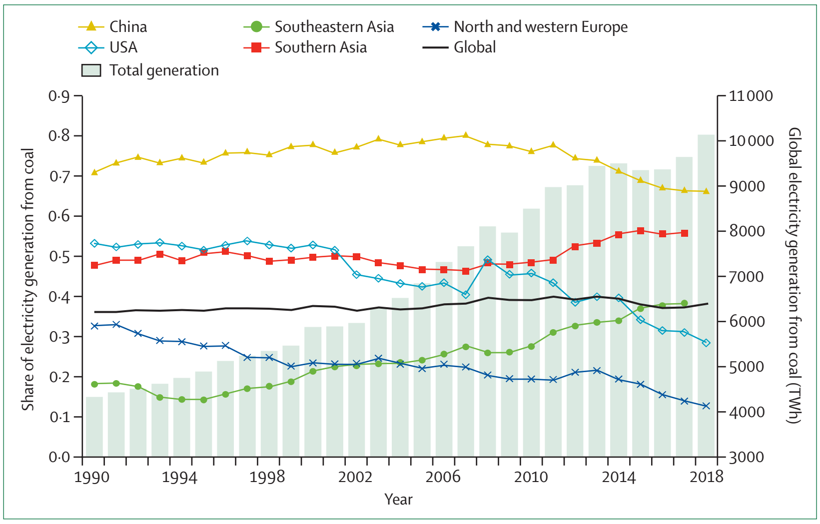

***Figure 12:* Share of electricity generation from coal in selected countries and regions, and global electricity generation from coal**

Regional shares of electricity generation from coal are shown by the trend lines (primary axis) and total electricity generation from coal by the bars (secondary axis). The global share of electricity generation from coal is shown with the thick black line. Data series are shown to at least 2017 and are extended to 2018 when data allow.

Indicator 3.1.3: zero-carbon emission electricity—headline finding: the average annual growth rate in power generation from wind and solar sources was 21% globally and 38% in China between 2010 and 2017, with all forms of low-carbon energy responsible for 33% of total electricity generation worldwide in 2017

Continued growth in renewable energy, particularly wind and solar sources, is key to replacing fossil fuels. This indicator tracks electricity generation and the share of total electricity generation from all low-carbon sources (nuclear and all renewables, including hydro) and renewables (wind and solar, excluding hydro and biomass). A full description of the methods and data can be found in the appendix (pp 79–80).[154]

Electricity generation from low-carbon sources continues to rise, growing by 10% from 2015 to 2017 to then account for 33% of total generation. In China during the same period, there was a 21% increase in low-carbon electricity generation, reaching 1800 TWh and 28% of all electricity produced.

Focusing on wind and solar energy reveals a similar picture, with global electricity generation from these sources increasing annually by 21% between 2010 and 2017. During the same period, China saw an even higher growth rate in power generation from wind and solar sources of approximately 38% per year due to a rapid increase in the use of solar energy, reaching 425 TWh in 2017. Despite this rise, China's share of electricity generation from renewables remained relatively small at 6·5%, similar to India's 5·0%. Contrary to the decline in demand for fossil fuels, the IEA expect the demand for renewable energy to increase

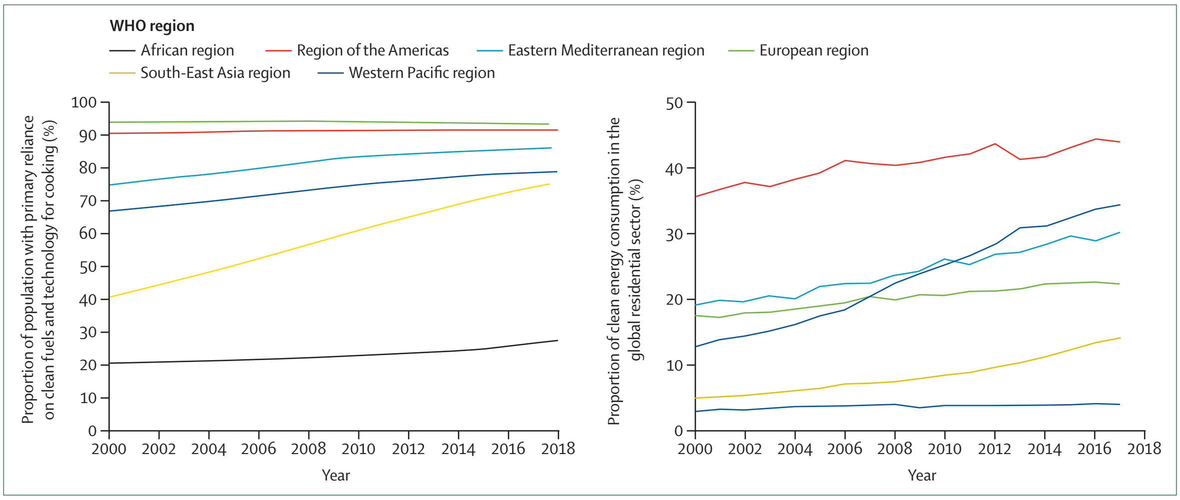

Figure 13: **Household energy usage**
(A) Proportion of population with a primary reliance on clean fuels and technology for cooking by WHO region, 2000–18. (B) Proportion of clean energy at the point of consumption in the global residential sector, 2000–16. Proportion is measured as the zero-emission energy consumed (fuels with no emissions at the point of use) over the total energy consumed in the residential sector. Electricity comprised 75% of total clean energy use in 2016.

in 2020 because of the lower operational costs of renewable sources compared with fossil fuel sources, but further policy support is necessary to continue this growth.[21,156]

Indicator 3.2: clean household energy

Headline finding: primary reliance on healthy fuels and technology for household cooking has continued to rise, reaching 63% of the global population in 2018. However, total consumption of zero-emission energy for all household needs remained low at 26%

The use of unhealthy and unsustainable fuels and technologies for cooking, heating, and lighting in the home contributes both to greenhouse gas emissions and to dangerous concentrations of household air pollution.[157] Primary reliance on such fuels and technologies for cooking is particularly problematic, resulting in recurrent direct exposure to high concentrations of poor quality air and causing more than 3·8 million premature deaths every year.[158] This issue disproportionately affects women and children, who, in many cultural contexts, spend more time in the home than do men, are in charge of food preparation, and face threats to their safety associated with the gathering of cooking fuels.[157]

This indicator draws on national surveys collected by WHO across 194 countries and tracks the proportion of the population who use clean fuels and technologies for cooking, defined as those that have emission rate targets meeting WHO guidelines for air quality. This indicator also tracks the usage of zero-emission energy in the residential sector, measured as fuels with both zero greenhouse gas and zero particulate emissions at the point of use (mainly electricity and renewable heating) with data from the IEA.[154]

In 2018, 63% of the global population relied primarily on clean fuels and technologies for cooking, an increase of 26% since 2000. In China, this proportion increased from 43% in 2000 to 64% in 2018; in Vietnam, this proportion increased from 13% to 64% during the same period. However, little progress has been made in sub-Saharan Africa, where only 15% of households rely on clean fuels and technology for cooking. Importantly, overall use of zero-emission energy in the home (for all sources, including heating and lighting) remains low (26% globally in 2017) and has increased by only 2% per year since 2010 (figure 13).

This section of the report is continuously evolving to understand the health co-benefits of mitigation efforts, and is now able to present findings from a new indicator under development that tracks mortality from household air pollution. Taking data on fuel and stove types used for cooking and the typical characteristics of housing ventilation, this indicator calculates household exposure to $PM_{2·5}$, both from cooking and from air pollution infiltrating from outside. A full explanation of the methods is described in the appendix (pp 81–82). Here, the estimated effect of household factors on deaths attributable to $PM_{2·5}$ pollution in 2018 are presented for selected countries (figure 14). In the middle-income countries assessed, the use of solid fuels for cooking, combined with poor housing ventilation, increased mortality from $PM_{2·5}$ exposure. For other mostly high-income countries, housing design and extract ventilation prevented ambient air pollution from entering the home. Combined with the use of healthy cooking fuels, this prevention resulted in a net negative effect in total (both household and ambient) mortality attributable to $PM_{2·5}$, showing a clear co-benefit of mitigation.

Indicator 3.3: premature mortality from ambient air pollution by sector

Headline finding: premature deaths from ambient $PM_{2·5}$ attributed to coal use are rapidly declining, falling from 440 000 deaths in 2015 to 390 000 deaths in 2018. However, total deaths from ambient $PM_{2·5}$ have increased slightly during this time period, from 2·95 million deaths in 2015 to 3·01 million deaths in 2018, highlighting the need for accelerated intervention

Many of the leading contributors to global greenhouse gas emissions also contribute to ambient air pollution, disproportionately impacting on the health of communities with a low socioeconomic status.[159] Indeed, some 91% of deaths from ambient air pollution occur in low-income and middle-income countries.[160] This indicator tracks the source-attributable premature mortality from outdoor ambient air pollution. The methods remain unchanged and are described in the appendix (pp 83–84).[161,162]

Trends in mortality due to air pollution vary by world region. In Europe and China, mortality from air pollution decreased from 2015 to 2018 as a result of the implementation of technologies to control emissions and reductions in the use of raw coal in the power and residential sectors.[163] The overall number of deaths attributable to ambient $PM_{2·5}$ in 2018 was estimated at 3·01 million, a slight increase from the 2·95 million deaths in 2015. Nonetheless, the total and per-capita deaths attributable to coal combustion have decreased from roughly 440 000 deaths in 2015 to less than 390 000 death in 2018 (figure 15). Decreases were also seen in the contribution from biomass burning to ambient $PM_{2·5}$ deaths (about 410 000 deaths in 2015, decreasing to 360 000 deaths in 2018) and were mostly due to the increasing access to cleaner household fuels (although, 2·6 billion people still rely on fuelwood combustion in the home).[164]

If measures to respond to the economic fallout from COVID-19 are aligned with the priorities of the Paris Agreement, transient reductions in air pollution following the sudden halt in economic activities and road transport could become more permanent, resulting in further improvements in health and air quality in 2020 and into the future.

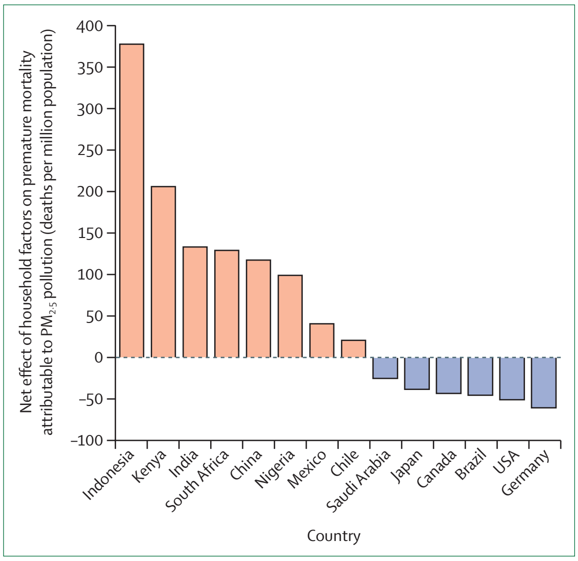

***Figure 14:* Estimated net effect of housing design and indoor fuel burning on premature mortality due to air pollution in 2018**
$PM_{2·5}$=fine particulate matter.

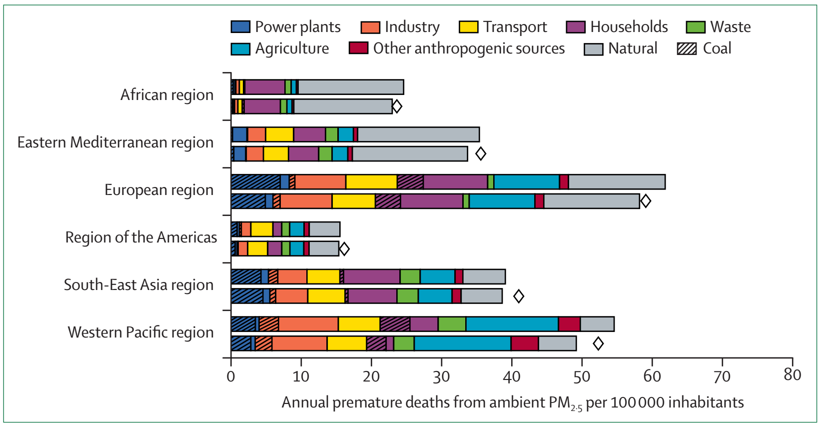

***Figure 15:* Premature deaths attributable to exposure to $PM_{2·5}$ in 2015 and 2018 by key sources of pollution in WHO regions**
The coloured bars represent the attributable deaths if there were a constant 2015 population structure. The diamonds represent the total attributable deaths for 2018 when considering demographic changes. $PM_{2·5}$=fine particulate matter.

Indicator 3.4: sustainable and healthy transport

Headline finding: although fossil fuels continue to dominate the transport sector, the use of electricity for road transport rose by 18·1% from 2016 to 2017, and the global electric vehicle fleet increased to more than 5·1 million vehicles in 2018 (a rise of 2 million vehicles in only 12 months)

The transition to ultra-low emission vehicles is another essential component of mitigating climate change. In addition, policies that reduce overall vehicle use and increase walking and cycling will yield the greatest benefits in terms of reductions in greenhouse gas emissions and air pollution and the health advantages of increased physical activity.[165] Well designed public transport and active travel infrastructure can also help to reduce inequality and improve mobility for those who otherwise have sparse travel options.[166] For the 2020 report, global trends in fuel use for road transport were monitored, with methods and data available in the appendix (p 85).[167]

Global per-capita use of fuel for road transport increased by 0·5% from 2016 to 2017, with the rate of growth slowing slightly compared with previous years (figure 16). Although fossil fuels continue to contribute to most total fuel use, the use of clean fuels is growing at a much faster pace. Between 2016 and 2017, total use of fossil fuels for transport increased by only 1·7%, whereas the use of electricity for road transport increased by 18·1%. From 2017 to 2018, the global electric vehicle fleet grew by an enormous 64·5%, rising to more than

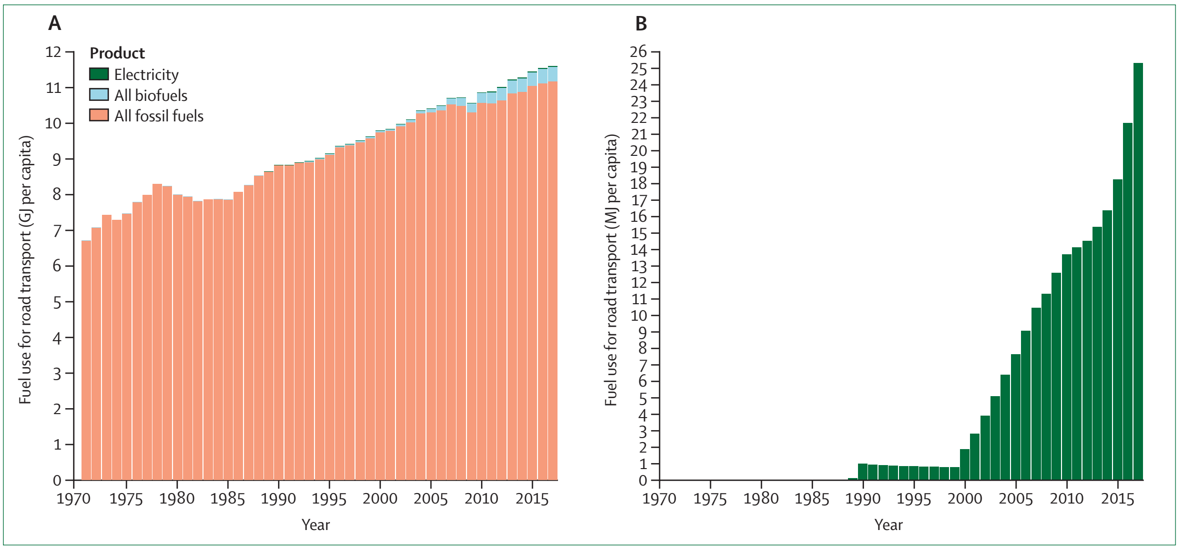

Figure 16: **Per-capita fuel use for road transport**
(A) All fossil fuels, biofuels, and electricity. (B) Electricity only. Please note the varying scales in the y-axes.

5·1 million vehicles in 2018. In line with this rapid growth, there are now more than 5·2 million charging stations available for passenger vehicles and another 157 000 fast chargers available for buses worldwide.

Indicator 3.5: food, agriculture, and health

Indicator 3.5.1: emissions from agricultural production and consumption—headline finding: ruminant livestock continue to dominate agriculture's contribution to climate change and are responsible for 56% of total agricultural emissions and 93% of all livestock emissions globally. This proportion represents a 5·5% increase in the per-capita emissions from beef consumption between 2000 and 2017, which is particularly concerning given the sharp rise in population during this time period and the health impacts of excess red meat consumption

The food system is responsible for 20–30% of global greenhouse gas emissions, most of which originate from meat and dairy livestock.[168] Improved for the 2020 report, agricultural emissions from countries' production and consumption (adjusting for international trade) were tracked by use of data from the Food and Agriculture Organization of the United Nations, with a full description of methods and data provided in the appendix (pp 86–91).[169,170] Although countries' emissions are typically measured on a production basis, it is their consumption that generates the demand and results in diet-related health outcomes.

For more on the **Food and Agriculture Organization of the United Nations** see http://www.fao.org/faostat/en/#home

Overall emissions from livestock production have increased by 16% since 2000 to more than 3·2 $GtCO_2e$ in 2017. Ruminants contribute to 93% of total livestock emissions, of which non-dairy cattle contribute 67%. Regarding emissions from consumption, products from the beef industry dominate, both in absolute and per-capita terms (figure 17). Average emissions from beef consumption were 402 $kgCO_2e$ per person in 2017, compared with 380 $kgCO_2e$ per person in 2000.

Ultimately, effective mitigation will maximise human health while reducing food and agricultural emissions; however, no one diet is applicable everywhere and there are important nuances and variations to be considered across regions and countries. Excessive consumption of red meat brings considerable health consequences, and plant-based sources that are less emissions-intensive are important alternatives, particularly in Europe and the Americas where per-capita emissions are high. In other parts of the world, sustainable farming and agricultural practices are being implemented to meet the nutritional requirements of rapidly growing populations while also keeping emissions low.[171]

Indicator 3.5.2: diet and health co-benefits—headline finding: the global number of deaths due to excess red meat consumption rose to 990 000 deaths in 2017, a 72% increase since 1990

An unhealthy diet is one of the leading risk factors for premature death, both globally and in most regions.[105] Combined with a range of food system-wide interventions, achieving dietary change consistent with the Paris Agreement and the sustainable development goals is possible by reducing reliance on red meat consumption and prioritising healthier alternatives, with various diets and choices available depending on the region, individual, and cultural context.[172,173] New to the 2020 report, this indicator presents the change in deaths attributable to dietary risks by focusing on one particular area—the consumption of excess red meat. Here, this indicator links food consumption from the food balance sheets of the Food and Agriculture Organization of the United Nations with dietary and weight-related risk factors, with a full description of methods and data presented in the appendix (pp 91–97).[107,174]

Globally, diet and weight-related risk factors have barely changed since 1990, accounting for 8·8 million deaths in 2017, representing 19% of total mortality. The regions with the largest proportion of diet-related deaths included the Eastern Mediterranean region (28%), the European region (25%), and the region of the Americas (22%). High red meat consumption was responsible for 990 000 deaths globally in 2017 (figure 18). The greatest contribution to this total came from the Western Pacific region, where red meat consumption was responsible for an estimated 411 500 deaths (3·3% of all deaths in this region). Although there has been an overall improvement in dietary risk factors in Europe, deaths attributable to red meat consumption still accounted for 3·4% of all deaths (306 800 deaths).

Indicator 3.6: mitigation in the health-care sector

Headline finding: the health-care sector was responsible for approximately 4·6% of global greenhouse gas emissions in 2017, with substantial variations in per-capita emissions and health-care access and quality

Health care is among the most important sectors in managing the effects of climate change and, simultaneously, this sector has an important role in reducing its own carbon emissions (panel 4). Emissions from the global health-care sector were modelled by use of environmentally extended multiregion input-output (EE MRIO) models combined with data on health-care expenditure from WHO.[177–181] Based on external review and feedback, the improvements in methodology included adjustments in the EE MRIO satellite accounts that reflect recent shifts in emissions intensities, particularly in the energy sector, with a full description of methods and additional analysis in the appendix (pp 98–99).

In 2017, the health-care sector contributed to approximately 4·6% of global greenhouse gas emissions, a rise of 6·1% from 2016. On a per-capita level, comparing emissions alone does not capture crucial differences in health outcomes among countries, including in access to care. Similarly, increases in emissions in a single country over time might reflect additional health-care spending that improves population health. Therefore, the 2015 per-capita greenhouse gas emissions from the health-care sector were plotted against the 2015 Healthcare Access and Quality (HAQ) Index (figure 19).[178] There was a clear positive relationship between the two variables until emissions reached 400 $kgCO_2e$ per person. After this point, countries achieved very similar HAQ levels with vastly different emissions profiles. For example, France, Japan, and the USA had very high HAQ scores, and had per-capita emissions ranging from 350 $kgCO_2e$ for France, through to 1220 $kgCO_2e$ for Japan, and to 1720 $kgCO_2e$ for the USA, suggesting that much of health care can achieve high-quality patient outcomes with considerably reduced emissions.

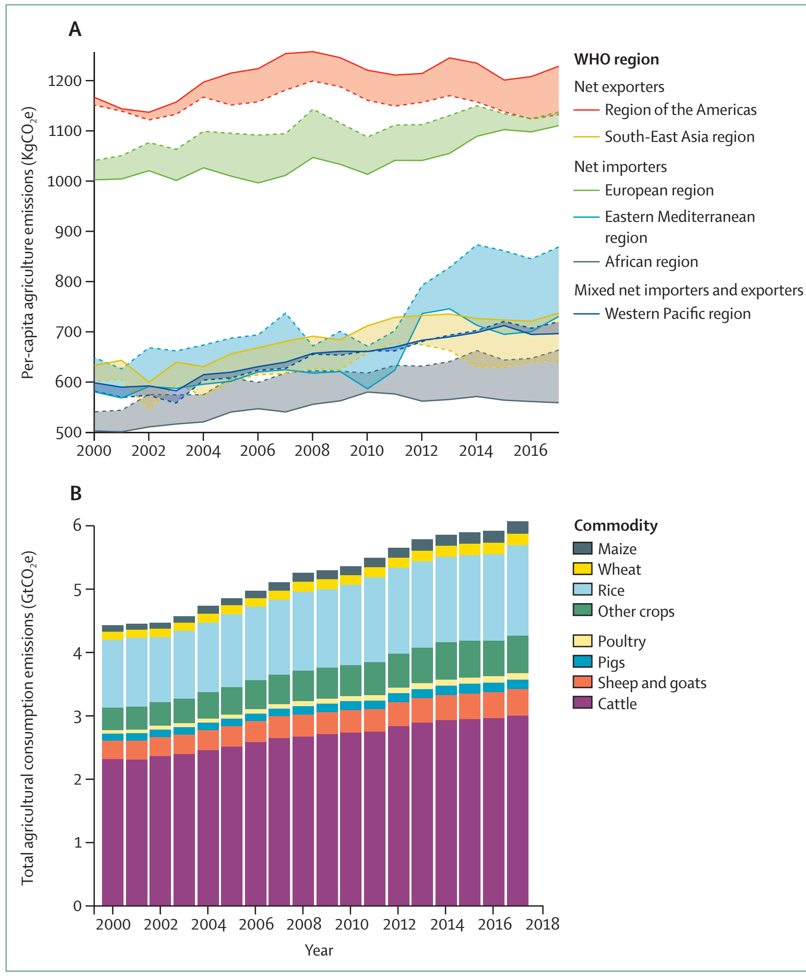

Figure 17: **Agricultural production and consumption emissions, 2000–17**
(A) Emissions by WHO region. (B) Global agricultural consumption emissions by commodity. Trade data from the Food and Agriculture Organization of the United Nations were used to calculate these numbers. Per-capita production is shown by the solid lines and per-capita consumption by the dotted lines. $GtCO_2e$=gigatonnes of carbon dioxide equivalent. $kgCO_2e$=kilograms of carbon dioxide equivalent.

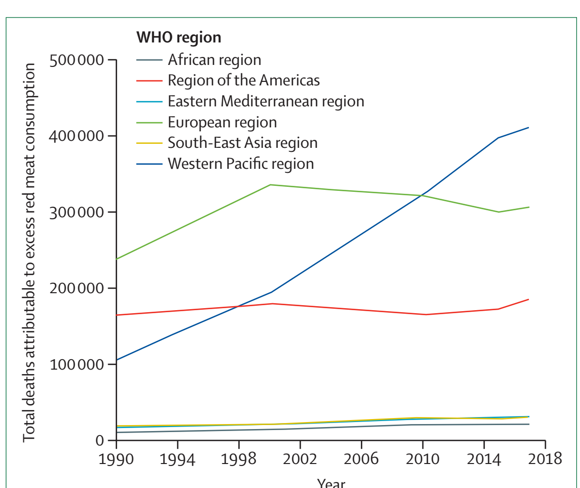

Figure 18: **Deaths attributable to excess red meat consumption in 1990–2017 by WHO region**

> ***Panel 4*: For a greener National Health Service**
>
> With more than 1·5 million employees, England's National Health Service (NHS England) is the largest single employer in Europe and the largest single-payer health-care system in the world, with an annual budget of £134 billion. Although providing high-quality health care to a population of almost 56 million people, NHS England contributes to 4–5% of the country's total greenhouse gas emissions. Accountable to both NHS England and Public Health England, the Sustainable Development Unit was founded in 2008 to ensure the health service met its commitments under the UK Climate Change Act. Since then, the NHS has achieved impressive reductions in greenhouse gas emissions while maintaining high standards of care and decreasing costs, reducing delivery of care emissions by 57% and emissions from its supply chain and broader responsibilities by 22% compared with 1990 levels.[175] In January, 2020, NHS England announced its commitment to become the world's first net zero health system, alongside a new campaign for a greener NHS.[176] A new baseline of NHS England's carbon footprint was quantified and different sources of emissions were identified by use of a hybrid model of bottom-up measurements of direct emissions (ie, onsite fossil fuel use, fleet and transport, and anaesthetic gases) and energy use, and top-down measurements based on multiregional input–output models to estimate other indirect emissions (eg, from the upstream energy system, pharmaceutical procurement, and patient use of metred dose inhalers). NHS England is now working to develop a strategy for how and when net zero emissions can be achieved.

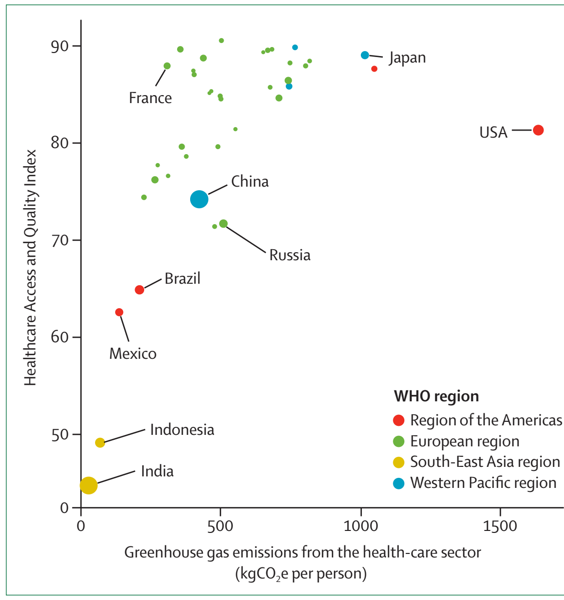

***Figure 19:* National per-capita greenhouse gas emissions from the health-care sector against the Healthcare Access and Quality Index for 2015**
$kgCO_2e$=kilograms of carbon dioxide equivalent.

Conclusion

The trends during the past year show a concerning paucity of progress in numerous sectors, including a continued failure to reduce the carbon intensity of the global energy system, an increase in the use of coal-fired power, and a rise in agricultural emissions and premature deaths from excess red meat consumption. These issues are in part counteracted by the growth of renewable energy and improvements in low-carbon transport. Although the use of these greener options continues to rise at a pace, it is important to consider that they are starting from a low baseline.

In many cases, 2020 will probably be an inflection point for several of the indicators presented during the coming decade, with the direction of future trends yet to be seen. Ensuring that the recovery from the pandemic is synergistic with the long-term public health imperative of responding to climate change will be crucial in the coming months, years, and decades.

Section 4: economics and finance

Section 1 described the emerging human symptoms of climate change, and sections 2 and 3 detailed efforts to adapt and mitigate against the worst of these effects. In turn, section 4 examines the financial and economic dimensions of the impacts of climate change and the efforts to respond.

The Intergovernmental Panel on Climate Change estimate that limiting warming to 1·5°C would require an annual investment in the energy system equivalent to around 2·5% of global GDP until 2035.[82] Such investment would limit the cost of the damage from climate change (up to $4 trillion per year by 2100 if warming is limited to 2°C rather than to 3°C) and generate a range of other economic benefits (eg, the creation of new technologies and industries) and health benefits from avoiding the effects of climate change and current carbon-intensive activities. Once such factors are considered, the overall economic implications of limiting warming to 1·5°C are likely to be positive, particularly if responses in policy are accelerated as soon as possible to a level commensurate with the scale of the challenge. Estimates suggest that investment to "bend the curve" from the world's current path and limit warming to a rise of 1·5°C by 2100 would generate a net global benefit of $264–610 trillion (3·1–7·2 times the size of the global economy in 2018).[12]

The global economy will look substantially different following the recovery from the COVID-19 pandemic. As governments around the world grapple with the challenge of restarting their economies, ensuring that these efforts are aligned with the response to climate change is important. If the enormous fiscal stimulus that will be required is directed away from high-carbon, and towards low-carbon, infrastructure and activities, an opportunity to permanently bend the curve presents itself. Metrics examining these core concepts are tracked in this report, allowing future data to reveal the long-term effect of COVID-19 on the low-carbon economy.

The nine indicators in this section fall into two broad domains. The first is the health and economic costs of climate change and its mitigation (indicators 4.1.1–4.1.4). This domain includes two new indicators for the 2020 report: the economics of heat-related mortality (indicator 4.1.2) and the potential reduction in earnings from heat-related loss of labour capacity (indicator 4.1.3). The second domain examines the economics of the transition to zero-carbon economies (indicators 4.2.1–4.2.5), which is fundamental to the improvement of human health and wellbeing. This domain also includes a new indicator (indicator 4.2.5) that merges three indicators presented in previous reports (ie, on fossil fuel subsidies, the strength and coverage of carbon prices, and carbon pricing revenues) to examine the net carbon prices in place around the world.

Indicator 4.1: the health and economic costs of climate change and benefits from mitigation

Indicator 4.1.1: economic losses due to climate-related extreme events—headline finding: in 2019, economic losses from climate-related extreme events were nearly five times greater in low-income economies than in high-income economies. Just 4% of these losses were insured in low-income economies compared with 60% in high-income economies

Section 1 presented the evidence linking the impacts of climate change to human health and wellbeing. The loss of physical infrastructure (eg, agricultural land, homes, and health infrastructure) because of such events will further exacerbate these health effects. This indicator tracks the total annual economic losses (insured and uninsured) that result from climate-related extreme events. The methodology has changed from previous reports and is described in full in the appendix (pp 101–103).[182]

In 2019, 236 climate-related extreme events were recorded, with absolute economic losses totalling $132 billion. Although most of these losses occurred in high-income economies, when normalised by GDP, the value of total economic losses in low-income countries was nearly five times greater. In addition, although 60% of losses in high-income economies were insured, this proportion reduced to 3–5% for other income groups. When normalised by GDP, relative economic losses have been decreasing as the number of total extreme events has been increasing, suggesting that adaptation and prevention are reducing the impacts of these events.[183]

Indicator 4.1.2: costs of heat-related mortality—headline finding: the monetised value of global heat-related mortality increased from 0·23% of gross world product in 2000 to 0·37% in 2018. Europe was the worst affected in 2018, with costs equal to the average income of 11 million of its citizens and 1·2% of regional gross national income

As indicator 1.1.3 highlights, rising temperatures and extremes of heat are resulting in worsening morbidity and mortality for populations around the world. The 2020 report introduces a new indicator that considers the economic impact of this problem by tracking the monetised value of global heat-related mortality. To do so, this indicator uses the value of a statistical life estimated for the member countries of the Organisation for Economic Co-operation and Development (OECD) and the fixed ratio of the value of a statistical life to gross national income for non-OECD countries, applying these values to the heat-related mortality data from indicator 1.1.3.[184,185] To address any distributional effects, and to more accurately capture the economic harm that climate change presents to low-income and middle-income countries, two indices have been calculated. The value of mortality is presented as a proportion of total gross national income (and gross world product) and as the average income per person this loss would be equivalent to in a given country and region. A full description of the methods, data, caveats, and further analysis are described in the appendix (pp 103–106).

As global heat-related mortality increased from 2000 to 2018, so too did the monetised cost of these deaths. At a global level and represented as a proportion of gross world product, the cost increased from 0·23% in 2000 to 0·37% in 2018. Because of the high number of heat-related deaths, Europe was the worst affected WHO region, reaching a cost equivalent to the income of 11 million of its citizens in 2018 (led by Germany at 1·9 million; figure 20) and 1·2% of regional gross national income. Although in terms of the proportion of gross national income the value of mortality for the Western Pacific region (0·43%) and the South-East Asia region (0·19%) was comparatively low, the impact is more substantial when considered against the average income in these regions.

For more on the **data used for this indicator** see https://www.sigma-explorer.com/

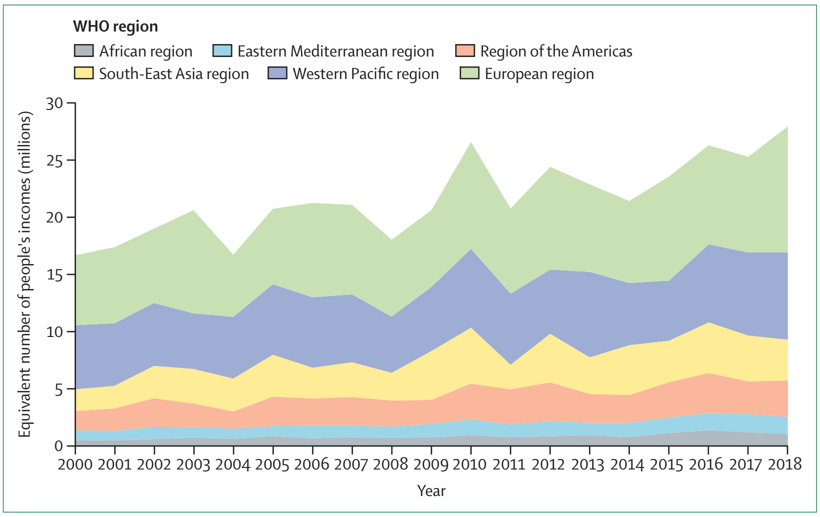

Figure 20: **Cost of heat-related mortality represented as the number of people to whose income this value is equivalent, on average, for each WHO region**

Indicator 4.1.3: loss of earnings from heat-related reduction in labour capacity—headline finding: rising temperatures make outdoor labour increasingly difficult, often resulting in public health and economic consequences for a wide range of occupations. By 2015, heat-related reduction in labour capacity resulted in earnings losses equivalent to an estimated 3·9–5·9% of GDP in the lower-middle-income countries tracked

Higher temperatures, driven by climate change, are affecting people's ability to work (indicator 1.1.4). This new indicator considers the loss of earnings that could result from such reduced capacity, compounding the initial cause of ill health and impacting on wellbeing. The indicator adopts the outputs of indicator 1.1.4 for 25 countries, selected by the impact their workers experience and for geographical coverage, and combines these outputs with data on average earnings by country and sector held in the International Labor Organization databases.[40] These estimates will be modified by various factors, ranging from whether or not sick leave was taken, the presence of workers' sick pay rights, and the availability of shade. A full description of the methods and additional analysis is provided in the appendix (pp 107–120).

When taken as a share of GDP, low-income and lower-middle-income countries are the worst affected by heat-related reductions in labour capacity, with economic losses predominantly seen in agriculture, despite this sector being on average the lowest paid of the sectors considered. By 2015, averaged estimated losses in earnings reached the equivalent of 3·9–5·9% of GDP for the lower-middle-income countries tracked, including Indonesia, India, and Cambodia, and between 0·6–1·0% for the upper-middle-income countries tracked, including China, Brazil, and Mexico.

Indicator 4.1.4: costs of the health impacts of air pollution—headline finding: across Europe, ambient $PM_{2·5}$ pollution from human activity reduced between 2015 and 2018. If held constant, this improvement alone would lead to an annual average reduction in years of life lost to the current population worth $8·8 billion

As described in indicator 3.3, global mortality due to ambient $PM_{2·5}$ pollution has risen from around 2·95 million deaths in 2015 to 3·01 million deaths in 2018. However, because of improvements in air quality, including the closure of coal power stations, premature mortality due to air pollution in Europe has decreased during the same period. This indicator captures the cost of that change in the EU by placing an economic value on the years of life lost that result from exposure to $PM_{2·5}$ from anthropogenic sources, with the methods and data described in full in the appendix (pp 121–122).[186]

If the population of the EU in 2015 were to be exposed to anthropogenic $PM_{2·5}$ emissions at 2018 levels instead of those present in 2015 consistently during the course of their lives, the total average economic value of the reduction in years of life lost would be around

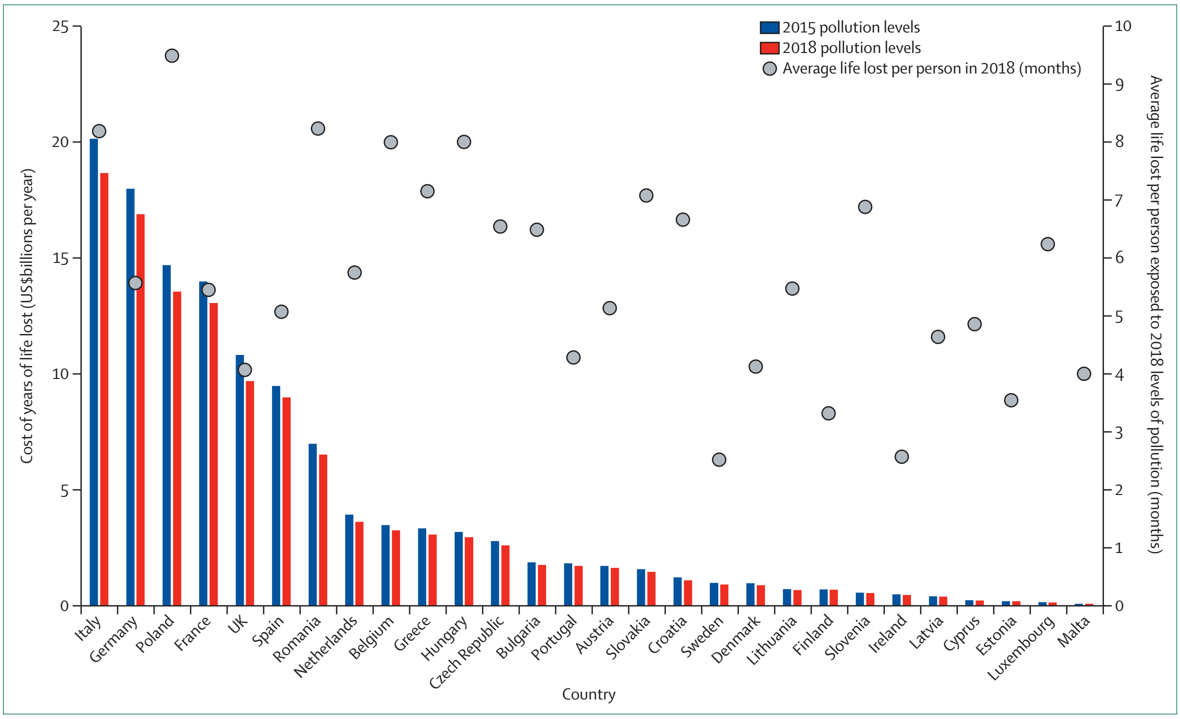

Figure 21: **Annual cost of years of life lost and average months of life lost per person due to anthropogenic $PM_{2·5}$ exposure**
$PM_{2·5}$=fine particulate matter.

\$8·8 billion (€9·85 billion) every year. Despite this, 2018 $PM_{2·5}$ levels are still damaging to the cardiovascular and respiratory systems, and the total average cost to the current population would still be \$116 billion (€129 billion) per year. Based on the levels of air pollution in 2018, the average life lost per person in the EU is 5·7 months, but this loss of life is estimated at more than 8 months per person for individuals in Poland, Romania, Hungary, Italy, and Belgium (figure 21).

Indicator 4.2: the economics of the transition to zero-carbon economies

Indicator 4.2.1: investment in new coal capacity—headline finding: largely driven by China, investment in new coal capacity has been declining since 2011 and decreased by 6% between 2018 and 2019. Despite this reduction, global coal capacity continues to increase, with fewer retirements than there were additions of coal plants for every year tracked

As identified in section 3, phasing out coal is essential, not only for the mitigation of climate change, but also for the reduction of premature mortality due to air pollution. Taking data from the IEA, this indicator looks at future coal use, tracking investment in new coal-fired power generation. The data represent ongoing capital spending, with investment in a new coal plant spread evenly from the year construction begins to the year the plant becomes operational.[187] For the 2020 report, data are presented for key countries and regions alongside the global trend. Further details on the methods and data can be found in the appendix (p 123).

Following the trend since 2011, global investment in coal-fired power decreased by a further 6% between 2018 and 2019 (figure 22). With a 27% reduction in investments during these 2 years, China has been driving this decline. Final investment decisions (the point at which the project's future development is approved) have reached their lowest point in 40 years and, driven by declining investment in Asia, in part as a result of COVID-19, a further 11% reduction in investment is forecast for 2020. However, despite a substantial decline in actual investment, there were more final investment decisions in China in 2019 than in 2018, and, with the approval of 8 GW of new capacity, the number of final investment decisions had reached 2019 levels by March, 2020. Additionally, with fewer retirements than there were additions of coal plants in 2019 (and in every year presented), there was an overall increase in global coal capacity.

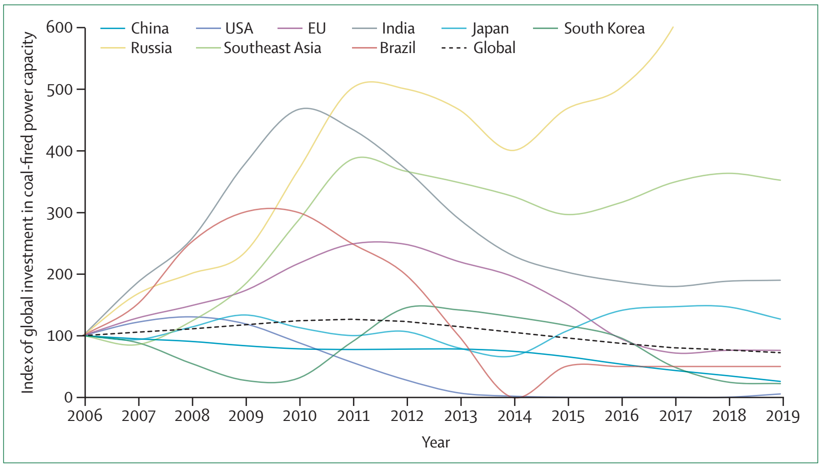

***Figure 22:* Annual investment in coal-fired capacity, 2006–19**
An index score of 100 corresponds to 2006 levels of capacity.

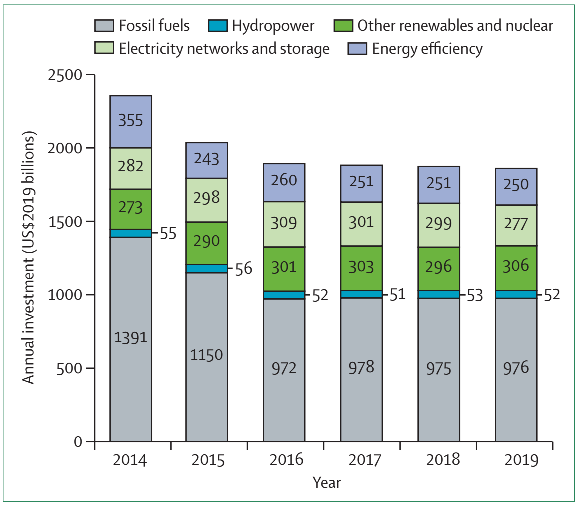

***Figure 23:* Annual investment in energy supply and efficiency**

Indicator 4.2.2: investments in zero-carbon energy and energy efficiency—headline finding: progress towards zero-carbon energy has stalled; investments in zero-carbon energy and energy efficiency have not increased since 2016 and are a long way from doubling by 2030, which is required to be consistent with the Paris Agreement

This indicator monitors annual global investment in zero-carbon energy, energy efficiency, electricity networks, and in all fossil fuels, complementing and providing a wider context to indicator 4.2.1. Data are sourced from the IEA and the methodology remains the same as that in the 2019 report of the *Lancet* Countdown, with hydropower now considered separately and all values presented in US\$2019.[187]

Since 2016, investment in global energy supply and efficiency has remained stable at just less than \$1·9 trillion, with fossil fuel supply consistently accounting for around half this value and all renewables and energy efficiency combined maintaining a share of 32% (figure 23). For a pathway consistent with 1·5°C of warming this century, annual investments must increase to \$4·3 trillion by 2030, with investment in renewable electricity, electricity networks and storage, and energy efficiency accounting for at least half this value.[188]

As a result of the COVID-19 pandemic, short-term disruption and long-term reassessments of probable returns mean that total energy investment is estimated to decrease by 20% in 2020 (the largest fall ever recorded), with investment in oil and gas supply to be reduced by a third. Investment in renewables is likely to fare better than is investment in fossil fuel capacity, with investment in zero-carbon energy (ie, nuclear, hydropower, and other renewables) and energy efficiency projected to increase from 32% to 37% in 2020 because of falling investments in fossil fuels.[187] Stimulus plans focused on boosting energy efficiency and renewable energy will be essential to ensure that the power generation system is on track to meet the sustainable development goals and the goals of the Paris Agreement.[156]

Indicator 4.2.3: employment in low-carbon and high-carbon industries—*headline finding: renewable energy provided 11·5 million jobs in 2019, a 4·5% rise from 2018. Although still employing more people overall than the renewable energy industry, employment in fossil fuel extraction declined by 3% from 2018 to 2019*

There is mounting evidence that employees in some fossil fuel extractive industries, particularly those in coal mining, and populations living in close proximity to these industries, have a high incidence of certain illnesses, such as chronic respiratory diseases, cancers, and congenital anomalies.[189,190] Combined with increased job certainty, a managed transition of employment opportunities away from fossil fuel-related industries and towards low-carbon industries will result in the improved occupational health of employees within the energy sector. This indicator tracks global direct employment in fossil fuel extraction industries (ie, coal mining, and oil and gas exploration and production) and direct and indirect (supply chain) employment in renewable energy for the most recent year available, with a full description of the methods and data available in the appendix (pp 125–126).[191–193]

For more on **350.org** see https://350.org/

Globally, around 11·5 million people were employed directly or indirectly by the renewable energy industry in 2019, representing an increase of 4·5% from 2018. The solar photovoltaic sector provided over a third of these jobs, with employment also rising in wind, bioenergy, and other technologies. Fossil fuel extraction industries continue to employ more people globally than do all renewable energy industries, although the number of jobs in 2019 (12·7 million) was slightly lower than the number in 2018 (13·1 million).

As the demand for fossil fuels declines, planned efforts, including retraining and job placements, are important to ensure the ongoing employment of those currently working in fossil fuel extraction industries. The same will be true as part of the response to COVID-19, with structured retraining and deployment programmes for renewable energy potentially forming an important component of a recovery plan. Indeed, the IEA estimates that such a strategy, which accelerates the deployment of low-carbon electricity sources, expands access to electricity grids and energy efficiency, and delivers cleaner transport, would create an additional 9 million jobs per year globally during the next 3 years.[156]

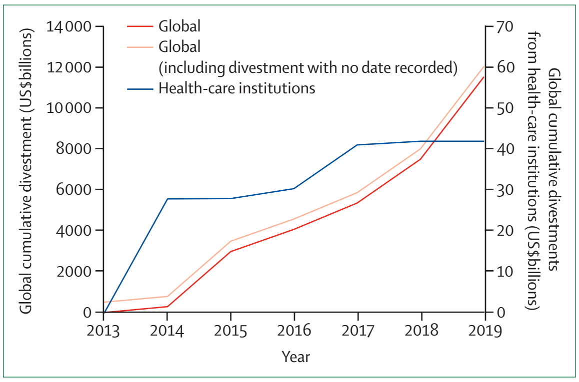

Figure 24: **Cumulative divestment globally and in health-care institutions**

Indicator 4.2.4: funds divested from fossil fuels—headline finding: the global value of new funds committed to fossil fuel divestment in 2019 was $4·01 trillion, of which health institutions accounted for around $19 million. From 2008 to 2019, there was a cumulative sum of $11·51 trillion divested from fossil fuels, with health institutions accounting for $42 billion

By encouraging investors to reduce their financial interests in the fossil fuel industry, divestment efforts both remove the social licence to operate and guard against the risk of losses due to stranded assets in a world in which demand for fossil fuels rapidly decreases.[194,195] This indicator tracks the total global value of funds divested from fossil fuels and the value of divested funds coming from health institutions by use of data provided by 350.org, with annual data and full methodology described in the appendix (pp 126–127).[196]

From 2008 to the end of 2019, 1157 organisations, with cumulative assets worth at least $11·51 trillion, have committed to fossil fuel divestment (figure 24). Of these organisations, only 23 are health institutions, including the World Medical Association, the British Medical Association, the Canadian Medical Association, the UK Faculty of Public Health, the Royal College of General Practitioners, the Royal Australasian College of Physicians, Gundersen Health System, the Berlin Doctors Pension Fund, and the Royal College of Emergency Medicine, with total assets of approximately $42 billion. The annual value of new funds committed to divesting increased from $2·14 trillion in 2018 to $4·01 trillion in 2019. However, divestment from health institutions has decreased from $867 million in 2018 to $19 million in 2019, owed mainly to divestment from particularly large institutions in previous years.

Indicator 4.2.5: net value of fossil fuel subsidies and carbon prices—headline finding: 58 of the 75 countries reviewed were operating with a net negative carbon price in 2017. The resulting net loss of revenue was, in many cases, equivalent to substantial proportions of the national health budget

Placing a price on greenhouse gas emissions provides an incentive to drive the transition towards a low-carbon economy.[197,198] This strategy also allows for a closer reflection of the true cost of emissions-intensive practices, particularly fossil fuel use, capturing some of the negative externalities resulting from their impact on health. However, not all countries explicitly set carbon prices, and, in some cases, the strength of any carbon price might be undermined by the opposing influence of subsidies on fossil fuel production and consumption.[199,200]

Indicator 4.2.5 has been created for the 2020 report by combining previous indicators on fossil fuel subsidies and carbon pricing. This indicator calculates net, economy-wide average carbon prices and associated net carbon revenue to government. The calculations are based on the value of overall fossil fuel subsidies, the revenue from carbon pricing mechanisms, and the total CO_2 emissions of the economy. Data on fossil fuel subsidies are calculated on the basis of analysis from the IEA and OECD.[201,202] Together, these sources cover 75 countries and account for around 92% of global CO_2 emissions. Carbon prices and revenues are derived from data in the World Bank Carbon Pricing Dashboard and include international, national, and subnational mechanisms within countries, 38 of which overlap with those covered by subsidy data and thus form part of this analysis. A full description of the methodology, other data sources, and the methods for integrating these sources, can be found in the appendix (pp 129–137).

Of the 75 countries, 61 (81%) countries in 2016 and 58 (77%) countries in 2017 had net negative carbon prices, and only 14 (19%) countries in 2016 and 17 (23%) countries in 2017 had a price higher than zero, a result of substantial subsidies for fossil fuel production and consumption (figure 25). The median net carbon revenue was negative, a pay-out of \$0·66 billion (IQR –0·04 to –3·48), with some countries providing net fossil fuel subsidies in the tens of billions of dollars each year. In many cases, these subsidies were equivalent to substantial proportions of the national health budget—more than 100% in eight of the 75 countries in 2017. Of the 38 countries that had formal carbon pricing mechanisms in place in 2017, 21 still had net negative carbon prices.

Conclusion

The economic and financial dimensions of public health and climate change are central to any comprehensive mitigation and adaptation effort. This section has covered the health and economic costs of climate change and the indicators of progress underlying a transition to a low-carbon economy. We have developed several new metrics to inform this section and will continue to expand the geographical coverage and reach of these indicators in subsequent reports.

The outlook presented here is mixed. On the one hand, investment in new coal capacity continues to decrease and employment in renewable energy continues to rise. On the other hand, composite indicators of net carbon pricing reveal that government policies are often miscoordinated, resulting in inefficiencies and disrupted price signals. The full economic effects of COVID-19 will continue to develop

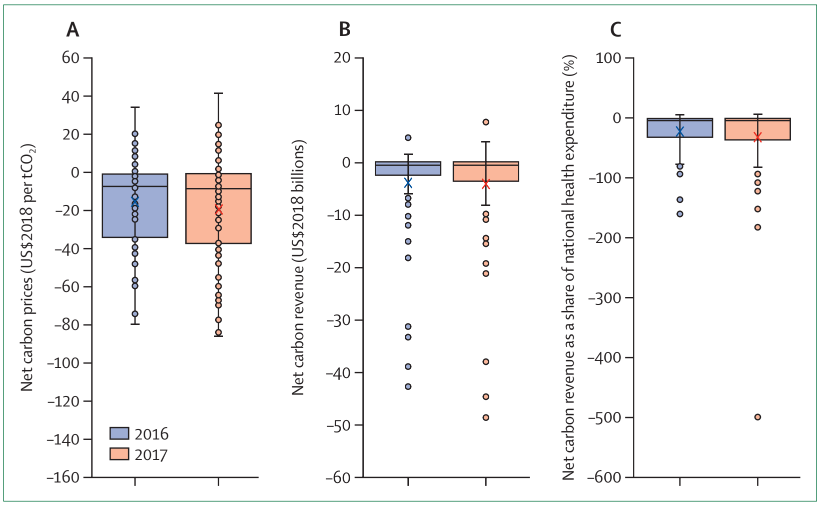

Figure 25: **Net carbon prices, net carbon revenues, and net carbon revenue as a share of current national health expenditure across 75 countries in 2016 and 2017**

(A) Net carbon prices. (B) Net carbon revenues. (C) Net carbon revenue as a share of current national health expenditure. The boxes represent the IQRs, the horizontal lines inside the boxes represent the medians, and the crosses represent the means. The brackets represent the range from minimum to maximum; however, points are represented as outliers beyond this range if their values are 1·5 times the IQR less than the first quartile or more than the third quartile. tCO_2=tonnes of carbon dioxide.

during the course of several years, leaving a lasting impact on the world. Indeed, the nature and extent of the economic impact and response to this pandemic will have a defining role in determining whether the world meets the commitments of the Paris Agreement. For this reason, strong investment in mitigation and adaptation technologies and interventions is more important now than ever before, and shall lead to healthier and more prepared hospitals, economies, and populations.

For more on the **World Bank Carbon Pricing Dashboard** see https://carbonpricingdashboard.worldbank.org/

Section 5: public and political engagement

As previous sections made clear, the health impacts of climate change are multiplying, disproportionately affecting those who have contributed least to rising global temperatures. The public are voicing concern as individuals, and as members of communities and new social movements, urging for greater ambition from those with the power to curb carbon emissions.[203–210]

This section tracks engagement in health and climate change across multiple parts of society, including the media, by individuals, scientists, governments, and the corporate sector. For each group, the methods used in previous reports have been enhanced, increasing the sensitivity and specificity of the metrics of health and climate change engagement.

The media, and national newspapers in particular, are central to shaping public perceptions of climate change.[211–214] The media indicator (indicator 5.1) tracks newspaper coverage of health and climate change in 36 countries, with additional analysis provided for China's *People's Daily* (the official voice of the government and China's most influential newspaper), and content analysis of newspaper coverage in India and the USA.[215,216]

Individual engagement (indicator 5.2) is tracked through the use of Wikipedia, an online information source that has outpaced traditional encyclopaedias in terms of reach, coverage, and comprehensiveness.[217–221]

Reintroduced in the 2020 report with a revised methodology, the scientific indicator (indicator 5.3) tracks academic engagement with health and climate change in peer-reviewed journals, the premier source of high-quality research that provides evidence used by the media, the government, and the public.[218,222,223]

The fourth indicator (indicator 5.4) focuses on the governmental domain, a key arena for driving the global response to climate change. This indicator tracks government engagement in health and climate change at the UN General Assembly, where the UN General Debate provides a platform for national leaders to address the global community.[224,225] New to the 2020 report, this indicator also examines engagement with health in the NDCs that underpin the UNFCCC 2015 Paris Agreement.[4,226,227]

The final indicator (indicator 5.5) focuses on the corporate sector, which, through the sector's behaviour and wider political influence, is central to the transition to a low-carbon economy.[228–230] This indicator tracks engagement with health and climate change in health-care companies within the UN Global Compact, the world's biggest corporate sustainability framework.

For more on the **UN Global Compact** see https://www.unglobalcompact.org/

Indicator 5.1: media coverage of health and climate change

Headline finding: although total coverage of climate change increased substantially from 2018 to 2019, the rise was even greater for coverage of health and climate change, which increased by 96% during this period and has considerably increased from 2007 to 2019

This indicator tracks coverage of health and climate change from 2007 to 2019 in 36 countries, together with separate analyses of China's *People's Daily* and the content of coverage in leading newspapers in India and the USA. The analysis of coverage was based on keyword searches (in English, German, Portuguese, and Spanish) for health and climate change in 61 newspapers selected to provide a global spread of high circulation papers. The search strategy was revised for the 2020 report to exclude false positives while retaining true positive articles. Additionally, coverage of health and climate change in *Renmin Ribao*, the Chinese language edition of *People's Daily,* was tracked by use of keyword searches, algorithm-based natural language processing, and manual screening. The content of coverage of health and climate change was analysed in India (in *The Times of India* and *The Hindustan Times*) and the USA (in *The New York Times* and *The Washington Post*) from July 1, 2019, to Sept 30, 2019, and from Nov 1, 2019, to Dec 31, 2019. These periods were chosen to include extreme weather (monsoons and drought) and the 25th Conference of the Parties (COP; COP25).[28] The newspapers form part of the elite press that, via their influence on the country's political and economic elites, have an influence on the policy agenda.[231–236] Articles were searched by health and climate change keywords and manually screened; the final sample of 209 articles was independently coded by use of the template developed for the 2018 analysis.[28,237] Full descriptions of the methods, data sources, and further analyses are presented in the appendix (pp 136–168).

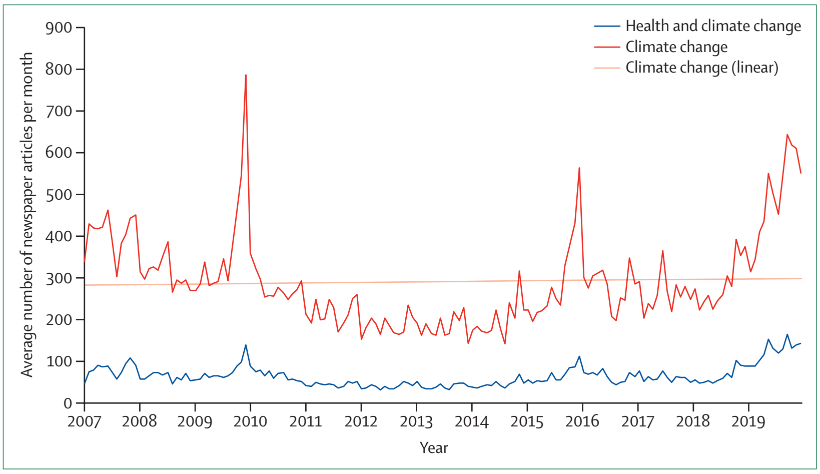

Figure 26: **Average monthly coverage of climate change, and health and climate change combined, in 61 newspapers from 36 countries, 2007–19**

The non-linear lines represent the average monthly coverage of climate change and health and climate change only across the 61 newspapers. The linear line represents the linear trend of the average number of climate change articles per month between 2007 and 2019.

Across the 36 countries, an increasing proportion of newspaper articles on climate change refer to human health. From 2018 to 2019, health and climate change coverage increased by 96%, outpacing the increase in overall coverage of climate change (74%). From 2007 to 2019, the average monthly number of newspaper articles on health and climate change increased by 57% and the average monthly number of articles on climate change increased by 23%. Overall, the coverage for health and climate change only made up 16% of all climate change coverage in the 2007–19 period (figure 26).

Coverage of health and climate change peaked in months that coincided with the 15th COP (COP15) in 2009 (Copenhagen, Denmark) and the 21st COP (COP21) in 2015 (Paris, France). Coverage rose again in late 2018 and remained high across 2019, corresponding with the rise of the school climate strikes and a series of extreme weather events, including the Californian and southern Australian wildfires.

Between 2008 and 2019, 275 (1·8%) of 15 001 articles on climate change in *People's Daily* were related to health. Health-related coverage spiked in 2013 because of coverage of the health threats of air pollution and heatwaves.[238]

Regarding the content of coverage in newspapers in India and the USA, three broad themes were identified in articles linking health and climate change. The dominant theme was the health impacts of climate change, discussed in 142 (68%) of 209 articles. References were often to the broad health impacts of climate change (eg, the *Hindustan Times* wrote, on Nov 14, 2019, that "few countries are likely to suffer from the health effects of climate change as much as India").[239] More specific connections were also made to climate-related stressors (eg, extreme weather events, wildfires, and population displacement) and health sequelae (eg, vector-borne disease and mental ill health).

The second theme related to the common causes and co-benefits of addressing climate change and health, discussed in 81 (39%) of 209 articles. Air pollution was the most frequently highlighted topic in this theme. The co-benefits of lifestyle changes to protect health and reduce emissions were also noted. The third theme focused on adaptation, discussed in 25 (12%) of 209 articles. For example, the *Times of India*, on Dec 10, 2019, noted that "all levels of government need to prioritize building health system resilience to climate change".[240] In addition, a small group of articles (six across the corpus) made a link between health and climate change with respect to activism and protests.

The relative prominence of the three main themes in the 2019 analysis matched that of the 2018 analysis, and the *Times of India* again gave more emphasis to the common causes and co-benefits of addressing climate change and health than did the other newspapers.[28]

Indicator 5.2: individual engagement in health and climate change

Headline finding: individual information seeking about health and climate change increased by 24% from 2018 to 2019, driven mainly by initial interest in health

Wikipedia usage provides a digital footprint of individual information seeking.[241,242] This indicator tracks individual engagement in health and climate change by capturing visits to pairs of articles (eg, an individual clicking from a page on human health to one on climate change). By use of data from the Wikimedia Foundation on the English version of Wikipedia (representing around 50% of global traffic to all Wikipedia language editions), this indicator is based on 6902 articles related to health and 1837 articles related to climate change.[243,244] Methods, data sources, and further analyses are described in the appendix (pp 169–182).

In both 2018 and 2019, individuals typically visited articles on either health or climate change, with little co-click activity between these pages. When these articles were linked, the majority (75%) of co-visits started from a health-related page. Although the overall number of health and climate change co-views was low, the value did increase by 24% from 2018 to 2019, pointing to a rising individual engagement in the links between these two topics. In both years, co-clicks increased in months coinciding with key events in climate politics. Co-clicks from articles on climate change to health in 2019 spiked during the COP and in September at the time of Greta Thunberg's speech at the UN's Climate Action Summit.[245]

Indicator 5.3: coverage of health and climate change in scientific journals

Headline finding: between 2007 and 2019, original research on health and climate change increased by a factor of eight, a trend driven by research led by scientists in high-income countries

This indicator is based on keyword searches for health and climate change in OVID MEDLINE and OVID Embase and used the comprehensive indexing systems and thesaurus of Medical Subject Headings for MEDLINE and Emtree for Embase. Methods, data sources, and further analyses are described in the appendix (pp 183–193).

Between 2007 and 2019, 5579 published academic articles referred to links between climate change and health. The period saw an increase in original research (ie, primary studies and evidence reviews) by a factor of eight and an increase in research-related articles (ie, editorials, reviews, comments, and letters) by a factor of three. In 2011, the number of original research articles surpassed the number of research-related articles, with new research representing 60% of total scientific output on health and climate change in 2019 (445 of 744 articles; figure 27).

Consistent with observations in section 1 (panel 3), the overall increase in research on health and climate change was mainly led by scientists based in high-income countries. USA-led research made up 1507 (27·0%) of 5579 articles in 2007–19 and 194 (26·1%) of 744 articles in 2019. UK-led research produced 826 (14·8%) articles in 2007–19 and 114 (15·3%) in 2019. Major contributions to the 2019 output also come from the Netherlands (63 [8·5%] of 744) and Switzerland (50 [6·7%] of 744). Increases were also evident for China, South Africa, and India.

Across the same period, articles on health and climate change represented only a small proportion (5579 [9·2%]) of a total of 60 883 articles on climate change. However,

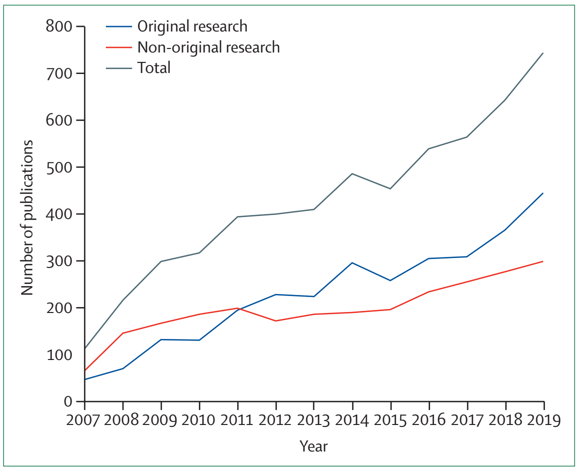

Figure 27: **Scientific journal articles relating to health and climate change, 2007–19**

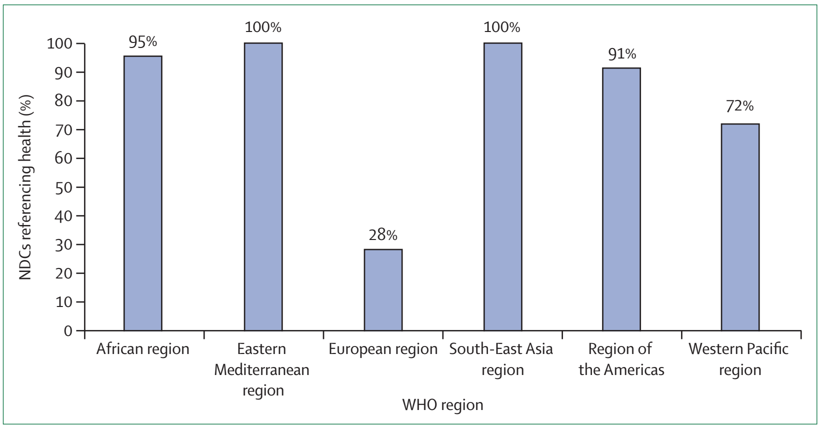

Figure 28: **References to health in NDCs by WHO region**
The European region, which consists of 53 countries, is adjusted for the single NDC representing 28 EU countries; treating the EU as one country would increase the regional proportion of NCDs referencing health to 60%. NDCs=Nationally Determined Contributions.

the increase in articles relating to health and climate change was greater than the increase in overall climate change output.

Indicator 5.4: government engagement in health and climate change

Headline finding: national governments are increasingly paying attention to health and climate change. Small island developing states are leading this trend at the UN General Debate, and poorer and more climate-vulnerable countries were more likely to reference health in their NDCs, with 95% of least-developed countries making these references

This indicator examines engagement with health and climate change in the UN General Debate and engagement with health in NDCs committed to as part of the 2015 Paris Agreement.[4,224] The indicator uses keyword searches of the UN General Debate corpus, with algorithm-based, natural language processing applied to the official English versions of the statements.[246,247] References to health-related terms (eg, "health", "illness", "disease", and "malnutrition") and climate-related health exposures were examined in the 185 countries who registered their NDCs in the UNFCCC repository by March, 2020, with a total of 2159 pages of text analysed. Building on previous analyses, this indicator analyses references and their prominence in the text.[227,248] Methods, data sources, and further analyses are described in the appendix (pp 194–218).

As part of the annual UN General Assembly, the UN General Debate provides a global forum for national leaders to discuss issues they consider important. Health has been a long-standing issue, but engagement with climate change was infrequent until the late 1980s. From the mid-2000s, national leaders began to focus on the connections between health and climate change, with the proportion of leaders making these connections rising rapidly from 2007 and peaking in 2014 at 24%.

Engagement in health and climate change continued to be led by the small island developing states, particularly in the Western Pacific region. By contrast, engagement remained low among the more powerful global actors, and particularly among those with the highest CO_2 emissions (eg, the USA, China, and the EU). For the third consecutive year, President Donald Trump's statement on behalf of the USA failed to make a single reference to climate change, let alone to the link between climate change and health. However, 2019 did see growing engagement with climate change and health by other high-income countries (eg, Australia, Canada, Germany, and Spain) and by low-income countries, particularly in the African region (eg, Burkina Faso, Botswana, Côte d'Ivoire, Niger, and Togo).

At the 2019 UN General Debate, the majority of health and climate change references focused on the health impacts of climate change. For example, Dominica broached the effects of climate change on small island developing states, highlighting "rising sea levels, violent tropical storms and hurricanes, periods of severe drought alternating with floods and forest fires, new plant diseases, and vector-borne disease such as chikungunya and Zika present an existential threat".[249] Similarly, Tonga's UN General Debate statement discussed how extreme weather events linked to climate change "are increasingly more intense, inflicting damage and destruction on our communities and ecosystems and putting the health of our peoples at risk".[250]

The 2019 UN General Debate also saw discussion of adaptation and resilience to "upgrade and climate-proof our health-care facilities" (Nauru),[251] improve "the quality of health care and the durability of health-care systems in the face of the climate crisis" (Palau),[252] and build "climate change resilience in our sectoral policies and strategies for health, transport, agriculture and pastoral production" (Niger).[253]

The second part of this indicator focuses on health within the NDCs, assessing both the references and their prominence within the text. Here, 135 (73%) of 185 NDCs included considerations of public health. At the WHO regional level, all countries in the South-East Asia and Eastern Mediterranean regions discussed these links (figure 28). At the country level, references to health were particularly common among the UNFCCC-defined least-developed countries (40 [95%] of 42). By contrast, the NDCs of the EU (representing the contributions of 28 countries) and the USA did not have any references.

A range of health dimensions were highlighted in the NDCs, including the direct impacts of climate change on health and health-related infrastructure. For example, in their respective NDCs, Morocco noted that climate change would increase deaths "by 250 000 annually between 2030 and 2050 due to malnutrition, malaria, diarrhea and heat-related stress"[254] and Cambodia discussed the effects of climate change on "death, injury, psychological disorders and damage to public health infrastructure".[255] There were also references to the co-benefits of interventions; for instance, Saint Lucia referred to "human health benefits" among "co-benefits associated with its [climate change] mitigation efforts".[256]

Among the 135 NDCs considering health and climate change, extreme weather events (eg, floods and droughts) and food security were the most commonly cited topics, with 70 (52%) discussing these links. The proportion of NDCs discussing an exposure term in relation to health was highest in the NDCs from countries in the South-East Asia region and was lowest in Europe. Examples included Sri Lanka's NDC that warned of "water borne diseases" that "can increase due to extreme heat and drought"[257] and Nepal's NDC that described "an increased frequency of extreme weather events such as landslides, floods and droughts resulting to the loss of human lives".[258]

Indicator 5.5: corporate sector engagement in health and climate change

Headline finding: in 2019, engagement in health and climate change increased to 24% among health-care companies in the UN Global Compact, although this engagement continues to lag behind that of other sectors

The UN Global Compact is a platform supported by the UN and created to promote environmental and social responsibility in the business sector.[259] This platform represents more than 10 000 companies from more than 160 countries. Focusing on the health-care sector, this indicator tracks engagement in health and climate change in the *Communication on Progress* reports that companies in the UN Global Compact submit each year (figure 29).

Analysis was based on keyword searches of terms related to health and climate change in 20 775 annual reports in the database of the UN Global Compact, and engagement in health and climate change was identified by use of natural language processing. Methods, data sources, and further analyses are described in the appendix (pp 219–228).

This indicator points to an increase in engagement by the health-care sector in 2019, with 12 (24%) of 50 companies referring to the links between climate change and health (figure 29). However, other sectors had higher levels of engagement than did the health-care sector, including the energy sector and the real estate investment sector.

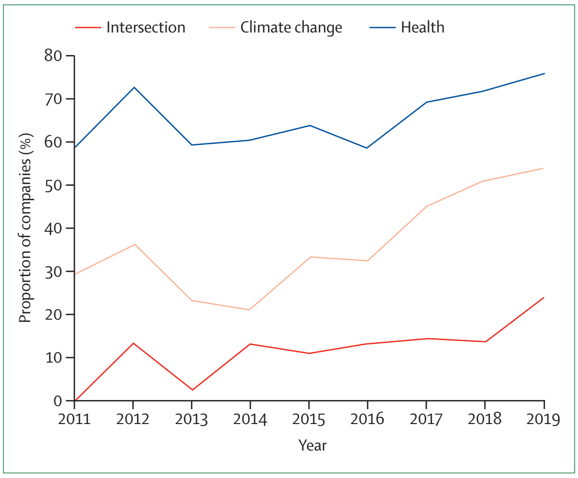

Figure 29: **Proportion of health-care sector companies referring to climate change, health, and the intersection of health and climate change in *Communication on Progress* reports, 2011–19**

Conclusion

Public and political engagement is essential to curb fossil fuel consumption and limit the global temperature rise to less than 1·5°C.[260] Section 5 has examined indicators of engagement relating to the media, the public, the scientific community, national governments, and the corporate sector. Taken together, the analyses point to two broad trends.

First, engagement with health and climate change continues to increase. Between 2007 and 2019, newspaper coverage increased by more than 50% and scientific journal output increased by more than 500%. Across 2018 and 2019, the proportion of Wikipedia users searching for articles that linked health and climate change also increased. There is evidence of dynamic and reinforcing relationships between these domains. Media coverage increased at times of heightened political and public engagement. As captured by Wikipedia use, there was a spike in individual engagement in health and climate change in September, 2019, coinciding with Greta Thunberg's speech at the UN Climate Action Summit.

However, beneath these trends are persisting inequalities in wealth and political influence. In both the UN General Debate and the NDCs, engagement in health and climate change is led by countries and regions that are affected most by the changing climate to which they have contributed the least. At the same time, the science of health and climate change continues to be led by high-income, high-emitting countries, which are mainly responsible for climate change.[208,261]

Second, in absolute terms, climate change continues to be framed in ways that pay little attention to its health dimensions. One-sixth of newspaper articles on climate change discuss its health dimensions; less than one-tenth of scientific articles do so, as do less than a quarter of health-care companies signed up to sustainable business practices. In the political domain, health and climate change are rarely connected by government leaders in their speeches at the UN's major global forum and, although most NDCs refer to health, the NDCs of countries with high per-capita carbon emissions, including EU countries and the USA, do not. Nonetheless, in key domains of engagement, the health dimensions of climate change are increasingly recognised, with media and scientific coverage rising more rapidly for health and climate change than for climate change as a whole.

Despite the fact that underlying inequalities in the drivers and effects of climate change remain, there is evidence that health is becoming increasingly central to public and political engagement.

Conclusion: the 2020 report of the *Lancet* Countdown

With the global average temperature having risen to 1·2°C more than that in preindustrial times, the indicators contained in the 2020 report provide insights into the health impacts of climate change today and in the future. Extremes of heat affect vulnerable populations the most, with some 296 000 deaths occurring as a result of high temperatures in 2018 (indicator 1.1.3).

The climate suitability for the transmission of a range of infectious diseases—dengue fever, malaria, and those caused by *Vibrio* bacteria—has risen across the world (indicator 1.3.1). At the same time, crop yield potential has fallen for each of the major crops tracked, with dire consequences anticipated for food-insecure populations (indicator 1.4.1).

And yet, the global response has remained muted. The carbon intensity of the global energy system has been stable during the past three decades, and global coal use for energy increased by 74% during the same period (indicators 3.1.1 and 3.1.2). This rise has resulted in approximately 390 000 deaths from $PM_{2·5}$ generated by coal-fired power, with total global mortality for all ambient sources exceeding 3·01 million deaths, in 2018 (indicator 3.3). In the agricultural sector, emissions from livestock grew by 16% from 2000 to 2017, with some 990 000 deaths occurring globally from excess red meat consumption in 2017 (indicators 3.5.1 and 3.5.2).

In the face of these problems, the response from the health profession continues to gain momentum. Spending on health system adaptation continued to increase, rising by 12·7% in 2019 to $18·4 billion (indicator 2.4). In just more than 10 years, original research on health and climate change has increased by a factor of eight, and, in half that time, health institutions with total assets of $42 billion have divested their holdings from fossil fuel industries (indicators 5.3 and 4.2.3). Led by low-income countries, more governments are linking health and climate change in their annual speeches at the UN General Debate and their NDCs under the Paris Agreement.

The public health and financial effects of COVID-19 will be felt for years to come, and efforts to protect and rebuild local communities and national economies will need to be robust and sustained. Despite concerning indicators across each section of this report, the 2021 UN Climate Change Conference presents an opportunity for course correction and revitalised NDCs. The window of opportunity is narrow, and, if the response to COVID-19 is not fully and directly aligned with national climate change strategies, the world will be unable to meet its commitments under the Paris Agreement, damaging health and health systems today, and in the future.

Contributors

The work for the *Lancet* Countdown was done by five working groups, which were responsible for the design, drafting, and review of their individual indicators and sections. All authors contributed to the overall paper structure and concepts, and provided input and expertise to the relevant sections. ER, CDN, NA, SA-K, JC, SD, LEE, IK, TK, DK, BL, YL, ZL, RL, JM-U, CM, MM-L, KAM, MO, FO, MRa, JCS, LS, MT, JTr, and BV contributed to Working Group 1. PB, DC-L, SCo, RD, KLE, LG, DG, JH, PLK, MM, KM, TN, MN, MOS, MPJ, JR, and JS-G contributed to Working Group 2. TO, IH, HK, MA, KB, CD, MDav, PD-S, ME, SH, S-CH, GK, ML, JM, DP, RQ, JS, MS, JTa, PW, and MW contributed to Working Group 3. PE, PD, and NH contributed to Working Group 4. HG, PL, MB, WC, SCa, MDal, ND, PH, SG, LM, SJM, SM, and OP contributed to Working Group 5. AC, HM, PG, NW, AM, MRo, and JB provided coordination, strategic direction, and editorial support.

Declaration of interests

We declare no competing interests.

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Article

Developing a Climate Change Vulnerability Index for Coastal City Sustainability, Mitigation, and Adaptation: A Case Study of Kuala Terengganu, Malaysia

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Abstract: Coastal hazards are an urgent issue of global concern considering the increasing population pressure in coastal regions, retreating coastlines, and rising seawater levels. Here we demonstrate the process of assessing the vulnerability of a coastal urban environment using the case of Kuala Terengganu, a coastal town in Malaysia, and evaluating the potential social, environmental, and economic impacts. Uncertainties in the human dimensions of global change deeply affect the assessment and responses to environmental, climatic, and non-climate impacts on coastal city population growth and communities. We address these uncertainties by combining a Delphi-Analytical Hierarchy Process (Delphi-AHP) model and Geographic Information System (GIS)tools to determine mitigation and adaptation probabilities as part of a Coastal City Vulnerability Assessment. We conclude by presenting calculations of the short- and long-term suitability for land use and recommending hazard mitigation measures to equip city planners and decision-makers in evaluating hazards and potential impacts on coastal city areas.

Keywords: Delphi-AHP model; GIS; erosion; climate change; vulnerability index; coastal city

1. Introduction

Close to 50% of the world's population lives within 200 km of a coastline, with projections suggesting this figure will rise to 70% by 2025 [1]. Knowledge of the vulnerability of coastal cities enables scientists and policymakers to anticipate impacts that could emerge from rising sea levels, floods, erosion, and other hazards [2]. This helps with prioritizing measures to minimize risks and mitigate impacts. Because of the high value of natural and socio-economic assets threatened or lost in coastal zones [3], it is important to identify the types and magnitude of problems affecting coastal cities and possible adaptations to them [4].

Due to combined environmental, climatic, and non-climatic influences, coastal cities in some countries are highly vulnerable to adverse environmental impacts. Research in this field has focused on three major strands [5]:

i. The first strand discusses non-climatic causes, such as accelerated urbanization, industrial growth, and property privilege, which have intensified vulnerability in certain coastal cities [6–11].
ii. The second strand explores global warming and rising temperatures and how they have jeopardized water supply, food production and security, and human health [12–18].
iii. The third strand studies the impacts of climate change on coastal cities and low-lying regions, which mainly focus on sea-level rise, flooding, erosion, storms, and typhoons [19–24].

Along the eastern coast of peninsular Malaysia bordering the South China Sea (SCS), flooding, coastal erosion, and coastal change constitute severe problems [25].

1.1. Land-Use Change and Destruction of Coastal City Regions

As noted [26] coastal flooding and sea-level rise in low-lying areas are expected to cause major damage unless significant adaptations take place.

As coastal populations continue to grow, better ways are also needed to increase coastal area resilience to the effects of storms, flooding, and erosion [27]. Many challenges are faced in assessing environmental and non-climatic impacts on coastal areas. Because of the rapid urbanization process, coastal regions have been densely populated and economically developed and so their protection needs to be a great social and economic priority [28].

Nevertheless, a holistic assessment of the effects of hazards on the coastal area is required to develop appropriate adaptation strategies to minimize potential damage [29]. Numerous factors need to be considered: The highly dynamic nature of the coastal environment may affect public safety and lead to the destruction of property due to submergence, flooding, saltwater intrusion in surface waters, and coastal erosion [30]. Consequently, coastal communities are exposed to a greater risk of property and infrastructure damage due to flooding [31]. Sea level rise increases coastal vulnerability to flooding, particularly during rainstorms, because as the level of the sea rises, low areas drain more slowly. Flooding occasioned by rainstorms may be aggravated if rises in temperatures increase rainfall intensity during heavy storms [32]. Sea level rise can also increase the vulnerability of low-lying areas to erosion and cause loss of beach [3]. Beaches and near-shore areas that offer habitats for fish, shellfish, shorebirds, as well as other species might shift inland or be lost. Conversely, coastal erosion aggravates the vulnerability to storms through the removal of dunes and beaches which offer protection against waves [33].

Malaysia in particular has been affected by sea levels rising on average 1.6–3.6 mm per year in the 1955–2003 period [34]. Coastal vulnerability index (CVI) studies are needed to assist in hazard management and planning in Malaysia and elsewhere to better understand the risk level that different coastal areas experience [4]. Coastal vulnerability encompasses bio-geophysical, economic, institutional, and socio-cultural factors. Knowing vulnerability may assist scientists and policymakers to forecast the effect of environmental impacts and consequently prioritize mitigation measures to minimize risks and impacts. Malaysia has developed an arsenal of programs and initiatives to manage coastlines, including an adaptation program initiated in the Ninth Malaysian Plan (2006–2010) which also focuses on the CVI. Also established was an Integrated Coastal Zone Management (ICZM) program, a coastline protection program, known as Storm Water Management and Road Tunnel (SMART), and a flood mitigation program. In our study, we focus on Terengganu, which has great value for the country as one of Southeast Asia's most popular tourist destinations and marine tourism gateways to the East Coast Economic Region (ECER) [35]. It is known for various unique tourism attractions catering to mainland coastal and island tourism, ecotourism, urban tourism, and its traditional culture and heritage tourism.

Using Terengganu as a case study area, the specific focus of our study was on three issues relevant for coastal cities:

i. What type of vulnerabilities exists?

ii. What are the options to adapt and mitigate vulnerabilities?
iii. What is the state of planning for adaptation?

Methodologically, we answered these questions by assessing the vulnerability and impact of Terengganu as a coastal city using Multicriteria Decision Analysis (MCDA) models and GIS tools. We will describe our approach in more detail in the following and also highlight the novelty, and importance, of this research.

1.2. Application of MCDA Model and GIS for Coastal City Vulnerability

Using MCDA models and GIS to determine the vulnerability of coastal cities is very effective at developing a consensus through soliciting expert opinions during successive stages of questionnaire administration and feedback [36]. This method is well suited as a research instrument when there is incomplete knowledge about a problem or phenomenon [37]. It has proven well suited for building frameworks, forecasting, prioritizing and decision-making, forecasting of uncertain factors capitalising on expert opinion where there is little or no definitive evidence and where opinion matters [38].

The Delphi technique was chosen as an efficient method of producing creative solutions [39]. This approach was applied successfully in environmental studies, industrial engineering, and project assessments [40]. The strength of the Delphi method lies in obtaining group opinions and expert judgment through anonymous, multilevel group interaction [41]. Remote data collection is an essential benefit of the Delphy technique, as participants may be spatially dispersed and questions can be administered by phone, Skype, fax, or post [42]. The Delphi method assigns priority ranks to the variables using pairwise comparisons at each level of the hierarchy [43].

The hierarchy approach, for instance, assessed the vulnerability criteria and subcriteria of erosion on the coastal city area, which required analysis of both qualitative information on coastal city areas [13]. The analytic hierarchy process (AHP) is one of the most widely used multi-criteria decision making (MCDA) techniques which has frequently been used for solving decision problems through minimizing complex decisions to a series of pairwise comparisons [44–48]. The AHP can accommodate both tangible and intangible criteria, individual values and shared-value measures, and the interaction between them, with the aim of synthesizing all the information and arriving at priorities that indicate preferences in the group decision process [28,30,49]. This technique enables analysts and decision-makers to organize the critical aspects of a complex decision-making problem in the form of a hierarchical structure like a family tree [50]. A Delphi and AHP model can evaluate many qualitative criteria and semi-quantitative criteria systematically based on expert judgments and through a process of determining the relative importance of a set of criteria [51]. One vital merit of MCDA is its ability to bring out the similarities and possible conflict areas among stakeholders in group decision-making that enhance a thorough understanding of the values of others [52].

Since the 1990s, coastal city planners have significantly increased their attention on the incorporation of the multi-criteria decision-making approach with GIS to solve the problems of spatial planning [53]. The ability of GIS to handle spatial facets of vulnerability assessments has improved its application in the criteria-based assessment for prioritization, and selection of possible appropriate and inappropriate areas, because the majority of the conditions for vulnerability assessment are spatial data [54]. GIS tools were thought to be a speedy tool for CCVA, especially for incomplete data situations.

We have developed a CCVA model by integrating GIS tools and the Delphi-AHP model for coastal city land use. The combination of the GIS technique and the Delphi-AHP model is a powerful approach that uses assessments of vulnerability in coastal city areas [55]. The assessment of the CCVA model aims to compare different regions and weigh them according to their vulnerability area. We showcase the capability of GIS to seamlessly integrate with the SMCDA method by presenting maps of the vulnerability of the city of Kuala Terengganu. In the GIS context, this study proposes a novel comparison framework that integrates the Delphi-AHP model for weighing GIS layers and creating vulnerability maps. This combination approach entails proper case retrieval and indexing, as well as the use of domain knowledge for feature weighting. The assignment of significance weights to each characteristic for knowledge-guided retrieval and indexing is of particular importance. The formulated CCVA constitutes an easily comprehensible tool to cope with and evaluate coastal city erosion areas. It compares regions of vulnerability in GIS maps and relative influences and sensitivity of diverse vulnerability layers.

2. Materials and Methods

2.1. Study Area

Kuala Terengganu is located in the southwestern part of the South China Sea, which is the largest semi-enclosed marginal sea in the Western Pacific Ocean. Terengganu is a constitutive state under the Federation of Malaysia and is located in Peninsular Malaysia on the mainland of the Asian continent. Kuala Terengganu is bordered by Kelantan in the North-West and Pahang in the South-West (Figure 1). The Terengganu people mostly live in coastal towns and villages. The Kuala Terengganu, which is situated at the entrance of the extensive Terengganu River, is the largest town in the state with an area of about 605 km^2. Terengganu has a 200 mile (320 km) long coastline along the South China Sea. It is located between the latitudes of 5°27′58.31″ N and 5°11′42.36″ N and the longitudes of 102°57′06.10″ E and 103°13′18.69″ E. This study is focused on the Kuala Terengganu coastline, which extends approximately 70 km from Merang to the southernmost point of the Setiu District to Rusila, the northernmost point of the Marang District.

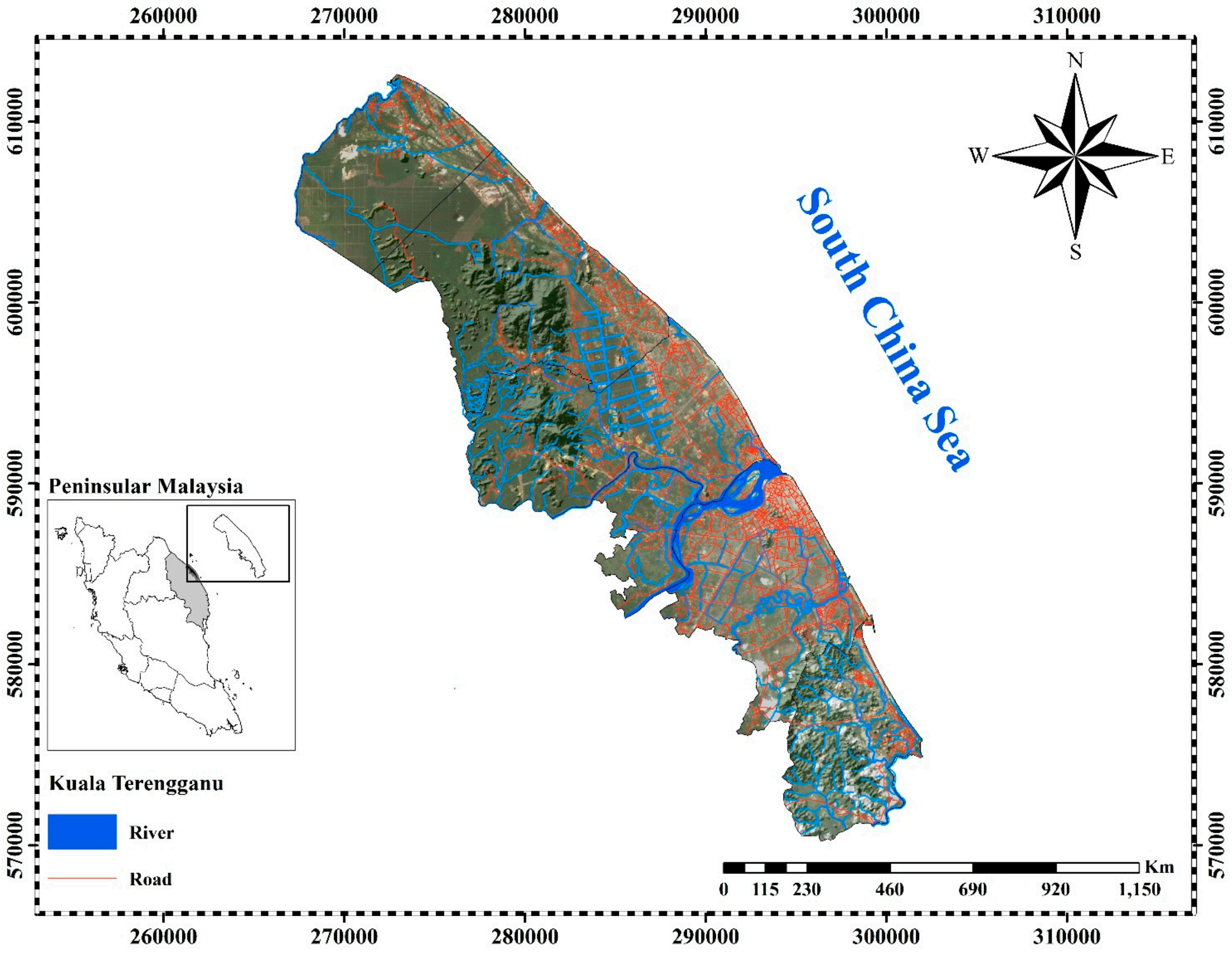


Figure 1. Location of Kuala Terengganu, Malaysia.

2.2. Data Requirement

In this chapter, we collected two types of data based on the CCVA model: primary and secondary data for the Delphi-AHP model and the GIS. The primary data for the Delphi-AHP model included expert knowledge and the expert choice matrix (ECM). ECM was sent to 12 experts from different agencies in Malaysia such as the Department of Irrigation and Drainage (DID), the SMART Control Centre, and the National Hydraulic Research Institute of Malaysia (NAHRIM). The ECM was used for three runs over seven months. The first run was carried out between 14 February 2014 and 17 April 2014, the second run occurred between 22 August 2014 and 20 September 2014, and the third run was carried out between 3 October 2014 and 7 November 2014. For GIS mapping, secondary data from related departments were collected. The secondary spatial data for GIS in this research were mainly retrieved from a topographic map (2002), a land-use map (2008) and a MUKIM map (2010) from the Department of Survey and Mapping Malaysia (JUPEM), a geology map from the Geology Department, a population map (2010) from the Department of Statistics, and a soil map (2008) from the Department of Agriculture (DOA) (Table 1).

Table 1. Primary and Secondary Data.

Primary Data (Delphi-AHP)	Secondary Spatial Data (GIS)			
	Digital Maps	Year	Resolution	Source
• ECM, send to the experts • Technical reports • Library survey	Topography Land use MUKIM	2002 2008 2010	1:50,000 1:100,000 1:100,000	JUPEM
	Population	2010	1:50,000	Statistic Department
	Geology	2008	1:100,000	Geology Department
	Soil	2008	1:100,000	MOA

The criteria were selected based on knowledge acquisition from the literature review, previous research, various Malaysian reports such as [18,56], and International reports such as those produced by the Ministry of Environment (2008), and the ETC CCA (2011).

2.3. CCVA Model Framework

The framework consists of six main segments, as indicated in Figure 2. The first segment of the framework sought to identify and design each coastal city's erosion vulnerability criteria and sub-criteria by using the Delphi-AHP model. The expert choice matrix was created in the second part, which was submitted to 12 experts from various Malaysian authorities (DID, SMART, NAHRIM). For six months, the expert choice matrix was in use (for three rounds). The first round took place from 14 February to 17 April 2014, the second round from 22 August to 20 September 2014, and the third round from 3 October to 7 November 2014. The vulnerability criteria, sub-criteria (qualitative data), and vulnerability GIS layer classes were ranked and scored by professionals from numerous Malaysian agencies (semi-quantitative data). The third segment examines the weights for qualitative and semi-quantitative data using expert choice software along with sensitivity analysis for every criterion and region (alternatives). In the fourth segment, the GIS vulnerability layers and classes were investigated and organized according to the AHP design. The fifth segment is there to apply the Delphi-AHP model and GIS technique for generating vulnerability maps by overlayer mapping and to calculate the weights of all layer classes in GIS software for generating the final vulnerability map. The final segment shows a wide variety of adaptation solutions.

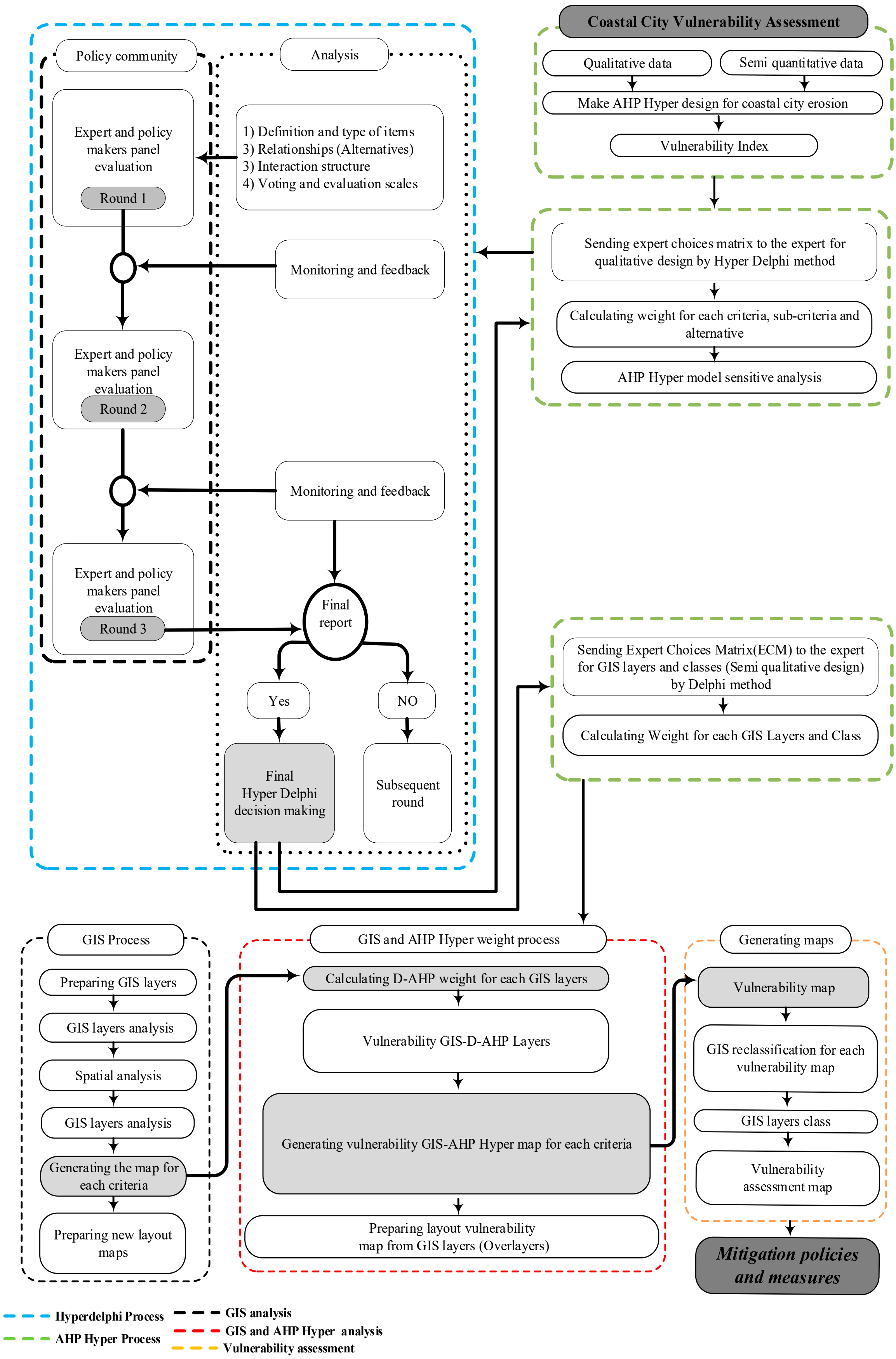


Figure 2. Coastal city vulnerability assessment and adaptation plan framework.

2.4. Application of the Delphi-AHP Model and GIS Technique

This article proposes a comparative framework model which integrates knowledge of the Delphi-AHP model in weighing CCVA. The Delphi-AHP framework involves an empirical study based on the Delphi method to refine important criteria gleaned from a literature review and other criteria resulting from an expert panel. This integration method represents an adequate case retrieval and indexing and incorporates domain knowledge for feature weighting. Our specific interest lies in the assignment of importance weights to each feature for knowledge-guided retrieval and indexing. This integration approach is recommended in intelligent modeling for a CCVA.

There are two types of vulnerability hierarchy designs: a qualitative design and a semi-quantitative design. A qualitative design is used for the evaluation of erosion assessments from expert knowledge. A semi-qualitative design is for erosion assessment from expert and GIS layers. Through the Delphi-AHP approach, we assessed the vulnerability criteria and sub-criteria of erosion affecting the coastal city area, which required analysis of both quantitative and semi qualitative information. The model measures erosion vulnerability in terms of a vulnerability index based on qualitative data and assesses semi-quantitative erosion vulnerability in GIS layers. This model assigns priority weights to the variables using pairwise comparisons at each level of the hierarchy. In the Delphi-AHP model, qualitative and semi-quantitative data improve the system's consistency and simplify the calculation of the weight for criteria and sub-criteria.

The vulnerability hierarchy design encompasses criteria and sub-criteria of which we select the best criteria based on expert knowledge by using the Delphi method and the ECM, along with fieldwork and observation, and a literature review. In this component of the research, one of the main objectives was to select one option from a set of known options. In real-world spatial decision-making problems, the decision-maker should choose the best geographical location of interest. GIS is known as a potential tool and powerful technique for monitoring the changes in land use on a regional scale and handling environmental spatial data in land-use assessment and planning. The combination of GIS and Delphi-AHP models has been proven to be a powerful approach since the numbers of alternatives originating from a GIS are very large (each location being represented by a line, point, or polygon). Thus, in the spatial decision, listing the alternatives from a GIS would be very difficult.

The sub-district map (MUKIM map) of Kuala Terengganu was divided into six regions representing different areas of vulnerability. Selecting the best region does not mean that it is the most suitable choice, rather it means that this area should be afforded the highest priority for deciding on the most suitable areas. The following alternatives (regions) available in the study area are: Merang; Batu Rakit; Kuala Nerus; Manir; Pengadang Buluh; and Rusila.

In the AHP model, the evaluation criteria are associated with geographical entities and the relationship between them. Hence, the evaluation criteria can be represented in the form of maps or GIS layers. We collected and analysed the GIS maps that contain geographical attributes. The following spatial layers have been incorporated as maps: (1) environmental layers, and (2) human activity layers.

There are nine stages in the Delphi-AHP modeling process and GIS approach. The CCVA model is produced by merging these two techniques with GIS. Stage 1: The decision for the problem is structured into a hierarchical model. It includes the decomposition of the decision problem into elements about their characteristics as well as the formation of a hierarchical model having various levels [57]. Stage 2: Application of the Delphi method and ECM. Stage 3: Collecting input data by making pairwise comparisons of decision elements and obtaining the judgment scales. Stage 4: Derivation of priorities where, after filling the comparison matrices, priorities can be computed [58]. Stage 5: Evaluating the weight consistency of comparisons. In this step, calculations were performed to find the maximum eigenvalue, the consistency ratio (CR), the consistency index (CI), as well as the normalized values for each alternative and criterion [56]. The Delphi-AHP measures the overall judgments' consistency through a consistency ratio (CR). The consistency of the judgmental matrix can be determined by examining the total CR [59], being the ratio of CI and RI, as given by:

$$CR = \frac{CI}{RI} \quad (1)$$

RI is the random consistency index of a randomly generated reciprocal matrix from the nine-point scale, with reciprocals forced [60]. If CR is less than 10%, the matrix is considered to have an acceptable consistency [61]. The scores were accepted when they reached a certain level of consistency, as determined by a consistency index (CI). [58] has proposed a CI, which is defined as:

$$CI = \sum_{j=1}^{\lambda} W_j * CI_j \quad (2)$$

W_j is the weight of criterion j and CI_j is the consistency index of criterion j. Stage 6: In this step, the local weights of the elements are calculated by using the Expert Choice software (EC) computing the Delphi-AHP weight. Stage 7: Weights across different levels are aggregated to get the final weights of the alternatives. This step collects all priorities from the decision table through a weighted sum of the type [51] and synthesizes the local priorities across all criteria to identify the global priority. The final weight of alternatives would be computed using an additive hierarchical aggregation rule Final Weight (5) by normalizing the sum of the local priorities to unity, as shown below:

$$Z_i = \sum_j w_j * S_{ij} \quad (3)$$

Z_i is a global priority of the alternative, S_{ij} is a local priority and w_j is the weight of the criterion j. The global priorities (Z_i) thus obtained are finally used for normalizing by dividing the score of each alternative only by the score of the alternatives and selection of the best alternative under each criterion [51]. Stage 8: Since the Delphi-AHP model is a responsive analysis, the input data is somehow modified to detect the effect on the output [60]. We used sensitivity analysis only for qualitative data in this section of the Delphi-AHP model, so experts rate and weight the qualitative data, where their findings could be used to make a semi-quantitative data judgment. The current rank of Delphi-AHP qualitative parameters is then provided based on a pair-wise comparison for land use vulnerability, hazard, and risk performed by experts from SMART, DID, and NAHRIM. One of the popular sensitivity graphs for expert selection is known as a radar graph. Each radar graph has its special menu commands, and it is possible to compare each sensitivity between the criterion and the alternative. If the priority sensitivity of one criterion or alternative is increased, the number of changes that can be made as a result of sensitive considerations may be found with other criteria or alternatives. Therefore, by using qualitative results, we can make decisions and rank for semi-quantitative data (GIS class) and ascertain the weight of each layer. Stage 9: The linear combination of the Delphi-AHP weights for the assessment of the vulnerability is given as follows:

$$HAL = L_{v7} \times W_{vlc7} + L_{v8} \times W_{vlc8} + L_{v9} \times W_{vlc9} \quad (4)$$

$$EL = L_{v1} \times W_{vlc1} + L_{v2} \times W_{vlc2} + L_{v3} \times W_{vlc3} + L_{v4} \times W_{vlc4} + L_{v5} \times W_{vlc5} + L_{v6} \times W_{vlc6} \quad (5)$$

$$CCVA = EL \times HAL \quad (6)$$

where EL signifies the Environmental Layer function, HAL refers to the Human Activity Layer function, and C_v signifies the vulnerability layer and W_{vlc} denotes the weight of the vulnerable layer class, representing the CCVA function of erosion.

3. Results

In Delphi-AHP, a model is used to identify the best criteria and to design the criteria and sub-criteria. We divided all criteria and sub-criteria into qualitative and semi-quantitative components. The qualitative component consisted of the vulnerability index, environmental criteria, and criteria relating to human activities, with each criterion having sub-criteria (Table 2). The weight of all criteria and sub-criteria was calculated, along with alternatives for the qualitative design in the expert choice software. By using a sensitivity analysis and weight for each criterion, ranks were established in the ECM for the semi-quantitative component and weights calculated for the GIS layer classes of the semi-quantitative data.

3.1. Delphi-AHP Qualitative Weights

For the environmental criteria, we selected six criteria based on erosion in the coastal city areas by using the ECM from the experts applying the Delphi-AHP model. The estimated final weight for each criterion, sub-criterion, and the alternative is as follows. The high weight, River Criteria (RC) W was 0.232 with CR being 0.09, and the high alternative being 0.439 in Pengadang Buluh and the low alternative being 0.053 in Merang. In this region, the river is not sensitive to erosion because there is no river, which was consequently given a low weight. However, in Pengadang Buluh, the substantive river traversing the city center was assigned a high rank from the experts and high weight in the expert choice software. In the (HAC), we had three criteria selected from the expert choice matrix. The high weight is Build up Criteria (BC) W: 0.071 with CR: 0.09 and high alternative being 0.434 in Pengadang Buluh, and low alternative being 0.055 in Merang (Table 2). The alternative, Pengadang Buluh is located in parts of Kuala Terengganu with built-up and coastal contracture. As a result, this area is both sensitive and important, especially when compared to other places in terms of environmental evaluation, evaluation of fieldwork observation, expert decision-making, and region-sensitivity analysis.

3.2. Delphi-AHP Model Sensitive Analysis

A sensitivity analysis shows the sensitivity of the alternatives for all the model's different criteria for the choice of the important erosion criteria in the Kuala Terengganu coastal areas. The sensitivity analysis originates from the use of the radar graph (A and B) through the application of the Delphi-AHP (Figure 3). Each radar graph has its unique menu commands and the sensitivity between criteria and alternatives can be compared with each other. If the priority sensitivity of each criterion or alternative is changed, the number of changes that would be made using other criteria or alternatives can be viewed as an output of the sensitivity analysis. Thus, the priorities of the alternatives will change in the right column by changing the positions of the nine criteria priorities in the left column. If a decision-maker thinks an objective might be more or less important than originally indicated, the decision-maker can drag that objective's bar to the right or left to increase or decrease the objective's priority and see the impact on the alternatives (Table 3 and Figure 3).

Table 2. Delphi-AHP weights for coastal city vulnerability criteria for Kuala Terengganu, Malaysia.

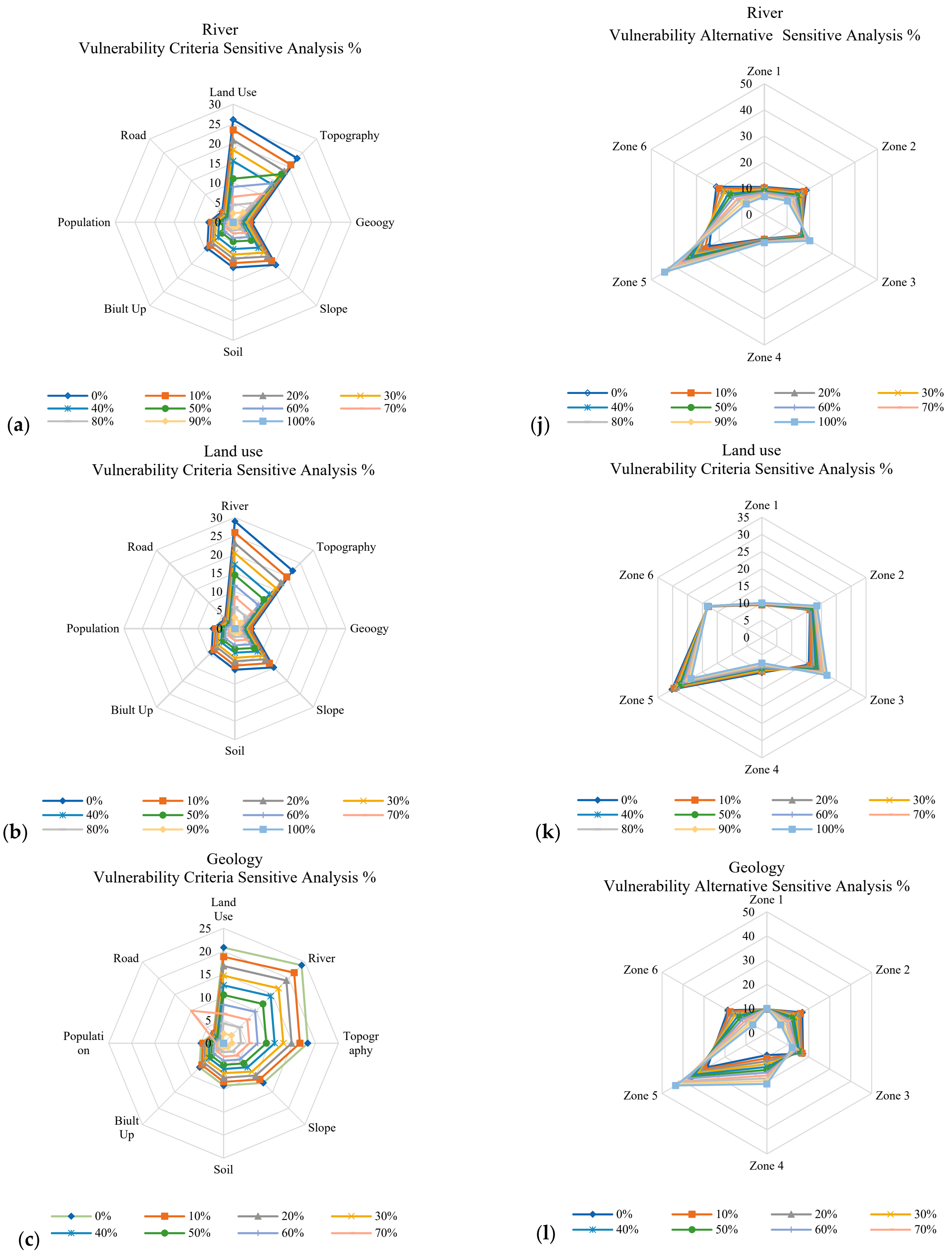
Goal	Index	Criteria		Criteria Consistency Ratio	Criteria Weight	Sub-Criteria	Sub-Criteria Consistency Ratio	Sub-Criteria Weight	Alternative	Alternative Weight
Coastal city vulnerability assessment	Vulnerability Index	Environmental Criteria	River	0.09	0.232	Seasonal shifts	0.06	0.084	Merang	0.053
						Discharge of water	0.06	0.207	Batu Rakit	0.129
						The severity of the flood	0.03	0.27	Kuala Nerus	0.199
						Sedimentology (Sediment rate)	0.06	0.123	Manir	0.105
						Water from runoff	0.07	0.06	Pengadang Buluh	0.439
						Relationship between Rainfall and Runoff	0.06	0.256	Rusila	0.075
			Land Use	0.04	0.201	Cultivation & Plantation	0.07	0.125	Merang	0.101
						Forestry	0.07	0.239	Batu Rakit	0.186
						Rangeland	0.07	0.046	Kuala Nerus	0.218
						Industrial, and the commercial development	0.09	0.361	Manir	0.075
						Watershed	0.06	0.105	Pengadang Buluh	0.237
						Cultural areas	0.05	0.05	Nerus	0.183
			Geology	0.08	0.058	Scale of geomorphology	0.08	0.566	Merang	0.101
									Batu Rakit	0.066
						Waterways	0.08	0.26	Kuala Nerus	0.121
						Tectonic movement	0.08	0.086	Manir	0.211
									Pengadang Buluh	0.435
						Epoch of geology	0.08	0.08	Nerus	0.067
			Slope	0.09	0.12	Slope level	0.08	0.582	Merang	0.052
									Batu Rakit	0.204
						The average waterway/floodway slope	0.07	0.161	Kuala Nerus	0.118
						The slope of land usage on average	0.09	0.197	Manir	0.103
									Pengadang Buluh	0.132
						Without-slope regions	0.04	0.06	Nerus	0.392
			Soil	0.09	0.092	Type of soil	0.08	0.373	Merang	0.075
						Erosion of the Soil	0.07	0.337	Batu Rakit	0.1
						Influence of the soil	0.06	0.099	Kuala Nerus	0.267
									Manir	0.038
						Organic material	0.09	0.045	Pengadang Buluh	0.472
						Amount of land used for agriculture	0.07	0.145	Nerus	0.048
			Topography	0.09	0.167	Vertical categorization	0.09	0.223	Merang	0.104
									Batu Rakit	0.163
						Vertical classification in coastal area	0.09	0.239	Kuala Nerus	0.096
						Classification area and location	0.08	0.425	Manir	0.138
									Pengadang Buluh	0.267
						Average height	0.08	0.113	Nerus	0.232

Table 2. *Cont.*

Goal	Index	Criteria		Criteria Consistency Ratio	Criteria Weight	Sub-Criteria	Sub-Criteria Consistency Ratio	Sub-Criteria Weight	Alternative	Alternative Weight
	Human Activity Criteria	Road		0.08	0.029	Type of grid	0.09	0.2	Merang	0.082
						The closeness of a water source to a road	0.09	0.148	Batu Rakit	0.039
									Kuala Nerus	0.093
						Location of the road to the seaside	0.09	0.607	Manir	0.035
						Materials Types	0.09	0.045	Pengadang Buluh	0.528
									Nerus	0.223
		Population		0.09	0.047	Density/ha	0.09	0.112	Merang	0.063
						Landforms are shaped by density	0.07	0.129	Batu Rakit	0.267
									Kuala Nerus	0.207
						The density of the coastline	0.06	0.501	Manir	0.069
						Density in rural and urban zone	0.06	0.045	Pengadang Buluh	0.299
						Density in a potentially dangerous location	0.08	0.213	Nerus	0.095
		Build up		0.07	0.071	The shape of the land	0.08	0.338	Merang	0.055
						Location of the river grid	0.04	0.184	Batu Rakit	0.170
									Kuala Nerus	0.172
						The distance from the coast	0.07	0.426	Manir	0.072
						Materials supply, both local and non-local	0.07	0.052	Pengadang Buluh	0.434
									Nerus	0.097

Table 3. Coastal city vulnerability sensitivity assessment.

	Human Activity and Environmental Criteria													
	%	Land Use	Topography	Geology	Slope	Soil	Built-Up	Population	Road	Merang	Batu Rakit	Kuala Nerus	Manir	Pengadang Buluh	Nerus
River	10	23.5	20.7	4.2	13.8	10.4	0.9	5.5	3.5	10.2	17.6	16.5	9.5	26.4	19.9
	50	11.1	17.3	2.0	6.5	4.9	3.9	2.6	1.7	8.7	14.2	17.6	10.4	34.4	14.7
	90	2.3	3.6	0.5	1.4	1.1	8.3	0.6	0.4	7.3	11.2	19.7	10.8	42.2	9.4



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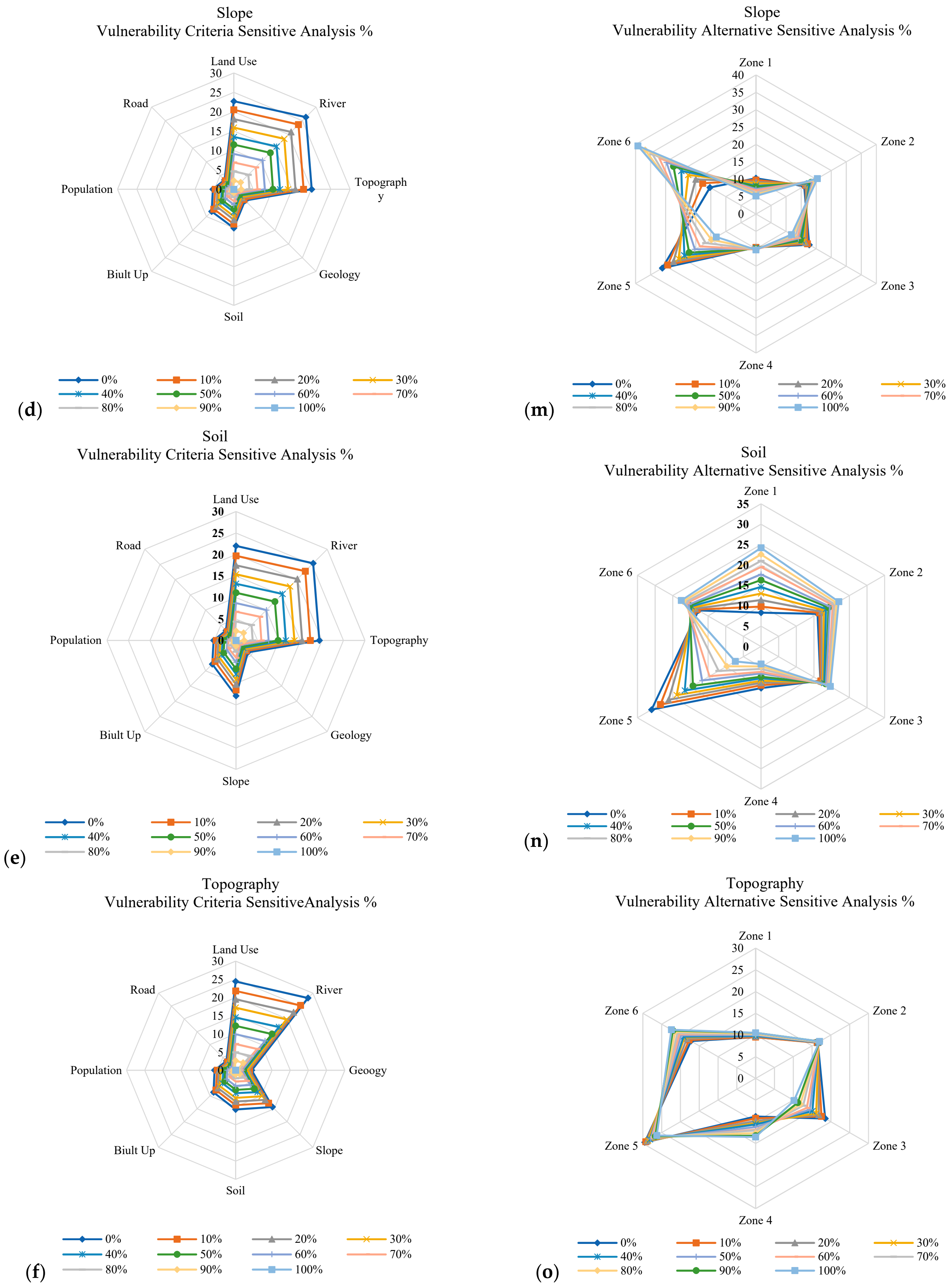

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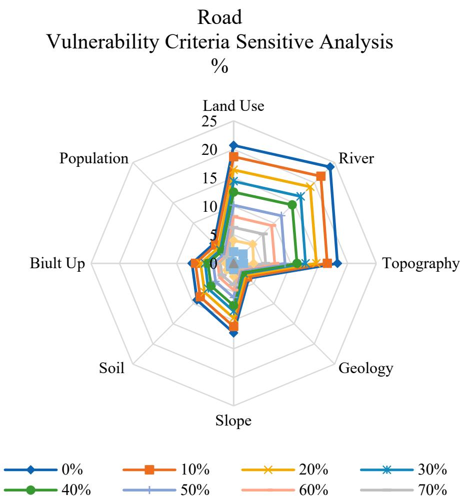

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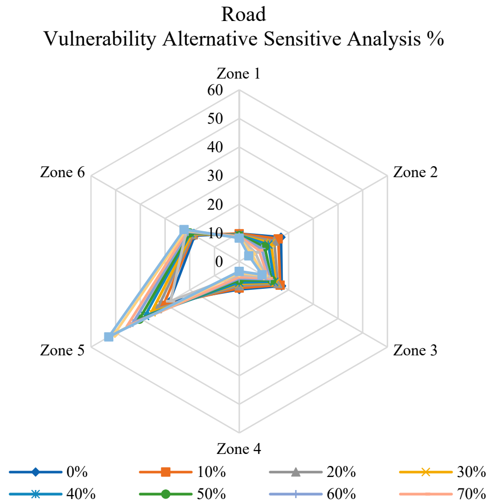

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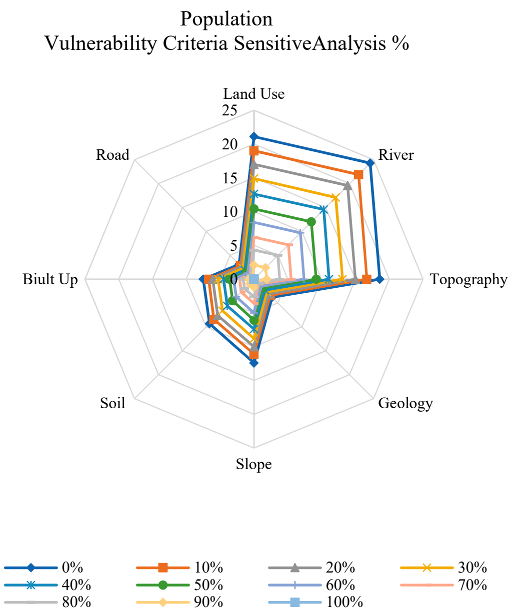

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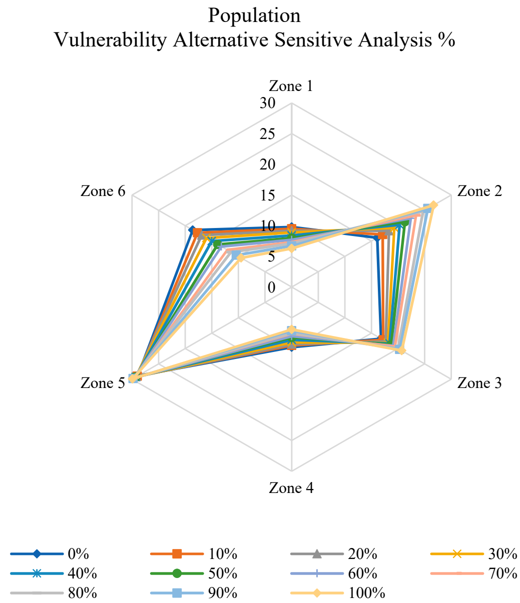

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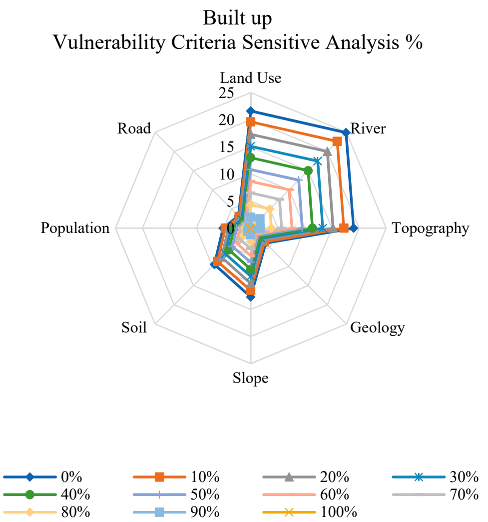

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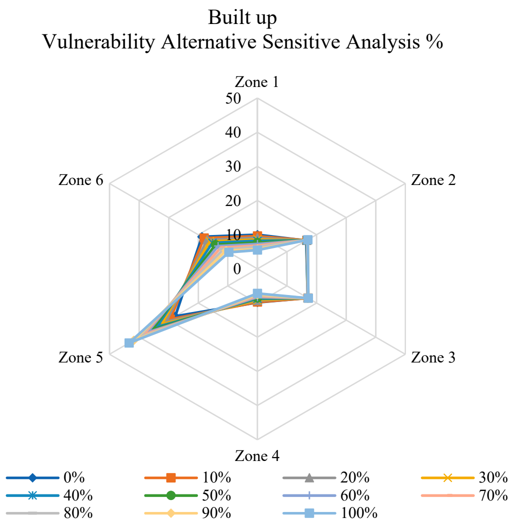

(r)

Figure 3. (**a**–**i**) Radar graph of the vulnerability criteria for coastal city erosion for Kuala Terengganu, Malaysia, as per sensitivity analysis conducted in Expert Choice software. (**j**–**r**) Radar sensitive graph between the vulnerability criteria and regions developed as an alternative.

The study considered the land use criterion from the environmental criteria because the Delphi-AHP results revealed that land use has a higher weight than the other environmental and human activity criteria. By increasing the share of the river criteria to an extreme value of 23.5% of the main goal, leaving 76.5% for the others, while keeping the proportionality between them, it was noticed that the model still favored Pengadang Buluh with a score of 26.4%. This was followed by Rusila with a score of 19.8%, Batu Rakit with a score of 17.9%, Kuala Nerus with a score of 16.4%, Marang with a score of 10.0% (Figure 3).

As for the environmental criteria, an increase in the sensitivity of the river criterion to a high weight (0.231 with a corresponding inconsistency of 0.09) to 10%, 50%, and 90% of the main goal in the radar chart, was noticed that the Delphi-AHP model is still in favour of the land use criterion with a score of 23.5%, 11.1%, and 2.3%, respectively. As for the human activity criteria, a build-up with scores of 8.3%, 3.9%, and 0.9%, respectively, is more sensitive than for population and road (Table 3).

The result is reasonable since more sensitivity exists towards the land-use criteria in the vulnerability index, which is significantly greater than the other criteria. With an increase in the sensitivity of the river criterion in Kuala Terengganu, land use criteria will be less vulnerable than other criteria. In the radar graph, the study explained which area is more vulnerable to erosion based on the criteria. The same conclusion could be drawn for the regions where Pengadang Buluh remains the most vulnerable and sensitive area with scores of 26.40%, 34.4%, and 42.20%. In contrast, Marang has scores of 10.20%, 8.70%, and 7.30%, respectively, and thus remains the least sensitive and vulnerable area for erosion in the central Terengganu coastal area. Pengadang Buluh is consistently at the top, with a score of more than 26.40%, followed by other Kuala Terengganu areas (Figure 3).

3.3. Delphi-AHP Semi Qualitative Weights and GIS Analysis

The erosion vulnerability assessment function of the coastal city is considered in terms of the environmental and human activity vulnerability. The more vulnerable an area is, the more important it is to protect the site. The erosion vulnerability functions of coastal city areas address the environmental and human activity retention capability of the city in this research. Weighted linear combinations of GIS layers were used for the vulnerability evaluation of the coastal city erosion relating to the environmental and human activity criteria.

The CCVA for the semi-quantitative Delphi-AHP design refers to a locale characterised by a specific relative weakness of exposure to natural disasters and their ability to handle them when they occur. CCVA can provide an understanding of relative future changes in coastal cities. It can also be regarded as the theoretical basis for estimating the vulnerability of coastal cities relating to erosion caused by environmental and social factors. Based on the results of the Delphi-AHP model from experts' opinion, the study constructed, classified, and quantified nine vulnerability GIS layers (VGL) into two domains, namely the environmental GIS layer (EGL) and the human activity GIS layer (HAGL) (Figures 4 and 5).

As can be seen from Figures 4 and 5 below, the EGL domain was constructed based on a comprehensive literature review which was subsequently examined by experts. Six layers were adopted for the EGL domain, namely: Land use; River; Geology; Slope; Soil; and Digital Elevation Map (DEM). Under the HAGL, three layers were adopted, namely; Population density; Build-up; and Road network. The EGL classes are weighted due to serious coastal city erosion problems. The river class has the highest weighting of 0.281 while the geology class has the lowest weighting of 0.028.

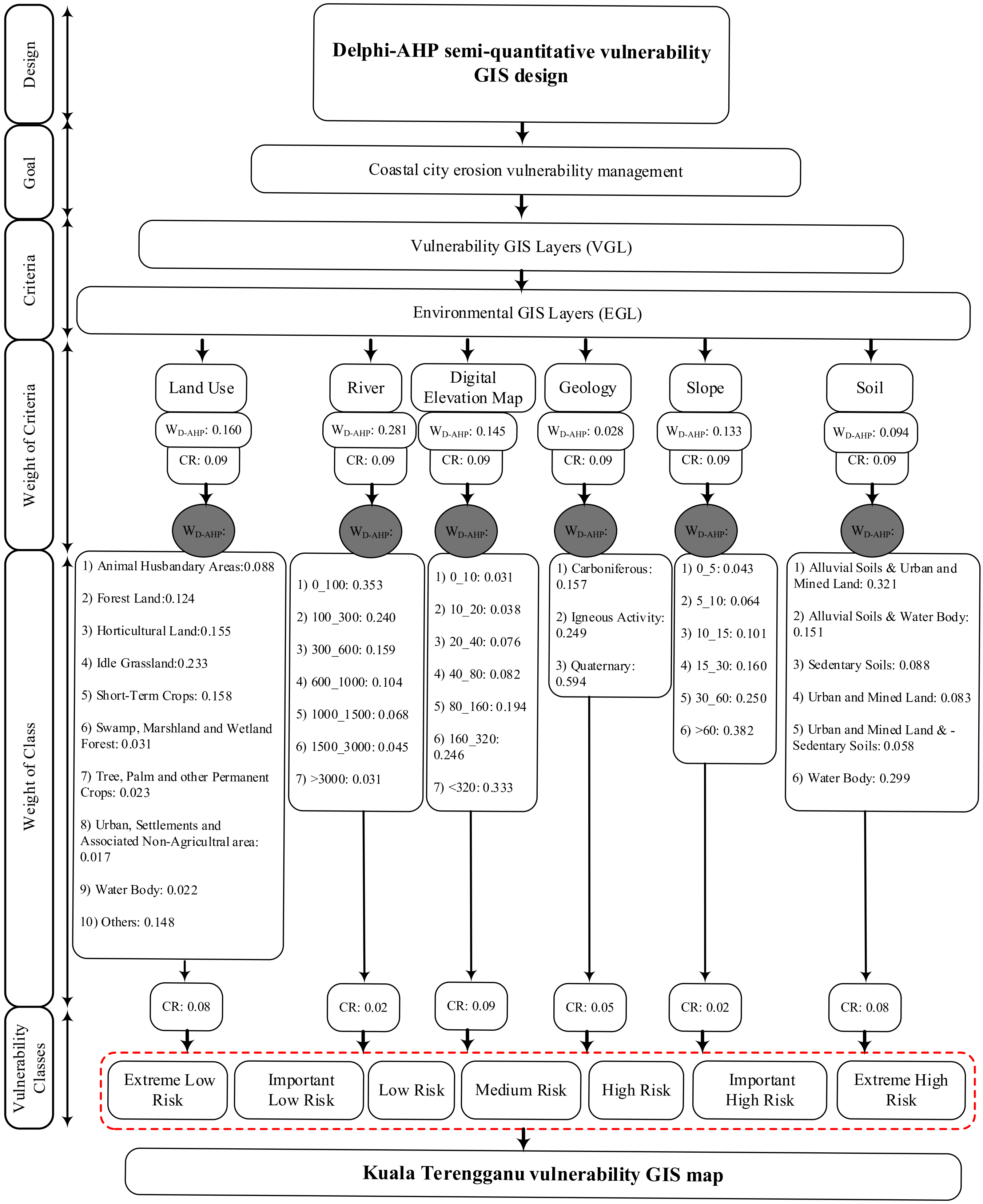

Figure 4. Delphi-AHP design and weights for EGL.

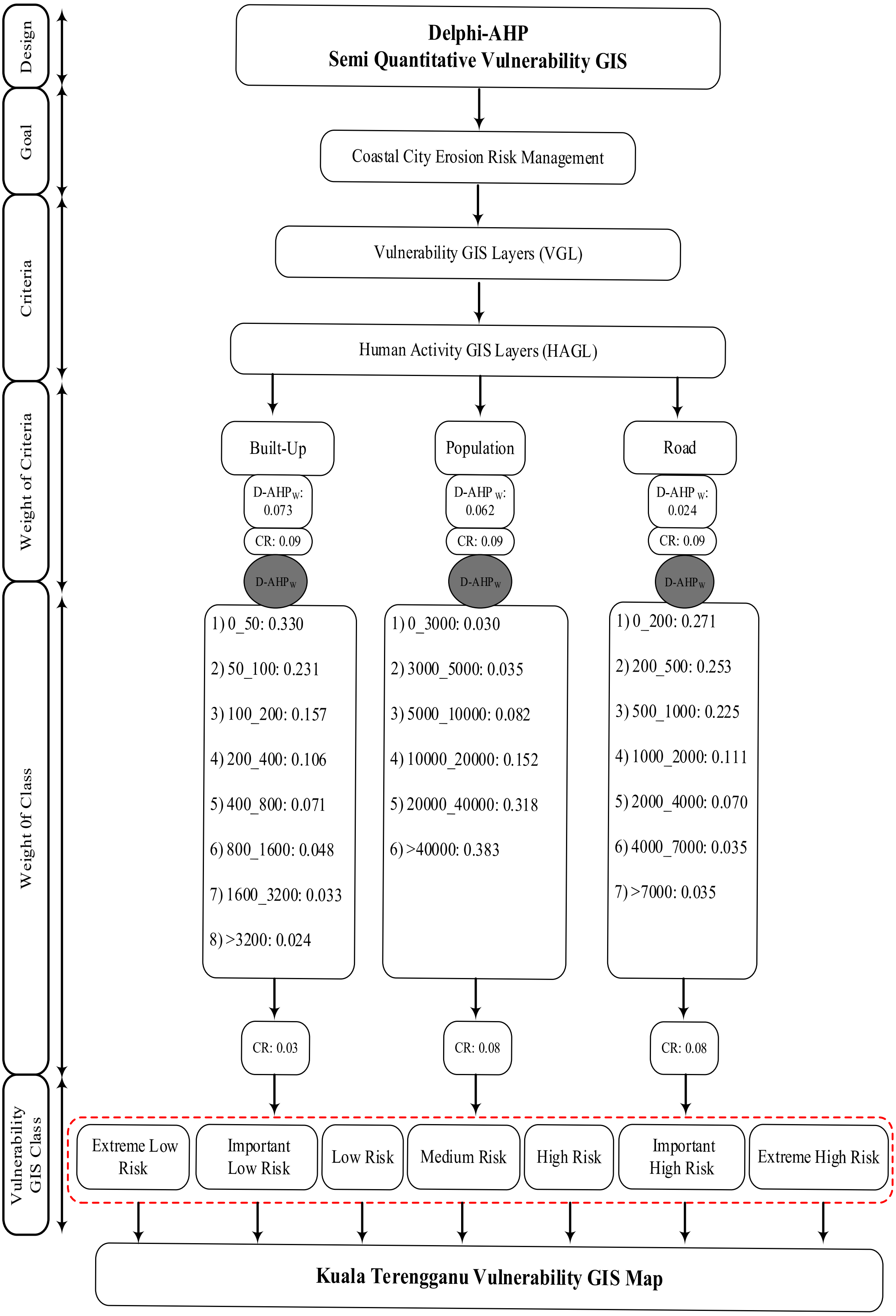

Figure 5. Delphi-AHP design and weights for HAGL.

Each layer illustrated in Figures 4 and 5 was weighted according to its importance and generated a GIS layer enabling the creation of maps in ArcMap. Figures 6 and 7 show the maps consisting of environmental and human activity vulnerability layers. Before calculating the Delphi-AHP weights for each layer, a classification, buffering, and distance calculation was made for each layer. Through the Delphi-AHP weights for the vulnerability layers, sensitive areas and vulnerable layers were identified for central Terengganu coastal areas. In this part of the GIS analysis, we calculated all layers with environmental and human activity functions for generating the final CCVA map. The linear combination of the weights and layers for the evaluation of the environmental and human activity functions are as follows:

$$\text{EL function} = [R] \times 0.281 + [L] \times 0.160 + [G] \times 0.028 + [S] \times 0.133 + [SO] \times 0.094 + [D] \times 0.145 \quad (7)$$

$$\text{HAL function} = [B] \times 0.073 + [P] \times 0.062 + [R] \times 0.024 \quad (8)$$

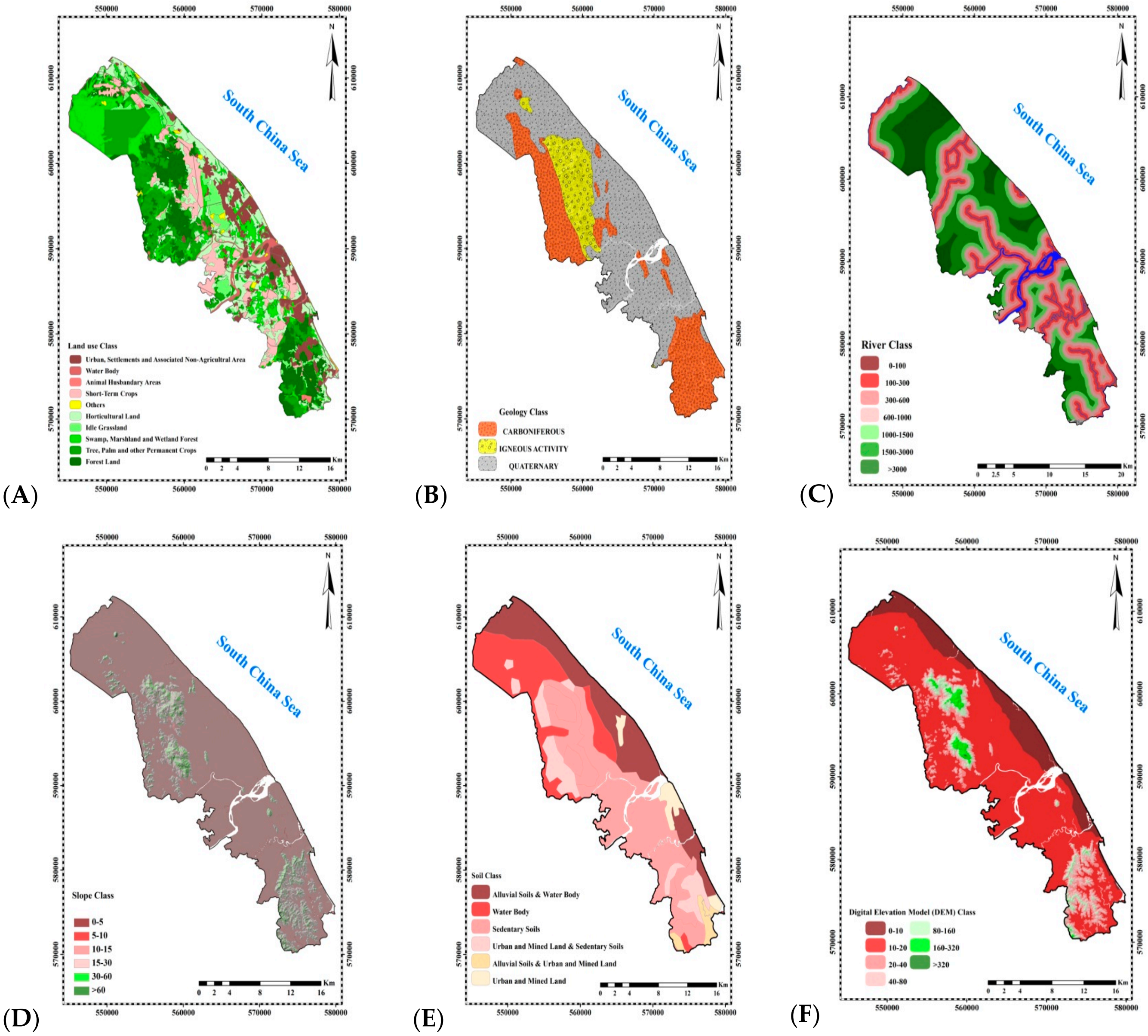

Figure 6. *Cont.*

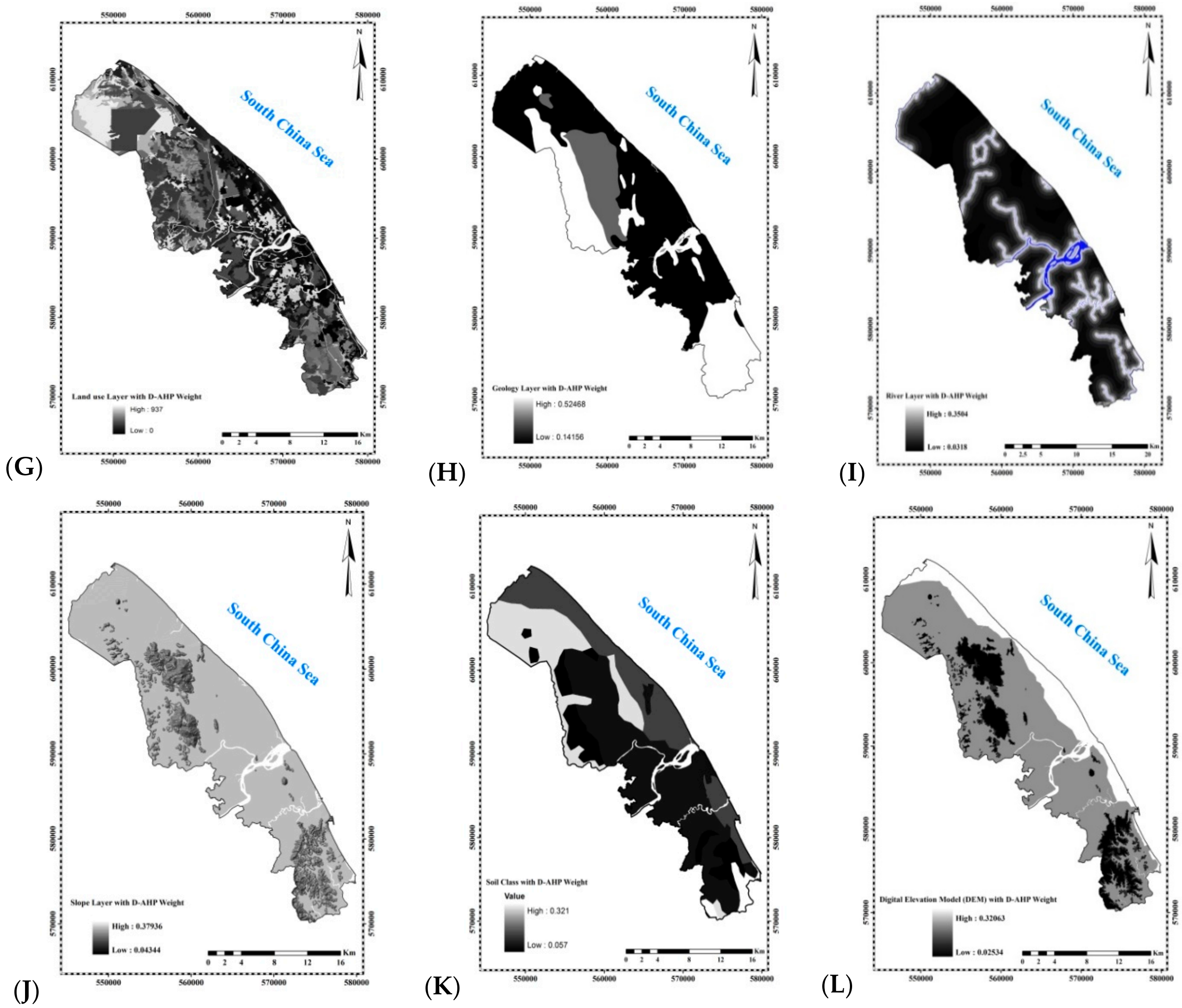

Figure 6. Environmental GIS layers class: (**A**) Land Use, (**B**) Geology, (**C**) River, (**D**) Slope, (**E**) Soil (**F**) Digital Elevation Map (DEM). Environmental GIS layers based on calculations of Delphi-AHP weights, (**G**) Land use layer, (**H**) Geology layer, (**I**) River layer, (**J**) Slope layer, (**K**) Soil layer, (**L**) Digital Elevation Map (DEM) layer.

By combining each layer weight and overlay with all layers to generate the environmental map and human activity map to calculate and generate the final CCVA, the functions are as follows:

$$\text{CCVA function} = EL_w \times HAL_w \quad (9)$$

The final CCVA map for the three regions in the Kuala Terengganu coastal area developed through the AHP weighting (Figure 8) was analysed and compared between the present conditions and GIS layers. Expert knowledge was used to rank vulnerability parameters for each region from extremely high (7) to extremely low (1).

The main tributaries of the Kuala Terengganu River basin are the Nerus, Sekati, Kepung, Telemung, and Berang. Agriculture, tourism, aquaculture, commercial industries, urban and rural communities, reserves, and forests are all part of the socioeconomic framework of these rivers. The aim of river research is to expand an area of knowledge that encompasses floods, erosion, and sedimentation. The river criterion in this study has the highest weighting of 0.232 and is particularly vulnerable to erosion in the environment index, whereas the slope criterion has the lowest loading of 0.012. After the river criterion, the land use criterion is the most sensitive and relevant to erosion in the environment layer, with the highest weighting of 0.201. Due to the loss of agricultural land during historical events, land-use activities cause land erosion and sediment yields. Land use is a sort of artificial land surface alteration that has a big influence on the environment and aquatic life. The kind and factors of land use will be used to assess this.

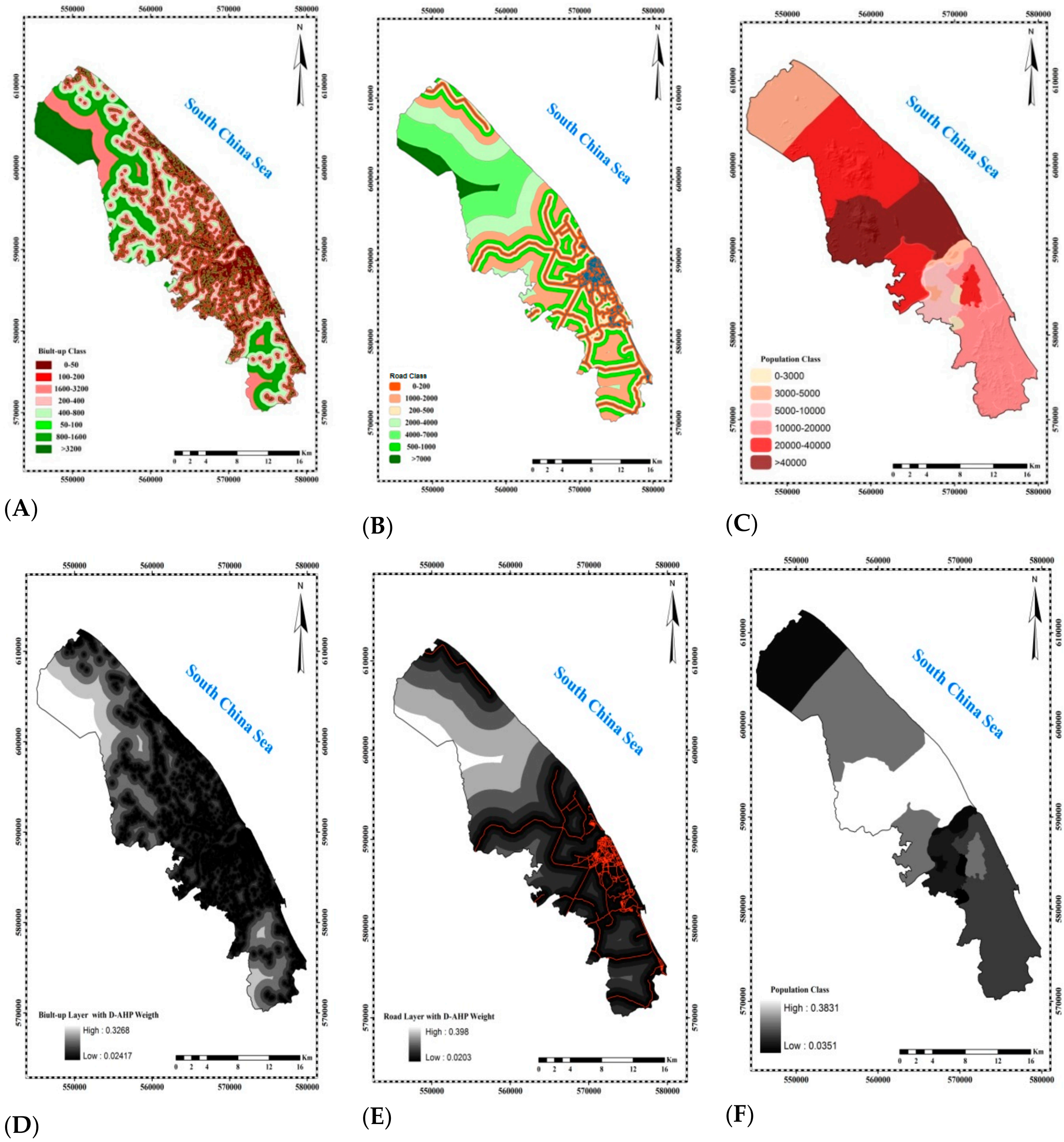

Figure 7. Human activity GIS layers: (**A**) Built-Up class, (**B**) Road class, (**C**) Population class. Human activity GIS layers after calculating with Delphi-AHP weights: (**D**) Built-Up layer, (**E**) Road layer, (**F**) Population layer.

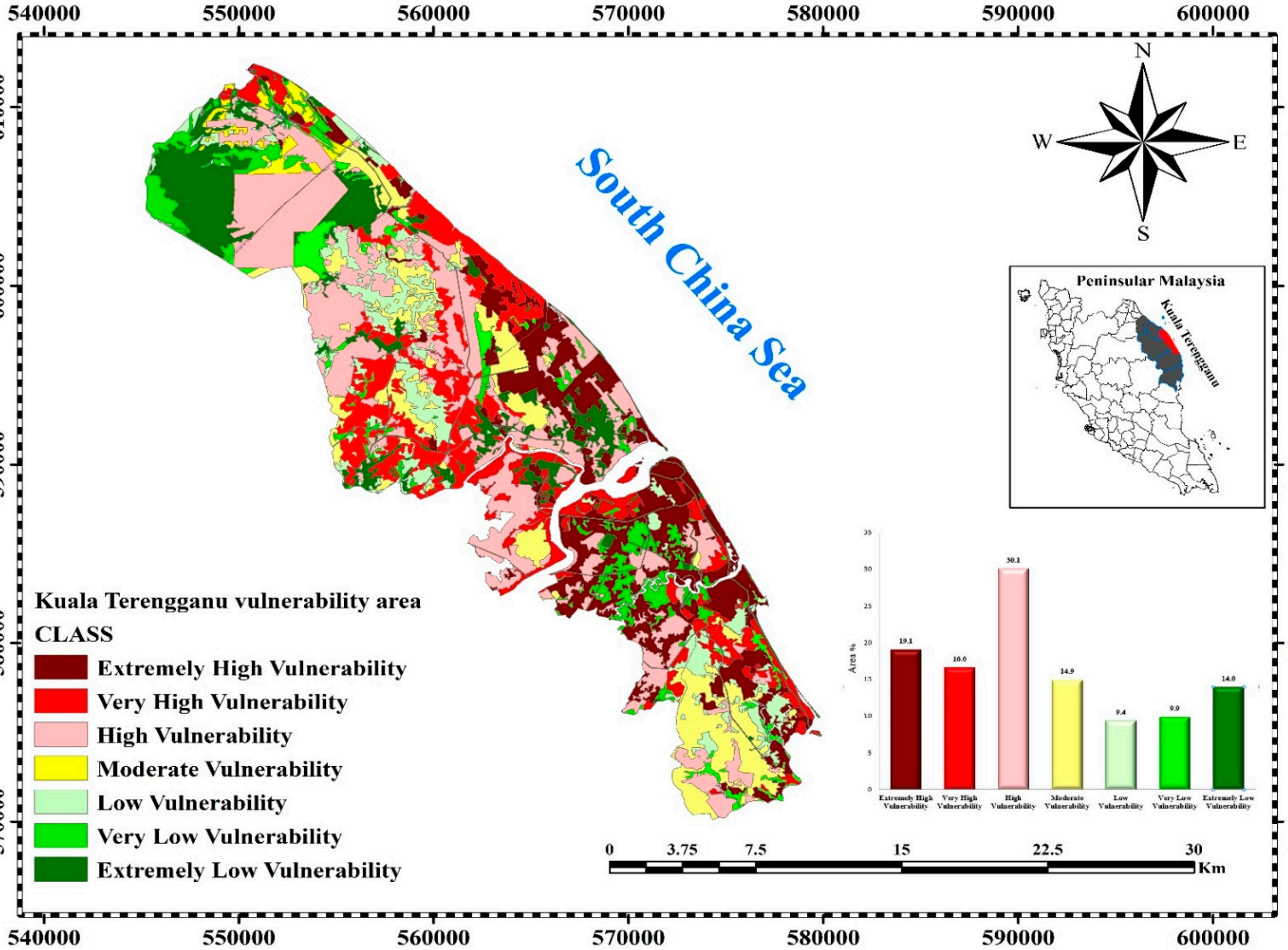

Figure 8. Final vulnerability map and vulnerability regions of coastal erosion for the coastal areas of Kuala Terengganu, Malaysia.

With the highest weighting of 0.092 in the environmental criteria, the soil criterion is sensitive and critical to erosion, and soil erosion is one of the factors that contribute to increasing total suspended solid concentrations. This is due to the fact that land erosion is one of the most difficult problems to anticipate, especially in rainy tropical climates. If the sediment lifting procedure is not handled, it will result in a plethora of problems in river and coastal area management. Total suspended solids concentrations were also caused by human activities such as municipal, industrial, aquaculture, and aquaculture. When the total suspended solid concentration in the Kuala Terengganu River and coastline region is high, this becomes apparent. This situation demonstrates the increase of land use development, such as residential, industrial, and tourism structures along the Kuaka Terengganu River and coastline area, increasing the vulnerability of land erosion.

The projected socio-economic consequences of critical erosion vulnerability regions suggest that erosion's social and economic costs may soon become unsustainable. Feasibility studies are needed in the Kuala Terengganu area to more clearly identify and quantify such expenses, as well as the costs of control, so that affected institutions can make protection investment decisions. According to sensitivity and vulnerability, three regions in this study have previously taken such decisions: Batu Rakit, Kuala Nerus, Manir, and Pengadang Buluh.

In Batu Rakit, which covers 11,500 ha, 6.2% (710 ha) of the area is considered extremely vulnerable, 14.16% (1678 ha) is considered very vulnerable, 38.7% (4452 ha) is highly vulnerable, 13.7% (1580 ha) is moderately vulnerable, 10.9% (1254 ha) shows low vulnerability, 6.4% (739 ha) shows very low vulnerability and 9.5% (1088 ha) represents an area of extremely low vulnerability. Kuala Nerus, which covers 10,418 ha, encompasses an extremely vulnerable area of 1880 ha (18%), a very vulnerable area of 2035 ha (19.5%), a highly vulnerable area of 2528 ha (24.3%), a moderately vulnerable area of 1157 ha (11.1%), an area of low vulnerability of 989 ha (9.5%), an area of very low vulnerability of 404 ha (3.9%), and an area of extremely low vulnerability of 1426 ha (13.7%).

In comparison to a very gentle profile, south of the river the beach and nearshore profile in Kuala Nerus is very steep. Pengadang Buluh covers a total area of 8059 ha, which includes 45.5% (3667 ha) of an extremely vulnerable area, 12.4% (1003 ha) of a very vulnerable area, 17% (1370 ha) of a highly vulnerable area, 1.4% (115 ha) of a moderately vulnerable area, 4.3% (350 ha) a low vulnerability area, 15.4% (1242 ha) and very low vulnerability area and 3.9% (313 ha), and an area of extremely low vulnerability. Accordingly, Pengadang Buluh shows the highest vulnerability with a vulnerability rate of 74.9% compared to vulnerability rates of 61.8% and 59.5% in Kuala Nerus and Batu Rakit, respectively.

Kuala Nerus and Pengadang Buluh are two neighborhoods in Kuala Lumpur that are separated by a big river (Kuala Terengganu River), which flows into the South China Sea. This low-lying, low-elevation area was found to have the highest susceptibility, and it might be used as a future reference for adaptive management planning. Kuala Nerus and Pengadang Buluh (most susceptible) are in Kuala Terengganu, with the Right Bank International Terrenganu Airport (ITA) and Universiti Malaysia Terengganu (UMT) (Behand) to the Left Bank Bt.

Low-lying areas are difficult to maintain, and controlling them may be one of the most onerous challenges facing coastal managers. The data also reveals that Terengganu's International Airport (Sultan Mahmud Airport), which is close to Kg. Telaga Batin, has the most erosion and is a high sensitivity region. The airport would be exposed to erosion and floods as a result of this. Kg. Telaga Batin is an area of significant vulnerability to erosion.

The average erosion rate for Kuala Nerus and Pengadang Buluh is 3.20 m/year and 5.13 m/year, respectively [24]. These areas would see more erosion and land loss than our research region. This is the greatest research area, which includes a major river (the Kuala Terengganu River). This area has also suffered some of the most catastrophic coastal erosion in the past. The beachfront is also fairly long from the south side of the Kuala Terengganu River to the Ibai River, a developed district with new hotels and significant mansions. The expected result in this part suggests that the Right Bank K. Ibai will be the most eroded. The beach retreat is rather sensitive and important from the south side of the Right Bank ITA and UMT to K. Ibai, a developed region with new hotels and the Sultan of Terengganu's palace.

4. Discussion

4.1. Coastal City Mitigation Policies and Erosion Control Measures

The consequences of coastal erosion can be severe because erosion oftentimes radically changes landforms, land usage, and land ownership. The impacts of such changes both directly and indirectly affect social, economic, and physical assets. A proper mitigation policies and erosion control (MPEC) program should be developed to keep the consequences within acceptable limits. The definition of "acceptable limits" is a matter of public policy that needs to be informed by engineers, scientists, and economists who offer specialist knowledge and rigorous analyses. The product of MPEC adaptation planning is a comprehensive plan including an action statement that lists deliverables. The impact of coastal city erosion can be mitigated on land through structural solutions, vegetation management, and planning, as well as beach improvements. Structural approaches may change the physical characteristics of the shoreline and offer a physical barrier to the sea. They always require great expenditures, and have immediate, and sometimes long-term environmental impacts. Thus, spatial knowledge of the distribution of vulnerability classes is important as efforts can be highly targeted.

4.2. Implementing Adaptation Plans

There are several constraints for integrated MCDA modeling and the implementation of GIS tools for vulnerable coastal cities such as Kuala Terengganu. One main limitation in using MCDA models is the risk of using inadequate sources to determine environmental criteria and sub-criteria for erosion in coastal areas. This fundamental limitation accrues from insufficient documentation and reporting on relevant qualitative and semi-quantitative data along and disintegrated environmental and non-climate data sets.

As we learned from the case of Malaysia, while attempts are made to implement mitigation measures to control coastal erosion, there is often a lack of coordination in undertaking the comprehensive mitigation strategies discussed above. Thus, we recommend four specific actions that can advance the implementation of mitigation and adaptation measures:

1. Designate an appropriate federal agency to be responsible for the general direction and coordination of adaptation plans and feasibility studies.
2. The final design and construction of protective works in accordance with feasibility studies should be undertaken by a dedicated department. In the case of Malaysia, this would be the Department of Irrigation and Drainage.
3. Establish a technical coastal city erosion control center to orchestrate proposed development in critical erosion areas, which requires coordination across all federal and state government agencies.
4. Initiate an inter-policy coordination process to negotiate trade-offs between potentially conflicting goals to determine optimal adaption across various socio-economic and environmental criteria.

The expected socio-economic implications of critical erosion vulnerability regions imply that the social and economic costs of erosion may soon be intolerable. For the Kuala Terengganu area, feasibility studies are needed to more accurately identify and quantify such costs, as well as the costs of control, so that a protective investment choice may be taken for affected institutions. In this research, those decisions and policies have already been taken for three high vulnerability areas: Batu Rakit, Kuala Nerus, and Pengadang Buluh. Kuala Terengganu's recreation resorts of Kuala Nerus and Pengadang Buluh are located near Gong Merbau and Left Bank. Ibai, K. The recreational facility is a sandy beach that is well-known and has a strong brand. Erosion has already had a significant physical impact [24]. There are other beach areas in the region where recreation might be relocated without too much difficulty. However, people are familiar with the Kuala Nerus and Pengadang Buluh beaches, as they have developed support services and are well-known.

When all of these factors are taken into account, a moderate demographic impact is predicted. It receives a modest economic effect rating based on similar reasoning. Damage has already been done; the beach has been eroded, and a swimming pool has been ruined. This gives the feasibility study a lot of weight and makes it a top priority. To establish the most optimal protection scheme, the feasibility study will assess groynes, breakwaters, jetties, and beach restoration separately and in combination.

Pengadang Buluh is a fishing town located between KG. Telaga Batn and S.K. Chendring in Kuala Nerus. The village's main access route has been ruined by erosion in this location. Other areas of the beach have been armored with gabion walls, although these offer just temporary protection. Threatened houses are low-cost, temporary buildings and road closures cause all traffic to and from the town to detour and experience a delay. Erosion has taken away the sand beach that formerly stood in front of the settlement.

The impending displacement of so many families, along with the loss of the village's principal access route, has a significant impact on and disrupts the village's established community life. As a result, the demographic impact is significant. Because a large demographic impact and a moderate economic impact are likely, a feasibility assessment is required immediately. The feasibility study will analyse revetments, seawalls, groynes, and breakwaters in high-vulnerability regions in Kuala Terengganu.

5. Conclusions

In a coastal city, environmental vulnerability is a complex and fuzzy problem that is influenced by many variables. Therefore, our research calls for a holistic planning strategy to resolve potential climate threats, current environmental, social, and economic sensitivities, emerging risks, and capability gaps. This study presents an analysis and approach for the formulation of environmental mathematical models for establishing integrated MCDA criteria and GIS tools to evaluate the vulnerability of the Kuala Terengganu coastal area in Malaysia to erosion. We presented vulnerability maps highlighting impacts on the coastal city that would potentially be caused by environmental factors.

An AHP model was used to investigate erosion vulnerability which proved efficient in conjunction with the GIS as a tool for decision making. Our Delphi-AHP model highlighted the presence of a river as the most influential (greatest weight) among all considered environmental and social criteria for erosion vulnerability of the Kuala Terengganu coastal area. Different coastal states will face different key impacts induced by environmental, climatic, and non-climatic factors which can be identified using our study as a methodological blueprint. We were able to pinpoint the greatest vulnerability to specific regions within Kuala Terengganu. This helps with prioritising and localising actions.

A comprehensive set of criteria was considered, capturing environmental, social, and economic development considerations, including data on the topography, presence of a river, slope, soil, geology, land use, presence of roads, build-up, and population. These criteria were thought to affect erosion directly or indirectly in the study area. The relative importance of these criteria may vary by region and the AHP model is well-suited to work with different sets of criteria. This is, however, also a limitation of our study, as new models will need to be built in accordance with regional characteristics.

A challenge for our study was the lack of sources of regularly measured coastal data that were sufficiently accurate and gathered in appropriate time intervals. Since this study has been conducted by using limited coastal city data and maps, it is clear that it provides a general view of environmental hazards for the Kuala Terengganu coastal area. However, as one of the first overall coastal assessment and adaptation planning studies in the Kuala Terengganu coastal area, future studies can build on it.

The study provides inputs for researchers, policymakers, and land-use planners and developers for their future adaptation planning in Kuala Terengganu, as the most vulnerable areas were identified. This study has direct planning implications for several coastal cities in Malaysia, including, for example, Kuala Kuantan. A network of shared knowledge and expertise will go a long way in connecting these cities and their planning efforts with a long-term view on establishing adaptation planning systems and best practice management in coastal city planning.

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Review

Mirror-mirror on the wall, what climate change adaptation strategies are practiced by the Asian's fishermen of all?

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A B S T R A C T

This systematic review article focuses on the adaptation strategies of Asian fishermen toward climate change impacts. Generally, the fact that climate change is not a new phenomenon has attracted scholars to conduct numerous relevant studies. Unfortunately, most past researches were not from the perspectives of social science of the Asian's community. Hence, the present study reviewed a considerable amount of past studies on the act of adjusting with environmental change among the Asian fishermen which is known as one of the communities that are highly dependent on nature stability. Meanwhile, Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) was adopted for the review of the current research which utilised two main journal databases, namely Scopus and Web of Science. Accordingly, the searching efforts resulted in a total of 18 articles that can be analysed systematically. Most importantly, the review managed to formulate five main themes, namely livelihood diversification, social, physical infrastructure, awareness-knowledge-experience, and conservation and enforcement based on the thematic analyses. Overall, further analysis of the five themes resulted in the establishment of a total of 21 sub-themes. Finally, a number of recommendations were presented at the end of this research for the reference of future scholars.

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1. Introduction

Similar to other regions, the Asian region is also affected by the formidable impacts of climate change. A report by Intergovernmental Panel on Climate Change stated that temperature, precipitation and monsoon, tropical and extratropical cyclones, surface wind speeds and oceans are among the symptoms of climate change on the natural elements (Hijioka et al., 2014). For example, the rising temperature in the Asian region has resulted in a declining amount of cold days and nights. Likewise, this increases the number of warm days and nights. Furthermore, scientists have conducted an in-depth observation on the scenario happening in East Asia which demonstrated the changes in the circulation of summer and winter monsoon that was believed to be the result of the weakening inter-decadal scale in the 1970s. Meanwhile, the sea level was rising at 5.4 ± 0.3 mm yr -1 in the Sea of Japan for a period of nine years (1993–2001). Another phenomenon is concerned with the regional changes of ocean level in the Indian Ocean that have developed since the sixties which refers to the changing surface winds that are connected with a consolidated improvement of Hadley and Walker cells (Hijioka et al., 2014).

Nevertheless, neither the 'symptoms' nor the situation are expected to improve in the future because the human beings are expected to be considerably influenced by the environmental change impacts, especially those who rely heavily on the strength of the nature in directing their financial routines (Shaffril et al., 2017a; Gawith and Hodge, 2018). Moreover, extreme wind and waves hinder the fishermen from operating their fishing activities, which causes them to deal with the declining quality and quantity of marine resources due to the rising temperature as well as loss of fishing tools and infrastructure resulted by the extreme weather (Badjeck et al., 2010; Barange et al., 2011). Obviously, the best method to respond to these impacts is by adapting to climate change. According to the European Commission (2014), the term 'adaptation to climate change' can be described as envisioning the unfavourable impacts of environmental change and making the suitable action to restrict or limit the harm that may occur or exploiting the chances that may emerge. Moreover, this shows that an arranged and early adjustment activity will be able to maximise the use of cash and lives later.

Meanwhile, a stronger adaptation ability leads to the decrease of the negative impacts of climate change among the community, which eventually enable them to cope with an uncertain future. Furthermore, Shaffril et al. (2017b) stated that stronger adaptation allows the community to strategize reactively and proactively against the formidable impacts of the changing climate.

1.1. The need for a systematic review

According to Petrosino et al. (2001), a systematic review can be defined as quantitatively and qualitatively recognising, combining, and evaluating all accessible data in order to produce a hearty, observationally determined response to an engaged research question.

The systematic review offers several advantages compared to the conventional style literature reviews. The reviews can be strengthened via a transparent article retrieving process, a more prominent wider area of research, more significant objectives which can control research bias. Apart from that, this also motivates the researcher to produce quality evidence with more significant results (Mallet et al., 2012).

Meanwhile, a considerable amount of existing systematic review related to climate change studies has been conducted across the globe. Nevertheless, only a limited number of studies was performed within the context of social science and the Asian community (Shaffril et al., 2018) because the available literature heavily focused on the hard science (Bonjean Stanton et al., 2016; Babatunde et al., 2017; Li et al., 2018; Rifkin et al., 2018) as well as western community perspectives (Thaler et al., 2019; Brunetta and Caldarice, 2019; Rohat et al., 2019; Garcia Sanchez et al., 2018). A scenario has led to several understandings on the ability of Asian community to adapt to climate change impacts, which in turns causes the planned programs to be inconsistent with the need, ability, and interests of the concerned communities. The current paper attempt to systematically review all the relevant literature with the aim of fulfilling the gap by examining a growing body of evidence of on the adaptation of Asian fishermen towards climate change, which is one of the communities that strongly depend on nature stability namely. The present study is vital due to the scarce amount of existing research which provides an all-encompassing pattern on the status of environmental change adjustment among Asian fishermen, while the existing systematic review articles on the adaptation strategies of Asian fishermen failed to present and in-depth information on the review procedures that were adopted in terms of the use of keywords identification, articles screening, articles eligibility, and database use. Moreover, this situation hinders future researchers to recreate the investigation, approve the understanding, or analyse the breadth of information. Furthermore, this study is important because it provides information on the extent of the focus of peer review literature which can assist the researchers in delivering the prospect with the aim of understanding the future attention related to climate change strategies that require scholarly attention.

The development of the current systematic review is based on the main research question: How do Asian fishermen strategize their adaptation to climate change impacts? The principal focus of the investigation was on human adaptation practices. More importantly, exceptional attention was given to Asian fishermen because this group is predicted to be significantly influenced by the environmental change impacts due to their high reliance on nature stability. Other than that, this section discusses the need to conduct a systematic review of Asian fishermen, while the following section presents the approach that is employed to obtain the answer to the research question formulated by the current research. Next, the third area conducts a systematic review and synthesises the scientific literature in order to distinguish, select, and evaluate significant research on the adaptation strategies of Asian fishermen towards environmental change. Finally, the last area discusses the measures that need to be taken by focusing on future scholars in relation to the issues being raised.

2. Material and methods

This section explains the five main sub-sections, namely PRISMA, resources, inclusion and exclusion criteria, systematic review process, and data abstraction and analysis which are employed in the current research.

2.1. PRISMA

PRISMA or Preferred Reporting Items for Systematic Reviews and Meta-Analyses is a published standard to conduct a systematic literature review. Generally, publication standards are required to guide authors with the related and necessary information that will enable them to evaluate and examine the quality and rigour of a review. In addition, PRISMA emphasises on the reviews report that evaluates randomised trials which can also be utilised as the fundamental in reporting systematic reviews for other types of research (Moher et al., 2009). However, Sierra-Correa and Cantera Kintz (2015) claimed that PRISMA is also suitable for environment management field because it clearly defines the research questions towards the need for a systematic review despite the fact that PRISMA is often utilised within medical studies, and at the same time, able to identify the inclusion and exclusion criteria for a particular study. Moreover, PRISMA examines the extensive database of scientific literature at a defined time which allows an accurate search of terms to be conducted in regard to the adaptation of Asian fishermen toward climate change. Other than that, the use of PRISMA enables coded information concerning future environmental management reviews.

2.2. Resources

The review methods of the present study were conducted using two main databases, namely Scopus and Web of Science considering that both databases are robust and cover more than 256 fields of studies including environmental studies. Specifically, Scopus indexes a total of 1360 journals related to environmental sciences, while Web of Science (Social Science Citation Indexed) indexes a number of 108 journals related to environmental studies. However, it should be noted that no database is perfect or comprehensive including Scopus and Web of Science. Accordingly, Younger (2010) suggested that researchers should conduct their searching process using more databases in order to increase the likelihood of obtaining relevant articles. Therefore, the present study conducted manual searching efforts on several established sources such as Science Direct, Taylor Francis, Springer, and Sage considering that they are reliable databases containing journals related to the environmental study. For example, Taylor Francis has published more than 4 million articles and covers subjects such as environment and agriculture as well as environment and sustainability, while Science Direct offers a total of 1063 publication titles related to environmental studies.

2.3. The systematic review process for selecting the articles

2.3.1. Identification

The systematic review process in selecting a number of relevant articles for the present study consisted of three main stages. The first stage is the identification of keywords, followed by the process of searching for related and similar terms based on the thesaurus, dictionaries, encyclopaedia, and past researches. Accordingly, search strings on Scopus and Web of Science database were developed in September 2018 (Refer Table 1) after all relevant keywords managed to be determined. Most importantly, the current research work successfully retrieved a total of 480 articles from both databases. As previously stated, manual searching based on similar keywords was conducted on other databases which resulted in an additional number of 14 articles. In total, 494 articles were retrieved in the first stage of the systematic review process.

2.3.2. Screening

The purpose of the first stage of screening was to remove duplicate articles. In this case, a total of three articles were excluded during the first stage, while 491 articles were screened based on several inclusion and exclusion criteria determined by the researchers in the second stage. The first criterion was the literature type in which the researchers decided to focus only on the journal (research articles) because it acts as the primary sources that offer empirical data. Hence, this further implies that publication in the form of systematic review, review, meta-analysis, meta-synthesis, book series, book, chapter in a book, and conference proceeding were excluded in the current research. In addition, it should be noted that the review only focused on articles that were published in English. Moreover, it is crucial to note that a 15-year period (2003–2018) was chosen for the timeline. Other than that, only studies conducted in the Asian territory were selected because they are in line with the objective of the review. Most importantly, articles published in the field of social science, environmental science and agricultural as well as biological science were selected in order to increase the possibility of retrieving related articles. Overall, a total of 403 articles were excluded based on these criteria (Refer to Table 2).

2.3.3. Eligibility

A total of 88 articles were prepared for the third stage known as the eligibility. At this stage, on a more important note, the titles,

Table 1
The search string.

Database	Search string
WoS	TS=(("Climat* chang*" OR "climat* risk*" OR "climat* variabilit*" OR "climat* extrem*" OR "climat* variability*" OR "climat* uncertaint*" OR "global warming*" OR "temperature ris*" OR "sea level ris*" OR "el-nino" OR "la-nina") AND ("Adapt* abilit*" OR "adapt* strateg*" OR "adapt* capacit*" OR "adapt* capabilit*" OR "adapt* strength*" OR "adapt* potential*" OR "adapt* practic*" OR "adopt* abilit*" OR "adopt* capacit*" OR "adopt* capabilit*" OR "Adopt* potential*" OR "adopt* strateg*" OR "adopt* practic*") AND (fisherm*n OR fisher* OR lobsterm*n OR trawler*))
Scopus	TITLE-ABS-KEY(("Climat* chang*" OR "climat* risk*" OR "climat* variabilit*" OR "climat* extrem*" OR "climat* variability*" OR "climat* uncertaint*" OR "global warming*" OR "temperature ris*" OR "sea level ris*" OR "el-nino" OR "la-nina") AND ("Adapt* abilit*" OR "adapt* strateg*" OR "adapt* capacit*" OR "adapt* capabilit*" OR "adapt* strength*" OR "adapt* potential*" OR "adapt* practic*" OR "adopt* abilit*" OR "adopt* capacit*" OR "adopt* capabilit*" OR "Adopt* potential*" OR "adopt* strateg*" OR "adopt* practic*") AND (fisherm*n OR fisher* OR lobsterm*n OR trawler*))

Table 2
The inclusion and exclusion criteria.

Criterion	Eligibility	Exclusion
Literature type	Journal (research articles)	Journals (review), book series, book, chapter in book, conference proceeding
Language	English	Non-English
Time line	Between 2003 and 2018	<2003
Countries and territories	Asian countries	Non-Asian countries
Subject area	Social Science, Environmental Science, Agricultural and Biological Science	Other than Social Science, Environmental Science, Agricultural and Biological Science

abstracts, and the main contents of all the articles were examined thoroughly to ensure that they fulfilled the inclusion criteria and fit to be employed in the present study in order to achieve the objectives of the current research. Consequently, a total of 70 articles were excluded because they are not based on empirical data and discovered to be hard sciences articles that did not focus on fishermen adaptation practices or Asian countries and territories. Finally, a total of 18 remaining articles is ready to be analyzed (see. Fig. 1)

2.4. Data abstraction and analysis

This study performed an integrative review, one of the review techniques that analyzes and synthesises diverse research designs together (qualitative, quantitative and mixed methods) and this can be settled by transforming one type into the other—qualitizing quantitative data or quantitizing qualitative data (Whitemore and Knafl, 2005). This study opt for qualitizing all selected data.

The processes of developing the appropriate themes and the sub-themes were carried out based on thematic analysis. The first phase within the theme development processes was the compilation of data. In this phase, the authors carefully analysed a group of 18 selected articles to extract statements or data that answers the research questions. Subsequently, in the second phase, the authors created meaningful groups via coding method according to the nature of the data. In other word, second phase converts raw data into useable data via the identification of themes, concepts, or ideas

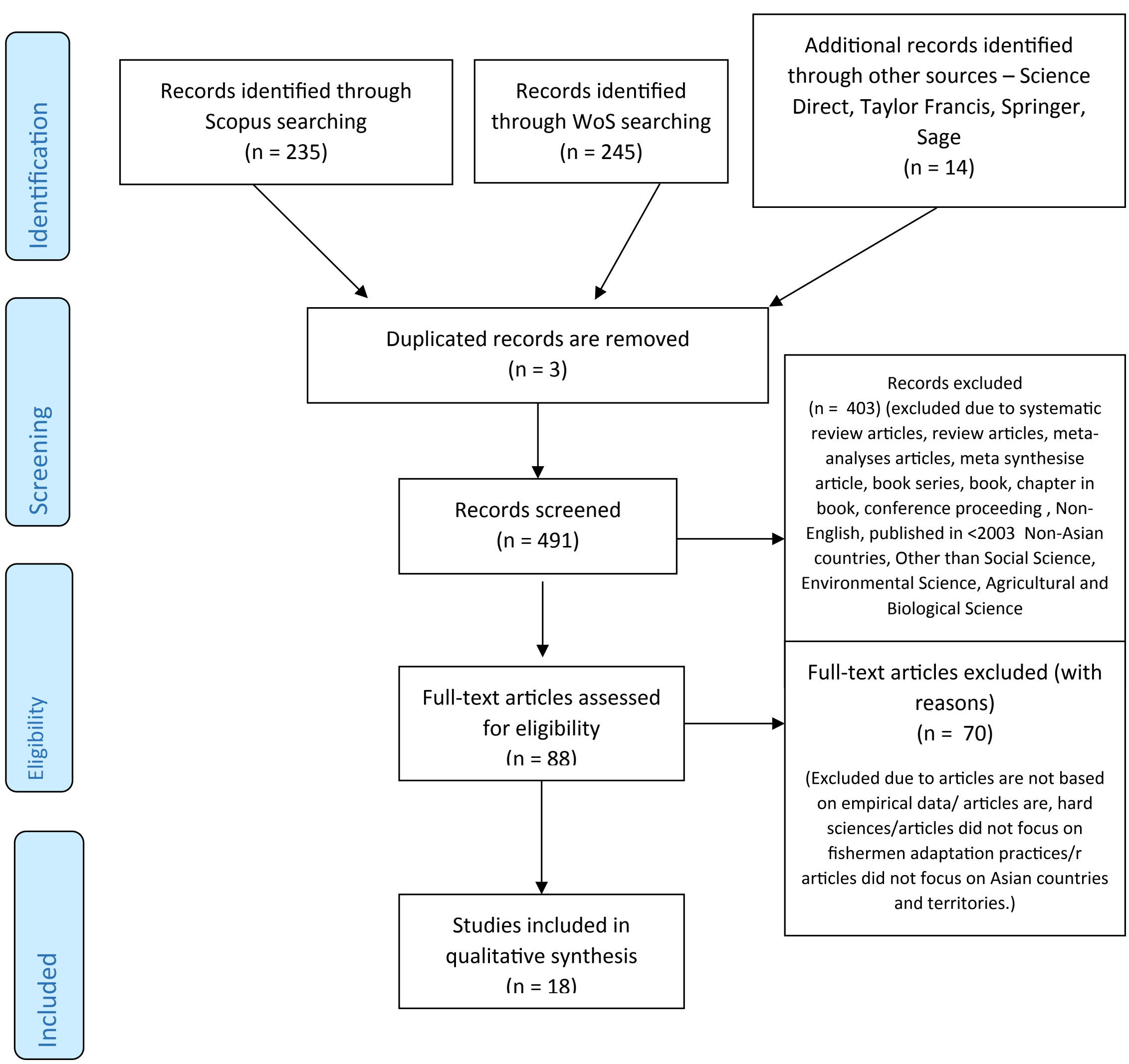

Fig. 1. Flow Diagram of the study (adapted from Moher et al., 2009).

for a more connected and related data (Sandelowski, 1995; Patton, 2002). Eventually, the process has resulted a total of five main themes namely livelihood diversification, social relationship, infrastructure, awareness, knowledge and experience, and conservation and enforcement. Thereafter, the authors resumed the process in each of the created themes whereby any themes, concepts, or ideas that have some connection with each other within that developed themes will be developed as sub-themes. This further process eventually has resulted in a total of 21 sub-themes. Within the scope of this review, the corresponding author developed the themes based on the findings with other co-authors to consistently theme the findings while a record was kept during the entire process of data analysis that document resulted analysis, thought, puzzles or any idea that can be associated with the interpretation of the data. The authors also compared the results with the aim of addressing any inconsistencies in the process of theme development and accordingly, the authors discussed with each other if there were any inconsistencies on the themes emerged. Finally, the developed themes and sub-themes were adjusted accordingly in order to ensure their consistencies. To ensure the validity of the themes and the sub-themes, expert reviews were performed by a total of three experts, where two of them are community development experts while the third person is a qualitative expert. The expert review process establishes the domain validity and helped to ensure the clarity, relevance and appropriateness of each sub-themes within its respective themes. Drawing on the experts' feedbacks and comments, adjustments were made based on the discretion of the authors.

3. Results

3.1. General findings and background of the studies included in the review

The analysis produced a total of five themes and 21 sub-themes related to adaptation strategies. As presented in Table 3, the five themes are livelihood diversification (9 sub-themes), social (six sub-themes), physical infrastructure (two sub-themes), awareness-knowledge-experience (three sub-themes), and conservation and enforcement (two sub-themes).

More specifically, it should be noted that five previous studies focused on Filipinos fishermen (Andriesse, 2018; Faustino and Jr, 2009; Graziano et al., 2018; Jacinto et al., 2015; Mamauag et al., 2013), five studies examined Bangladeshi fishermen (Hossain et al., 2018; Rahman et al., 2018; Monirul Islam et al., 2014; Saroar and Routray, 2012; Hasan and Nursey Bray, 2018), and four past research concentrated on Indian fishermen (Coulthard, 2008; Krishnan et al., 2016; Malakar et al., 2018; Ramachandran et al., 2016). Other than that, each study on Vietnamese fishermen (Da costa and Turner, 2007), Cambodian fishermen (D'Agostino and Sovacool, 2011), Malaysian fishermen (Shaffril et al., 2017b), and Pakistani fishermen (Salik et al., 2015) were also included in the review (see Fig. 2).

In the case of the present study, regarding the year of publication, six articles were published in 2018 (Andriesse, 2018; Graziano et al., 2018; Hossain et al., 2018; Rahman et al., 2018; Hasan and Nursey Bray, 2018; Malakar et al., 2018), an article was published in 2017 (Shaffril et al., 2017b), and two articles were published in 2016 (Krishnan et al., 2016; Ramachandran et al., 2016). Next, two articles were published in 2015 (Jacinto et al., 2015; Salik et al., 2015), followed by an article published in 2014 (Monirul Islam et al., 2014) and an article published in 2013 (Mamauag et al., 2013). Apart from that, an article was published in 2012 (Saroar and Routray, 2012), was another one published in 2011 (D'Agostino and Sovacool, 2011), an article published in 2009 (Faustino and Jr, 2009), another article published in 2008 (Coulthard, 2008), and one article published in the year 2007 (Da costa and Turner, 2007) (see. Fig. 3).

3.2. Main findings

In this section, the discussion revolves around five main themes, namely livelihood diversification, social, physical infrastructure, awareness, knowledge and experience, and conservation and enforcement along with the emerging 21 sub-themes (Refer Table 3).

3.2.1. Livelihood diversification

Livelihood diversification is one of the adaptation strategies that are able to empower the fishermen community. In particular, this adaptation strategy assists them in varying their income generating activities as well as diversifying their fishing skills, strategies, and fishing tools for the enhancement of their livelihood. In this case, a total of 13 previous studies were found to focus on the livelihood diversification, particularly in their climate change adaptation strategies. Specifically, it should be noted that income diversification was the common strategy under this theme (8 studies), followed by making loan/borrowing money (5 studies) and selling items/assets (4 studies). Next, diversifying fishing technique and fishing tools (6 studies), increasing working hours (2 studies), government/private organisation initiatives (3 studies), productivity and market expansion (2 studies), family support (2 studies), and others (1 study).

3.2.1.1. Government/private organisation initiatives (GI). The adaptation towards climate change among Asian fishermen seems to be related to the initiatives made by the governments or relevant organizations in their respective countries (Andriesse, 2018; Krishnan et al., 2016). Most of these organizations have placed their efforts to provide short-term relief goods as well as long-term programmes that can revive their livelihoods. For example, poor households were given access to Pantawid Pamilya Programme known as a conditional cash transfer programme established in 2008 after Typhoon Yolanda hit the Philippines in 2003 and this program managed to benefit more than 4.4 million families (Andriesse, 2018). Meanwhile, Nestlé Philippines ran a coffee buying station in the areas where smallholders are allowed to sell their related products and seek for advice (Andriesse, 2018). Most importantly, both examples are strategies that provide the fishermen with the opportunities to double their income and prevent them from falling further into the poverty trap. Other than that, one of the poverty alleviation programmes established by the government was run through the Agriculture Bank that granted the rural poor access to credit. Subsequently, the villagers of Thuy-Dien were able to access credit via the bank upon receiving their Land Use Certificates for the purpose of increasing their income through investment (Da costa and Turner, 2007).

3.2.1.2. Loan (L). The Asian's fishermen require some capitals to financially invest in productive activities with the aim of supplementing losses or expediting their recovery process due to the potential climatic and non-climatic stresses. Hence, taking loans or borrowing money is another adaptation strategy that should be employed by fishermen who are driven by these needs. In most cases, the main sources of loan opted by the fishermen are the NGOs, microcredit institution, local money lenders, wholesalers, relatives, and neighbours (Hossain et al., 2018; Hasan and Nursey Bray, 2018; Rahman et al., 2018; Krishnan et al., 2016; Faustino and Jr, 2009). The avail of interest-free loans from cooperatives has offered many benefits to the local fishermen in the Philippines.

Table 3
The main themes and the sub themes.

Authors	Livelihood diversification									Social relationship					Infrastructure		Awareness, knowledge and experience			Conservation and enforcement	
	GI	L	PM	ID	FS	SI	DF	IW	OT	OU	IN	SR	FS	M	SB	OT	EA	TR	AI	CN	EF
Andriesse (2018) (Philippines)	✓			✓											✓						
Coulthard (2008) (India)				✓			✓														
Da costa and Turner (2007) (Vietnam)	✓		✓							✓		✓									
Krishnan et al. (2016) (India)	✓	✓					✓				✓								✓	✓	
Faustino and Jr (2009) (Philippines)		✓		✓									✓	✓	✓	✓					
Graziano et al. (2018) (Philippines)										✓							✓			✓	
Hossain et al. (2018) (Bangladesh)		✓		✓	✓				✓				✓	✓							✓
Rahman et al. (2018) (Bangladesh)		✓				✓										✓	✓	✓			
D'Agostino and Sovacool (2011) (Cambodia)						✓												✓	✓		
Monirul Islam et al. (2014) (Bangladesh)					✓	✓	✓							✓							
Malakar et al. (2018) (India)				✓			✓				✓										
							✓														
Saroar and Routray (2012) (Bangladesh)												✓		✓					✓		
Hasan and Nursey Bray (2018) (Bangladesh)		✓		✓	✓	✓	✓							✓	✓						
Shaffril et al. (2017) (Malaysia)												✓					✓		✓		
Jacinto et al. (2015) (Philippines)																	✓		✓		
Mamauag et al. (2013) (Philippines)				✓														✓			✓
Ramachandran et al. (2016) (India)			✓	✓							✓			✓		✓					✓
Salik et al. (2015) (Pakistan)												✓		✓	✓						

Livelihood diversification	Social relationship	Infrastructure	Awareness, knowledge and experience	Conservation and enforcement
GI = Government/NGO/private organizations initiatives L = Loan PM = Productivity and market expansion ID = Income diversification FS = Family supports SI = Sell items/assets DF = Diversify fishing technique and fishing tools IW = Increase working hours OT = Others	OU = Involvement in Organizations/Unions IN = Insurance SR = Maintain a good and strong social relationship with the surrounding community FS = Family support M = Migration	SB = Strengthening buildings/house structure/Re-settlement OT = Others	EA = Experience and awareness TR = Training AI = Access to information	CN = Conservation EN = Enforcement

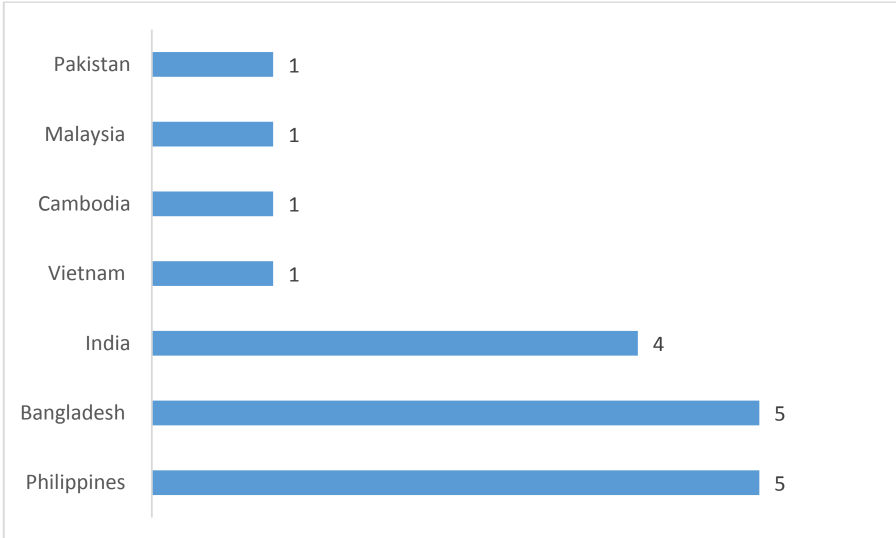

Fig. 2. Countries where the studies were conducted.

However, it is important to note that there are still some organizations that provide loans with high interests, while some operate with unreasonable loan scheme (Hossain et al., 2018; Faustino and Jr, 2009).

3.2.1.3. Productivity and market expansion (PM). Asian fishermen increase their productivity and expand their market as another income diversification strategy (Da costa and Turner, 2007; Balakrishnan et al., 2016). In Vietnam, the *sampan* dwellers increase their aquaculture productivity in either human-made ponds on land or in government-designated areas of the lagoon. More importantly, some of them even managed to export their products outside Vietnam (e.g. Taiwan), while others enjoy double or even triple the amount derived from their fishing activities (Da costa and Turner, 2007)., Accordingly, the diversification of market and products is a good adaptation strategy considering that the fishermen have to maintain and build up new linkages with the wholesalers in ensuring a continuous supply of resources to sell their catch and avoid 'poor sales'. Unfortunately, the wholesalers tend to manipulate the fishermen by buying their catches below the actual market prices (Da costa and Turner, 2007; Balakrishnan et al., 2016).

3.2.1.4. Income diversification (ID). In this case, the fishermen tend to diversify their income and change their economic activities due to the climate change impacts caused by the rising of temperature and frequent occurrence of extreme events (Faustino and Jr, 2009; Malakar et al., 2018; Hasan and Nursey Bray, 2018; Ramachandran et al., 2016). More importantly, their income diversification is divided into two types, namely internal and external diversifications within the context of this review. External diversification refers to various income-generating activities that are not related to the environment, while internal diversification refers to different income generating activities related to the environment. Specifically, a number of examples for internal diversification

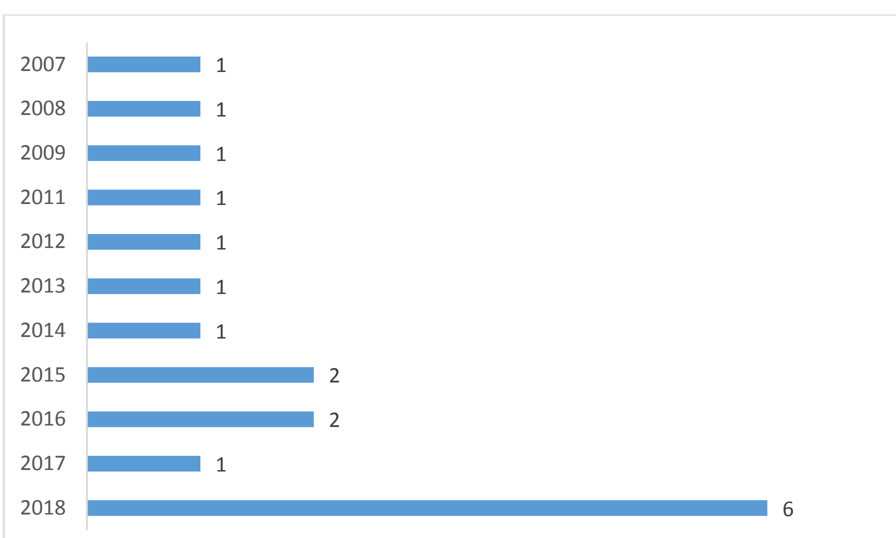

Fig. 3. Year of publication.

include farmer/labour, post-larvae collector, crab fattener, fish farmers, fish retailers, seaweed farming, milkfish pond and cage culture, rabbit fish and grouper fry grow-out culture, sea cucumber culture, backyard-scale hog and goat raising, and hand-weaving handicraft from *nipa*, small-scale rice farming, and coconut farming-related (Hossain et al., 2018; Mamauag et al., 2013). Meanwhile, external income diversification activities for the fishermen include rickshaw puller, driver, public transportation services, shopkeeper, brick kiln worker, street vendor, quack (local doctors without proper certificate), nurses, policemen, firm employees, school teacher, cooking fuel collector/seller, tailoring, labouring work, working with a nearby NGO, factory work, carpentry, and house construction jobs (Hossain et al., 2018; Andriesse, 2018; Mamauag et al., 2013; Coulthard, 2008).

3.2.1.5. Family support (FS). On another note, some of the fishermen tend to receive support from their family members in the effort to increase their household income. According to Hossain et al. (2018), some of the housewives in Bangladesh are involved in laborious works such as repairing dyke, working in the crop field for transplanting rice, weeding and harvesting (though the wage is usually lower than men). Meanwhile, the fishermen's children in Bangladesh are required to work by being involved in income-generating activities with the aim of sustaining the livelihood of their families. However, it is important to note that this is a negative adaptation because the children will be taken out of school and left behind in their education, thus causing them to lose focus and stop schooling (Hasan and Nursey Bray, 2018; Hossain et al., 2018).

3.2.1.6. Sell items/assets (SI). On an important note, extreme events have contributed to crops failure which forces them to sell their assets or livestock despite having alternative sources of income such as crops cultivation (Monirul Islam et al., 2014; Hasan and Nursey Bray, 2018). Meanwhile, a case in point has been experienced by fishermen in Cambodia who are forced to sell motorcycles, pigs, and cows in order to buy staple food particularly referring to rice (D'Agostino and Sovacool, 2011). On a similar note, most fishermen in Bangladesh are landless; hence, they usually keep natural capitals such as domestic animals which might end up being sold during periods of stress (Rahman et al., 2018). Nevertheless, it is a concern that they are forced to sell their livestock at a low price in a pressing situation. Consequently, this may result in social instability among the fishermen due to the negative activity that is left unchecked.

3.2.1.7. Diversify fishing technique and fishing tools (DF). According to Malakar et al. (2018), another livelihood diversification strategy is by varying their fishing technique and usage of multiple types of nets. For example, Coulthard (2008) stated that Dhoniveru fishermen in South Indian Lagoon tend to diversify their fishing technique into *siruthollі* (small scale or poor fishing) which is a technique that uses a smaller unregulated gear. Interestingly, this strategy allows the fishermen to diversify their catches and reduce their reliance on merely one type of marine catches with the aim of increasing their productivity and income.

On another note, fishermen in India and Bangladesh need to improve their fishing tools in order to adapt to the climate change impacts (Krishnan et al., 2016; Malakar et al., 2018; Hasan and Nursey Bray, 2018). Accordingly, several efforts that can be adopted include strengthening their fishing nets and gears (Krishnan et al., 2016; Hasan and Nursey-Bray, 2018), improving the net materials, practising proper farming of the net, and using appropriate colour, preservatives, and diameter of the thread to ensure that the catching tools are more resilient and able to withstand weather uncertainties. Meanwhile, another appropriate adaptation strategy that can be employed by the fishermen is to improve the condition of their fishing boat which includes changing to a bigger boat, using proper materials in constructing the boat or using motorised and mechanised boats (Hasan and Nursey-Bray, 2018; Malakar et al., 2018). Subsequently, the improved and enhanced ability of the boats will enable the fishermen to expand their catching areas and withstand extreme climates.

3.2.1.8. Increase working hours (IW). In this matter, some of the fishermen tend to increase their working hours. A case in point refers to Bangladeshi fishermen who have taken the risks by operating their fishing routines during cyclones despite knowing how dangerous it is. According to Monirul Islam et al. (2014), they dare to take the risks because the opportunity to land more catches is higher during that period compared to a normal season (Monirul Islam et al., 2014). Meanwhile, the fishermen in India have widened their catching areas and explored opportunities by navigating and venturing new areas, which results in diversification that could land more catches (Malakar et al., 2018).

3.2.1.9. Others (OT). On another note, fishermen in Southwest Bangladesh are unable to catch fish due to their geographical location which tends to receive formidable impacts of global storm surges and more prone to severe cyclones. Hence, it is crucial to understand that the consequences of these extreme events are disastrous, especially during the Ali Cyclone attack that resulted in the salinity intrusion of the water. According to Hossain et al. (2018), the Bangladeshi fishermen try to diversify their livelihood by increasing their ponds productivity in response to this issue. In particular, on the adaptation strategies practised by them is to stock valuable species and try to diversify their rearing. In addition, they use invasive and low-value tilapia to feed crabs in ponds as well as for household food supply with the aim of reducing the cost for their rearing as well as family consumption (Hossain et al., 2018).

3.2.2. Social

Fishermen have a strong sense of belongingness and attachment to their place of residence as well as their surrounding community. Unsurprisingly, this leads to the need for strengthening social related aspects as part of the adaptation strategies. Regarding this matter, a number of studies have focused on this aspect which managed to lead to the emergence of six sub-themes under the social theme, namely involvement in organizations/unions (2 studies), insurance (3 studies), maintaining a good and strong social relationship with the surrounding community (4 studies), saving/sharing food (2 studies), and migrating (7 studies).

3.2.2.1. Involvement in organizations/unions (OU). In this case, it should be noted that several mass organisation programs have managed to strengthen the adaptation strategy among Asian fishermen. In particular, the programs are used to disseminate information and offer a chance to the fishermen that enables them to be more involved in the community. In addition, it must be understood that access to social capital offers 'safety net' to the fishermen when coping with the change of livelihood, which minimises the vulnerability towards the formidable impacts of climate change (Da costa and Turner, 2007; Graziano et al., 2018). Meanwhile, the involvement in Women and farmers Unions provides fishermen in Vietnam the country with the opportunities to learn, socialize, discuss important issues, gain knowledge on fish and shrimp diseases, access credit facilities, and receive technical support from officers or members of different strata of society (Da Costa and Turner et al., 2007). Accordingly, this enables resources, ideas, and information to be disseminated to the fishermen from formal institutions beyond the immediate community. Overall, it is crucial to note that these initiatives are significant for economic survival and progress.

3.2.2.2. Insurance (IN). Due to their increasing awareness for climate change impacts, the fishermen are found to insure their boats. Within the scope of fisheries industry, insurance acts as a monetary safeguard to address some elements of uncertainty and it assists the fishermen to secure their income and productivity. Such is due to the fact that fishermen are often risked by extreme events at the sea - storms, cyclone, extreme waves and wind, and by having insurance, it serves as an important adaptation strategy among them. Likewise, it reduces the economic risks and improves their resilience towards climate change impacts (Krishnan et al., 2016; Malakar et al., 2018; Ramachandran et al., 2016).

3.2.2.3. Maintain a good and strong social relationship (SR). According to Da costa and Turner (2007), another adaptation strategy that has been practised by Asian fishermen is building a strong social relationship with wholesalers. For example, fishermen in Vietnam with aquaculture outputs sell their products to the wholesalers who come to the village. Subsequently, this situation creates networks which bond and bridge social capital. In this regards, villagers will suggest to the wholesalers or other fishermen who have stocks to sell, and at the same time, recommends reliable wholesalers to other fishermen. Consequently, this leads to the bonding of social capital links amongst the villagers that further assure them through a 'good word' as well as a recommendation to the wholesaler (Da costa and Turner, 2007).

Meanwhile, fishermen in Bangladesh work on maintaining a good relationship with officials by being involved in social groups. Accordingly, these initiatives enable them to gain instant assistance and wider access to alternative livelihoods from the groups before or during extreme events (Saroar and Routray, 2012). Furthermore, it is undeniable that this relationship opens up opportunities for the fishermen to share adaptation knowledge which will be helpful in enhancing their adaptive capacity.

On a similar note, fishermen in Bangladesh and Pakistan also receive assistance from relatives and family networks (Saroar and Routray, 2012; Salik et al., 2015). A possible explanation for this may be the fact that these social sources are trusted and reliable which helps to ease and strengthen their adaptation strategies due to the high level of cooperation between them (Saroar and Routray, 2012; Salik et al., 2015). Apart from that, Shaffril et al. (2017b) stated that fishermen in Malaysia also work on maintaining a strong social relationship with their community by providing mutual help (referred to by locals as *gotong-royong*), *rewang* (mutual help during wedding ceremony), and evening gatherings at *wakaf* and coffee stalls. Overall, it is safe to say that these practices tend to create a sense of belongingness, togetherness, and attachment to the community in encouraging them to cooperate with one another. Therefore, this will strengthen their responses before and during the impacts and subsequently expedite their recovery process.

3.2.2.4. Food savings/sharing (FS). The community in Southwest Bangladesh do not only have to face death as a result of the tropical cyclones and tidal surges, but their vital livelihood resources such as rice production and livestock resources are also damaged due to the extreme events. More importantly, this situation directly contributes to the shortage of cooking fuel considering that the rice straw and dried dung of livestock are regarded as the two most common fuels in rural households, particularly in the area of coastal Bangladesh. Hossain et al. (2018) further stated that this situation forces the fishermen to reduce the number and the size of their daily meals, while others tend to opt for cheaper food. Apart from that, as they already know the impacts of climate change on food resources, some fishermen have been taking proactive measures by storing sufficient supply of food knowing the impacts of climate change on food resources, while others choose to share and exchange food with others (Faustino and Jr, 2009).

3.2.2.5. Migration (M). Migrating to other places is another adaptation strategy practised by fishermen in several countries which include Bangladesh, India, and Pakistan. Specifically, this strategy demonstrates the ability of fishermen to migrate in times of natural disasters with the aim of seeking shelter and job opportunities away from their villages. Regarding this matter, it should be noted that some non-climatic reasons that drive migration include the decreasing trend of livelihood, unavailability of civic facilities, and seeking better job opportunities; while the climatic factors that lead to migration are floods and heavy rainfalls (Hasan and Nursey Bray, 2018; Ramachandran et al., 2016; Salik et al., 2015). On the other hand, Hossain et al. (2018) found that Bangladeshi fishermen tend to practise seasonal migration by moving to locations where fishes are available. More importantly, this strategy has a significant role in sustaining the livelihood of fishermen, particularly in dealing with the impacts of climate change. Furthermore, other migration strategies include staying a distance from the coast, opting not to operate related fisheries activities during monsoon or extreme events, and moving to a new settlement. Other than that, some have also opted to transfer their assets and family members to a higher area within a period of time, move their relative houses in an inner area or strong building, or leave in cyclone shelters (Faustino and Jr, 2009; Saroar and Routray, 2012; Monirul Islam et al., 2014; Hasan and Nursey Bray, 2018).

3.2.3. Physical infrastructure

Climate change impacts do not only risk the lives of the fishermen but also tend to damage their vital livelihood assets such as houses and jetty. Hence, this has encouraged the fishermen to fortify their physical infrastructure in several ways. As previously mentioned, a total of six studies were found to focus on physical infrastructure related to the adaptation strategy. Nevertheless, the analysis for this theme has resulted in a total of two sub-themes, namely strengthening buildings/house structure/Re-settlement (4 studies) and others (3 studies).

3.2.3.1. Strengthening buildings/house structure/re-settlement (SB). In this case, it should be noted that another adaptation strategy practised by the fishermen is to improve their house structure (Faustino and Jr, 2009; Salik et al., 2015; Hasan and Nursey-Bray, 2018). For example, several efforts to reduce the vulnerability of the community have been implemented after Typhoon Yolanda hit and affected fishermen's houses. As a result, several national agencies in the Philippines have enforced the existing no-building of new buildings rules in order to minimise the number of fishermen who are settling within 40 m of shoreline. According to Andriesse (2018), the effort was initiated by the National Housing Authority together with the local government units for the relocation schemes. On a more important note, it must be understood that this particular effort is necessary; for instance, most of the fishermen's houses in Bangladesh are constructed with fragile materials such as bamboo, mud, and tin which are not able to withstand the extreme weather. Hasan and Nursey-Bray (2018) further added that the fishermen have responded to this matter by improving their house structure in terms of re-constructing their houses with cement brick as well as raising the height of plinth (Hasan and Nursey-Bray, 2018). Overall, it is safe to say that a better infrastructure provides the fishermen with better protection against extreme events, reduces their vulnerability as well as minimises the damage to their houses and loss of life and valuable assets.

3.2.3.2. Others (OT). On another note, it is also important to realise that fishermen have taken other initiatives. For example, the fishermen in the Philippines put up sandbags along the shoreline to prevent worsening coastal erosion. Meanwhile, an early warning system is employed to assist the fishermen in India to identify the risk zones as well as occurrence date and time, which will accordingly allow them to respond to the disaster by rescheduling their fishing activities (Faustino and Jr, 2009; Ramachandran et al., 2016). Most importantly, loss of lives and damages of property can be reduced with the help of the early warning system. According to Rahman et al. (2018), fishermen in Bangladesh especially the landowners have more access and more familiar with different services such as training facilities, government subsidized agricultural equipment and formal banking systems that are usually only available in urban areas.

3.2.4. Awareness, knowledge, and experience

In this section, it is crucial to understand that having more awareness, gaining more knowledge, and obtaining greater experiences are the keys for better adaptation towards climate change impacts. As previously mentioned, a total of seven studies focused on the adaptation related to awareness, knowledge, and experience. The present study managed to further categorise this theme into three sub-themes as follows: (1) experience and awareness (4 studies), (2) training (3 studies), and (3) access to information (5 studies).

3.2.4.1. Experience and awareness (EA). The awareness among the fishermen has geared them to value the environment and motivated them to become the main supporters of resource-protection. Moreover, conservatory related actions such as releasing smaller fish and not using illegal fishing tools are able to sustain and protect the natural resources, and at the same time, assist the fishermen in their proactive and reactive preparation that is capable of delaying or absorbing the impacts of climate change (Jacinto et al., 2015; Shaffril et al., 2017b; Graziano et al., 2018). Regarding this matter, Rahman et al. (2018) stated that experience plays an important role in the fishermen adaptation strategy. In addition, it should be noted that this valuable experience is able to assist them to respond well to weather instability; for instance, some of them will seek refuge at nearby islands when they are suddenly hit by extreme weather. Most importantly, the use of 'conventional GPS' which include the use of the star, moon, or wind direction enables them to return safely to the jetty and most often employed when the degree of visibility is low due to bad weather.

3.2.4.2. Training (TR). In this case, fishermen in 18 coastal towns in the Philippines attended workshops based on the vulnerability assessments of coastal fisheries ecosystems to climate change, particularly a tool that is used to understand the resilience of fisheries (VA–TURF). According to Mamauag et al. (2013), the focus of the workshops is to strategize enforcement activities with the aim of discouraging illegal fishing practices, establishing marine protected areas, prioritising socio-economic strategies, and emphasizing their latent capacities to be upgraded wherever appropriate.

Meanwhile, Rahman et al. (2018) stated that fishermen in Bangladesh empower their adaptation strategy by attending several programs that offer training in advanced agricultural techniques and technologies. Moreover, it should be noted that the programs are commonly organised by government agencies such as the Agricultural Extension Department and Bangladesh Agriculture Development Corporation. Apart from that, capacity building at the community level is another component of the adaptation strategy that has been employed by the Bangladeshi fishermen. On another note, fishermen in Cambodia have been involved in pilot studies to experiment on alternative cropping techniques. This project attempts to empower village stakeholders in making better-informed decisions with the aim of reducing the damages predicted from severe climate stresses (D'Agostino and Sovacool, 2011).

3.2.4.3. Access to information (AI). One of the sources that enable the fishermen to prepare against climate change impacts is by obtaining climate-related information via mass media (television, radio, newspaper), the internet, government, and non-government agencies (Saroar and Routray, 2012; Jacinto et al., 2015; Krishnan et al., 2016). For example, the Cambodian fishermen are given access to local climate information systems which offer them the opportunity to improve the implementation of locally-appropriate adaptation actions (D'Agostino and Sovacool, 2011). On the other hand, the Malaysian fishermen tend to rely on extensive local environmental knowledge such as referring to their conventional method to navigate their catching areas or guide them to return back safely to the jetty (Shaffril et al., 2017b). Nevertheless, it is considered inaccurate to rely on indigenous knowledge nowadays due to the inconsistent weather patterns.

3.2.5. Conservation and enforcement

As the impacts of climate change are forecasted to worsen, more conservation efforts need to be placed while enforcement activities are required to ensure all actions that harm nature can be controlled. A total of five studies focused on adaptation strategy associated with conservation and enforcement. Under this theme, a total of two sub-themes were developed namely conservation (2 studies) and enforcement (3 studies).

3.2.5.1. Conservation (CN). The climate change impacts such as rising temperature and extreme events (e.g. cyclone and typhoon) have endangered marine species in terms of reduced quality and quantity or marine resources, affected certain species fertility, and caused coral bleaching. Hence, Krishnan et al. (2016) suggested that conservation of natural resources is an effective adaptation strategy that should be implemented by the fishermen. Furthermore, it should be understood that conservation can maintain the environmental balance for future generation. In addition, it is interesting to discover that both women and men in the Philippines are equally sharing their responsibilities in climate change mitigation project. A possible explanation for this refers to their connections to nature which seem to strengthen their senses of responsibilities in climate change related programs such as mangrove planting with added responsibilities to an already congested schedule (Graziano et al., 2018).

3.2.5.2. Enforcement (EF). Mamauag et al. (2013) stressed that the Filipino fishermen are obliged to use certain fishing gears that are regulated by laws which are enforced in marine protected areas. The efforts concentrated in reducing the fishing mortality are currently fully exploited or overexploited fisheries which may reduce the climate change impacts, and at the same time, able to serve as precautionary management for the restoration of the ecosystem (Mamauag et al., 2013; Ramachandran et al., 2016).

4. Discussion

In this section, the practised adaptation strategies are grouped into two categories. The first category refers to the positive adaptation strategy which is described as a sustainable strategy that is not dependent on the environment as well as can be practised regardless of the environmental situation. Meanwhile, the second strategy refers to a negative adaptation strategy that is defined as a short-term solution and cannot be sustained due to its strong reliance on nature stability. In fact, it should be noted that certain adaptation practices in this category are considered as unethical and involves crimes.

4.1. Positive adaptation strategies

The livelihood diversification practised by fishermen is able to lessen their dependency on nature's stability, which allows them to sustain the impacts regardless of the weather conditions. According to Hossain et al. (2018), those with education certificates have a strong advantage because they are qualified to work as professionals and have the opportunity to work in the public sectors. Furthermore, a study conducted by Shaffril et al. (2017b) confirmed the importance of the strategy; however, it must be in line with their need, interest, and ability. For example, the senior fishermen who were approached by the related agencies to be involved in boat or engine repairing with the aim of generating extra income may fail to adapt effectively due to their great interest in entrepreneurship rather than vocationally related activities (Shaffril et al., 2017b). On a more important note, drawing on the studies conducted by Shaffril et al. (2013) and Hossain et al. (2018), the livelihood diversification strategy should be extended to other household members in order to reduce the strong dependency on the fishermen as the sole income generator. In addition, it must be understood that this strategy helps to vary their sources and distance themselves from 'specialization trap' which is a term coined by Coulthard (2008) to describe a community that relies mostly on one activity for their livelihood. Meanwhile, another adaptation effort related to income increment that can be practised by the fishermen is by expanding the markets for their products. Moreover, this is believed to be a good adaptation strategy because it ensures continuous supply of their resources that can be sold as their outputs, and at the same time, avoid 'poor sales' which is known as a situation where the price of their products is manipulated by the middle man (Da costa and Turner, 2007).

Other than that, the lack of knowledge and awareness increase the vulnerability to climate change impacts among largely illiterate, unskilled, and resource-poor community (Badjeck et al., 2010). Generally, Asian fishermen tend to recognise and rely on their valuable experiences in developing adaptation strategies via the provision of indigenous forecasting abilities as well as an observation on local environmental changes. For example, the Malaysian fishermen often refer to the mountain or hill in relocating their fishing areas, while some are guided by the direction of the waves to return safely to their jetty (Shaffril et al., 2017b).

On another note, the purpose of the insurance scheme is to protect the fishermen and accelerate their recovery processes during a post-natural disaster (Badjeck et al., 2010; Monirul Islam et al., 2014). Generally, insurance is considered as an important adaptation strategy but some fishermen refuse to do so due to low awareness, expensive cost, lack of provision for claim settlement in case of partial losses, bureaucracy during claim settlement process, and long time needed for claiming approval (Parappurathu et al., 2017; Zheng et al., 2018). On the other hand, the strengthening of buildings/house structures offers fishermen with better protection against extreme events, reduces their vulnerability as well as minimises the destruction to their houses, loss of life, and damage to valuable assets. Nevertheless, it is unfortunate that this strategy is hardly practised by the poor. Therefore, the poor seem to be vulnerable at practising this adaptation strategy without any assistance from the agencies due to the high cost of some items (e.g. cement brick) (Mallick et al., 2017).

A strong social relationship encourages cooperation and reduces social conflicts between the fishermen and the surrounding community which enables them to respond efficiently before, during, and after the impact. Moreover, this will facilitate rescue works, minimise associated risks, and reduce the number of deaths (Shaffril et al., 2017b; Iwasaki et al., 2009). Other than that, a strong social relationship also enables fishermen to gain support during difficult times and encourages the sharing of ideas and technological innovation (Mazuki et al., 2013). Meanwhile, migration is another adaptation strategy which allows the fishermen and their family to temporarily take refuge from extreme events threats. In this sense, their strong cooperation will expedite the transfer process, reduce social conflicts as well as decrease the risks of injury, loss of life, and damage of assets (Shaffril et al., 2013; Adger, 2003). In addition, migration allows fishermen to take available advantage in other areas, and at the same time, offers them the opportunity to diversify their livelihood. Regarding this matter, Rai (2018) emphasised that fishermen who want to migrate should be economically and socially ready and without both, there is a possibility that their lives will be worse than before. For example, the fishermen may have difficulty to obtain the basic necessities during the post-migration period without strong financial resources, while those who are not socially ready may experience culture shock and become socially depressed (Rai, 2018; Klein et al., 2018). Hence, the expected climate change impacts have driven fishermen to save their foods in order to enable them to enjoy continuous food access and supply in the event of extreme weather with the high possibility of food shortage (Islam and Ahmed, 2017). Moreover, some even share with others and practice the barter system which may be regarded as a primitive way; however, the barter system seems to stimulate the local economy, offers continuous food supply, eludes starving, and bolsters the relationships of the poor and those in a struggling country with their surrounding communities (Singh et al., 2017). Moreover, Islam and Ahmed (2017) stated that it is important to practise this adaptation strategy because the impacts of the unstable climate will reduce food availability and accessibility up to 28%.

Several conservation efforts related to laying artificial reefs in the sea, releasing seedlings/fish to the sea, and involving in coral reef breeding project are able to create reproduction zones, benefit biological productivity, enhance the population of fish and invertebrates, and improve fishermen catch. On another note, mangrove planting and restoration are significant strategies because it protects the fishermen assets (house, jetty, vessels, fishing tools) from flood, erosion, and sea level rise. According to Massel et al. (1999), mangrove planting provides protection to the coastal community due to its ability to absorb 75% of the wave strength. Additionally, it should be noted that enforcement on marine resources allows the fishermen to obstruct or minimise any prohibited activities that can cause harm and threats to the marine ecosystem. Therefore, frequent monitoring of illegal fishing (e.g. illegal bottom trawling and blast fishing) have resulted in a significant and positive impact to the quality and quantity of marine resources (Mamauag et al., 2013; Sander et al., 2014; Selvaraj, 2015).

More importantly, a number of organizations (government, private, NGOs) have placed their efforts within the scope of climate change adaptation by providing short-term relief goods and long-term programmes to revive livelihoods. For example, access to cash transfer program and poverty alleviation offer 'safety net' to the fishermen as well as their family members when coping with livelihood change, thus sinking the vulnerability towards climate change formidable impacts. However, Shaffril et al. (2013) stated that the climate change adaptation program must be consistent over time to ensure its success, and most importantly, it must take into consideration the following three focal questions: (1) Are the programs in line with the fishermen's needs? (2) Do the programs fit their interests?, and (3) Are the programs in line with their adaptation abilities? Moreover, it is crucial to emphasise that any planned programs between the government, private, and NGOs should be centralised considering that they may cooperate in the implementation of policies and strategies, establishment of partnerships with pertinent stakeholders and the strengthening of the community's adaptation ability (McCarney et al., 2011). However, these initiatives are usually obstructed by limited financial resources, inadequate human resources skills, and access to timely information (McCarney et al., 2011).

4.2. Negative adaptation strategies

According to Iwasaki et al. (2009), internal livelihood diversification is a short-term solution and not sustainable during bad weather or extreme events. In particular, this hinders them from operating their fishing activities at the sea during a typhoon regardless of the precautions that they have taken (e.g. upgrade boat engines, improve boats and nets). Meanwhile, those who are involved in aquaculture are risked by saltwater intrusion and their cage culture are vulnerable to damage and loss from natural disaster, which consequently causes them to invest largely without any guarantee in return (Da costa and Turner, 2007).

On another note, some of the external livelihood are seen as unsuitable because they are related to unethical activities. For example, some fishermen in Bangladesh work as a quack in which they are perceived as a doctor by the locals. However, in truth, they have no proper medical degrees or education. In addition, quack includes individuals who practise herbal and other alternative medicines such as Siddha, Ayurvedic, or kaviraj. Moreover, they do indulge in high-risk practices such as the use of injections and IV fluids even without proper qualification. As stated by Datta (2013), many doctors believe that quacks should be banned because they are posing a threat to people which can cost their life. Furthermore, some of the fishermen are criminals because they are involved in pirate activities such as swooping down the fishers who are fishing in Sundarbans, snatch the catch, nets, and other valuables and even to the extent of kidnapping other fishermen for ransom (Hossain et al., 2018).

Meanwhile, employing their young children with a job is an erosive adaptation strategy which results in an intergenerational leaning towards poverty and vulnerability (Hossain et al., 2018; Venton, 2015). In particular, taking out their children from school narrows the chances for a family to change despite their purpose of contributing additional income and helping to sustain the livelihood of the families. Perry et al. (2009) stated that education is a powerful adaptive strategy for individuals, families, and communities considering that higher educational attainment enables children to have a better job and increase the possibility to change their family life.

On a more important note, it is undeniable that taking loans/borrowing money or selling items/assets offer short relief to the fishermen; however, it actually drives them further into the poverty trap. Specifically, the fishermen are tied to a strict repayment schedule which can intensify their debts and dependency. Moreover, some opt to take loans from illegal lenders – an easier, non-complicated, and less bureaucracy process of applying for money due to the high number of bureaucracies involved when making a loan application from the bank. Generally, these lenders usually charge high interest on the loan which results in difficulties to repay the loan, and eventually causing the loan cycles to continue for a longer duration (Rao et al., 2017). Meanwhile, some fishermen request for an advance from the wholesalers despite knowing the low profit, and in return, they are forced to sell their fishes to the wholesalers later on during the fishing season. The fishermen are also linked to desperate sales which require them to sell their belongings and assets (e.g. motorcycle, livestock) as one of the options because extreme events forbid them from operating their routines. However, the repetition of this activity would lead to the term of social instability as coined by D'Agostino and Sovacool (2011). Consequently, this situation leads to food shortage which potentially occurs in poor states where the community is most at risk of violent uprisings because they are having difficulties to respond well to climate change.

5. Recommendations

The findings and systematic review process of the present study have led to a number of recommendations that may be helpful for future studies. First, future scholars should focus on the negative adaptation strategies for their future research despite its unsuitability by figuring out the reasons why fishermen are still practising them even knowing that the strategies merely offer short term solutions. Furthermore, it is vital to examine which factors including culture, social pressure, or economic have been gearing them to still depend on negative adaptation strategies considering that the climate change impacts are forecasted to worsen in the future.

Meanwhile, it should be noted that several improvements can be made to the established flow diagram developed by Moher et al. (2009) based on the article retrieving process for future systematic review. In the case of the present study, problems started to arise when there are too many articles that are retrieved as more time and effort were required to download all the articles and screen out all of the duplicated articles even with the assistance of tools such as Mendeley and Endnote. Therefore, it is appropriate to remove the duplicated articles once the screening process is completed. This process is believed to ease the authors to remove any duplicated articles as the number of remaining articles should be reduced following the inclusion and exclusion process during screening stage (Refer to Fig. 4).

On another note, it should be realised that all of the studies were only concentrated on the Southern Asian Region and the Southeast Asian Region. Hence, this demonstrates the need for more similar research to be conducted in other regions such as the East Asian (e.g. China, South Korea, Hong Kong, Japan) and the Western Asian (e.g. Saudi Arabia, Yemen, Oman). In this case, it is imperative to obtain empirical data about climate change impacts from the countries because such condition is witnessed globally. In other words, these studies are important because the events have been well observed. For example, the annual mean temperature in the Eastern Asian region has shown an increasing trend, while a weak but non-significant downward trend in mean precipitation was reported in the Western Asian region over the last decades despite the increase in intense weather events (Hijioka et al., 2014). Furthermore, strategies implemented by the fishermen in the developed countries should be further investigated because most of the studies only focused on fishermen in developing countries.

6. Conclusion

The recent literature on the adaptation strategies of Asian fishermen reflects a basic understanding of how they respond towards the worsening climate change impacts. Furthermore, five main themes that represent the adaptation strategies of Asian fishermen towards climate change impacts were identified based on the systematic review performed by the current research. The first theme refers to the livelihood diversification which is described as a strategy employed with the aim of diversifying the livelihood options of the fishermen as well as attempting to lessen their reliance

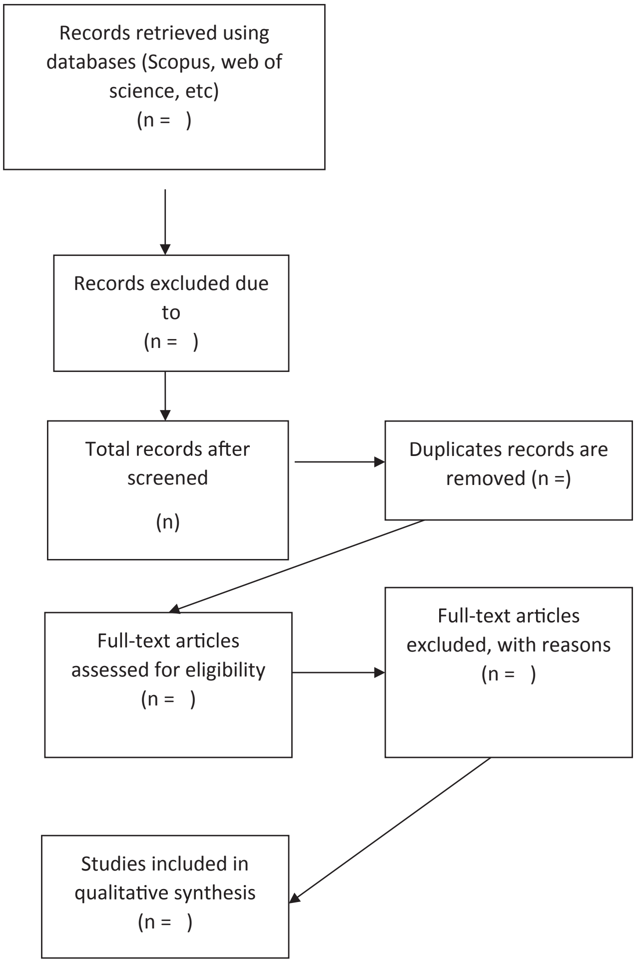

Fig. 4. Suggested flow diagram.

on fisheries-related activities. Second, the theme refers to a social relationship that is developed based on the good relationship with their social surrounding (e.g. family members, the related organizations, and their colleagues) in order to survive against the climate change impacts. Next, the third theme is known as infrastructure which explains the efforts of the fishermen in improving or building a new building or house structure. The fourth theme emphasises awareness, knowledge, and experience despite the rapid emergence of advanced tools, while the final theme is related to conservation and enforcement. Overall, this strategy is able to strengthen the environmental balance and satisfy the fishermen by offering them a healthy planet for their future generation. Therefore, further broadening of this basic understanding through the integration of diverse researches findings may be able to assist the concerned parties in developing strategies that are in line with the needs, abilities, and interests of the fishermen.

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RESEARCH REVIEW

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Incorporating climate change adaptation into marine protected area planning

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Abstract

Climate change is increasingly impacting marine protected areas (MPAs) and MPA networks, yet adaptation strategies are rarely incorporated into MPA design and management plans according to the primary scientific literature. Here we review the state of knowledge for adapting existing and future MPAs to climate change and synthesize case studies (n = 27) of how marine conservation planning can respond to shifting environmental conditions. First, we derive a generalized conservation planning framework based on five published frameworks that incorporate climate change adaptation to inform MPA design. We then summarize examples from the scientific literature to assess how conservation goals were defined, vulnerability assessments performed and adaptation strategies incorporated into the design and management of existing or new MPAs. Our analysis revealed that 82% of real-world examples of climate change adaptation in MPA planning derive from tropical reefs, highlighting the need for research in other ecosystems and habitat types. We found contrasting recommendations for adaptation strategies at the planning stage, either focusing only on climate refugia, or aiming for representative protection of areas encompassing the full range of expected climate change impacts. Recommendations for MPA management were more unified and focused on adaptative management approaches. Lastly, we evaluate common barriers to adopting climate change adaptation strategies based on reviewing studies which conducted interviews with MPA managers and other conservation practitioners. This highlights a lack of scientific studies evaluating different adaptation strategies and shortcomings in current governance structures as two major barriers, and we discuss how these could be overcome. Our review provides a comprehensive synthesis of planning frameworks, case studies, adaptation strategies and management actions which can inform a more coordinated global effort to adapt existing and future MPA networks to continued climate change.

KEYWORDS
adaptive management, biodiversity protection, climate change, connectivity, marine protected area network, marine reserve, systematic conservation planning, vulnerability

1 | INTRODUCTION

Marine protected areas (MPAs) and MPA networks are rapidly growing cornerstones of marine conservation efforts worldwide (UNEP-WCMC, IUCN, & NGS, 2018). MPAs can help to increase local biodiversity, restore functional food webs, protect threatened species and sensitive habitats and support adjacent fisheries among other benefits (McCook et al., 2010). Originally, MPAs were designed to protect marine biodiversity from the impacts of overfishing and other human impacts under the implicit assumption of stationary environmental conditions characterized by a mean state with variance, but no long-term trend. Yet, anthropogenic climate change has invalidated that assumption causing rapid and unprecedented shifts in environmental conditions across all ocean basins (IPCC, 2019; Lotze et al., 2019). Marine communities have responded in a multitude of ways including range shifts to higher latitudes or greater depths, altered phenology, and species turnover, among many others (Poloczanska et al., 2016; Worm & Lotze, 2016).

The global MPA network has rapidly expanded over the past two decades as nations work towards meeting the Convention on Biological Diversity's Aichi Target 11 to protect at least 10% of their coastal and marine areas by 2020 (Lubchenco & Grorud-Colvert, 2015). This is particularly relevant in the face of changing ocean conditions as there is evidence that MPAs can help buffer marine communities against the impacts of climate change (Roberts et al., 2017). For instance, benthic invertebrates in an MPA in Mexico had greater resilience to a climate-driven hypoxia event than populations outside of the MPA (Micheli et al., 2012). However, MPAs do not always increase ecosystem resistance to climate-driven events. For example, a global analysis of temperature-driven loss in coral cover found that observed impacts were comparable between protected and unprotected areas (Selig, Casey, & Bruno, 2012). Hence, dramatic reductions in greenhouse gas emissions may be the only comprehensive solution to mitigate the effects of climate change on marine ecosystems (Bates et al., 2019). Regardless, climate change will continue to impact the global network of MPAs (Bruno et al., 2018), posing a significant challenge to managers as to how best to protect marine biodiversity in a changing seascape. To maximize the conservation benefits of MPAs now and into the future climate-change adaptation strategies are critical (Roberts et al., 2017). Yet so far, climate change adaptation is largely limited to conceptual frameworks, and rarely considered in protected areas objectives and management plans (IPBES, 2019; Tittensor et al., 2019).

Here we review the current state of scientific knowledge for adapting MPAs to ongoing climate change. For this review, 'MPA' can refer to a single MPA, an MPA network and partially protected MPAs (including 'other effective area-based conservation measures'; OECMs) or fully protected marine reserves. We started with existing reviews and then performed an extensive search of the primary literature accessible via Google Scholar to answer the question of how marine conservation can best adapt to shifting environmental conditions in a changing climate. Specifically, we introduce conservation planning frameworks that incorporate climate change adaptation into the design and management of MPAs. We derive a simplified generalized planning framework as a guide and then examine how climate change adaptation has been included in MPA planning, design and management with empirical case studies. This includes a discussion of conservation goals, vulnerability assessments, climate change adaptation strategies and management actions in the context of the broader climate change adaptation literature. We further discuss the perceived barriers to including climate change adaptation into MPA design and management, and end on a discussion of research gaps. By summarizing the planning frameworks, case studies, adaptation strategies and management actions, our work can help to inform the development of climate-adaptive MPAs globally.

2 | CONSERVATION PLANNING FRAMEWORKS THAT INCLUDE CLIMATE CHANGE ADAPTATION

Planning frameworks for biodiversity conservation can be used to help design and manage MPAs. A number of frameworks have been proposed which incorporate climate change adaptation (Abrahms, DiPietro, Graffis, & Hollander, 2017; Gross, Woodley, Welling, & Watson, 2016; Poiani, Goldman, Hobson, Hoekstra, & Nelson, 2011; Reside, Butt, & Adams, 2018; Wyborn, van Kerkhoff, Dunlop, Dudley, & Guevara, 2016). These include systematic conservation planning (SCP; Mačić et al., 2018; Margules & Pressey, 2000; Reside et al., 2018), climate-smart conservation (CSC; Stein, Glick, Edelson, & Staudg, 2014), adaptation for conservation targets (ACT; Cross et al., 2012), portfolio decision analysis (PDA; Convertino & Valverde, 2013), and the IUCN adaptation cycle (Gross et al., 2016; see Appendix S1 for details).

The most popular of these planning frameworks are SCP and CSC. SCP is widely implemented in the marine literature, although as of 2015 only ~8% of this literature had considered climate change (Álvarez-Romero et al., 2018). SCP is an 11-step process centred around clear objectives to allocate limited conservation resources (Appendix S1). This process readily allows the incorporation of clear climate change adaptations objectives and three recent reviews have examined SCP in the context of climate change (Álvarez-Romero et al., 2018; Mačić et al., 2018; Reside et al., 2018). CSC, ACT and IUCN adaptation cycle are very similar frameworks based on linking specific climate vulnerabilities and adaptation options to the MPA conservation goals with the IUCN adaptation cycle being the most simplified of the three. PDA is the most dissimilar from the other four planning frameworks and it is based on creating a management action portfolio, similar to a financial portfolio, to maximize conservation benefit while minimizing impacts on human uses in the MPA (Convertino & Valverde, 2013). A recent review and comparison between CSC, ACT and PDA is provided in Abrahms et al. (2017).

We used the five individual planning frameworks to collectively guide our understanding of how climate change adaptation has been incorporated into MPA planning (see Appendix S1 for information on how each framework was included in our summary). To incorporate climate change adaptation into conservation planning, there are four principal steps (Figure 1), based on the general features of the five frameworks listed above. All frameworks set clear conservation goals, which includes defining conservation features (what to protect: such as threatened species) and objectives for the MPA (how to protect: such as defining representation and persistence targets across an MPA). These conservation goals then

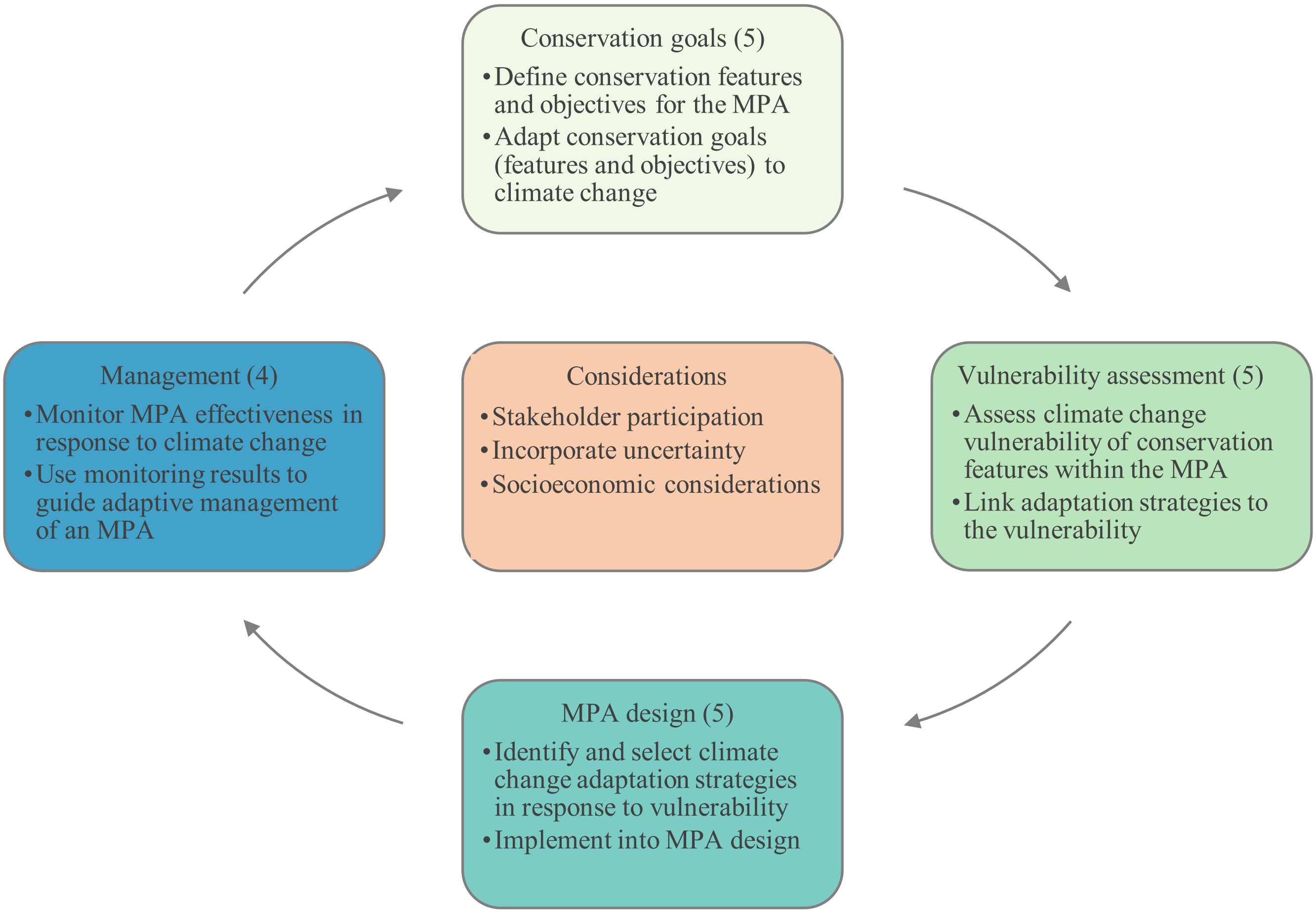

FIGURE 1 Integrating climate change adaptation in all stages of marine protected area (MPA) planning, design and management. Shown is a simplified planning framework based on the general features of five common existing frameworks for biodiversity conservation (see Appendix S1 for details on individual frameworks including how they implemented each measure). Number in brackets indicates number of frameworks (out of five examined) that included these (or equivalent) measures [Colour figure can be viewed at wileyonlinelibrary.com]

need to be adapted to be effective with climate change and may need to be evaluated over time as conservation features may range shift or network connectivity may be disrupted (Carr et al., 2017; Fredston-Hermann, Gaines, & Halpern, 2018). A second step identified by all frameworks is to perform a vulnerability assessment to examine how climate change will impact conservation goals. For example, one conservation feature may be to protect all examples of coral reef bioregions (defined area with unique species assemblages and physical features), with a conservation objective to maintain a certain representation target (e.g. protect 20% of each bioregion). Then a vulnerability assessment may examine how climate change may alter the representation of each bioregion within an MPA (e.g. reductions in spatial coverage results in 10% representation of one bioregion within the MPA) to determine if conservation goals will be met in the future (Game, Watts, Wooldridge, & Possingham, 2008). The third step consists of identifying and selecting climate change adaptation strategies to mitigate against the climate change impacts identified in the vulnerability assessment. These are then incorporated into MPA design, for example by focusing protection on reef features in climate refugia that are projected to experience little or no change in the near future.

Finally, as a fourth general step, the MPA would be continually monitored for effectiveness to ensure the conservation goals are being met. The monitoring results can then be used to guide the adaptive management of the MPA against ongoing climate change impacts. Throughout the planning process (Figure 1), it is generally important to (a) include stakeholder participation (Álvarez-Romero et al., 2018); (b) assess the socio-economic impacts of protection (Mangubhai, Wilson, Rumetna, Maturbongs, & Purwanto, 2015); and (c) account for uncertainty in climate change projections, ecological responses and management effectiveness (Hannah, Midgley, & Millar, 2002; Kujala, Moilanen, Araújo, & Cabeza, 2013). This entire planning process may need to be repeated and adapted over time, depending on the results of vulnerability assessments and monitoring data. Although the outlined planning frameworks are generally seen as top–down approaches, bottom-up community efforts can also incorporate climate change adaptation. For example, a locally managed MPA network in Fiji has used adaptive management, in partnership with an NGO, to iteratively refine individual MPA boundaries with coral reef boundaries to enact MPA design principles which may increase resilience to climate change (Weeks & Jupiter, 2013).

3 | HOW CLIMATE CHANGE ADAPTATION CAN BE INCLUDED IN MPA PLANNING, DESIGN AND MANAGEMENT

3.1 | Conservation goals: Define and adapt to climate change

As species and ecosystems continue to respond to a changing climate, MPA conservation goals will need to be re-evaluated and adapted over time (Figure 1; Hopkins, Bailey, & Potts, 2016a). To preserve marine biodiversity in a warming ocean, it is important to include conservation features which focus both on conserving species (fine-filter approaches), while also protecting higher level ecological or environmental aggregations, such as a habitats, eco/bioregions or community/species assemblages (coarse-filter approaches; Tingley, Darling, & Wilcove, 2014). As some species, including threatened, or commercially important species, may be missed when only looking at higher level aggregations, it is important to include both (Tingley et al., 2014). For studies which incorporated climate change adaptation into MPA design, 15% used only species-based (fine-filter) approaches (Figure 2a; Appendix S2), with the rest relatively evenly split between only focusing on higher level aggregations (coarse-filter; 37%) or a mix of the two (both; 48%).

When higher level aggregations were prioritized for conservation, the most common focused on habitat type (e.g. Klein et al., 2013; Maina et al., 2015), followed by eco/bioregions (e.g. Levy & Ban, 2013; Makino et al., 2014), and communities/species assemblages (e.g. Malcolm & Ferrari, 2019; Appendix S2). These approaches were originally designed to protect specific biological communities (Tingley et al., 2014). For instance, Malcolm and Ferrari (2019) used fish assemblage patterns to define a habitat classification system to use in MPA planning within an ocean warming hotspot. They found that despite some tropicalization (increase in proportion of warm water species), the general assemblage patterns persisted over 16 years within the MPA, suggesting that the habitat classification scheme remained a valuable tool. Yet studies like these are likely to remain the exception; species react to a changing climate differently, and re-organizations of biological community structure are likely (Rilov et al., 2019). As such, focus has shifted somewhat from community-centred approaches, such as bioregions, to focus on environmental characteristics or more permanent seascape features, such as habitat type (Tingley et al., 2014).

Habitat type can focus on habitat-forming species, such as corals, oysters or macrophytes, which can provide ecological services to increase community resilience (Simard, Laffoley, & Baxter, 2016), and were included in several design studies (Appendix S2). Some habitat-forming species, such as mangroves and seagrasses, have the added benefit of acting as carbon sinks (Brock, Kenchington, & Martínez-Arroyo, 2012). Yet these habitat-forming species may undergo range shifts requiring a reanalysis of conservation goals. Habitat type can also refer to unusual geological features with complex structure (Stratoudakis et al., 2019), which are permanent even under climate change. Examples include efforts to protect seamounts and underwater canyons (Green et al., 2009; Perdanahardja & Lionata, 2017). Lastly, environmental or climatic conditions can be used to define areas to protect. Typically areas of climate refugia,

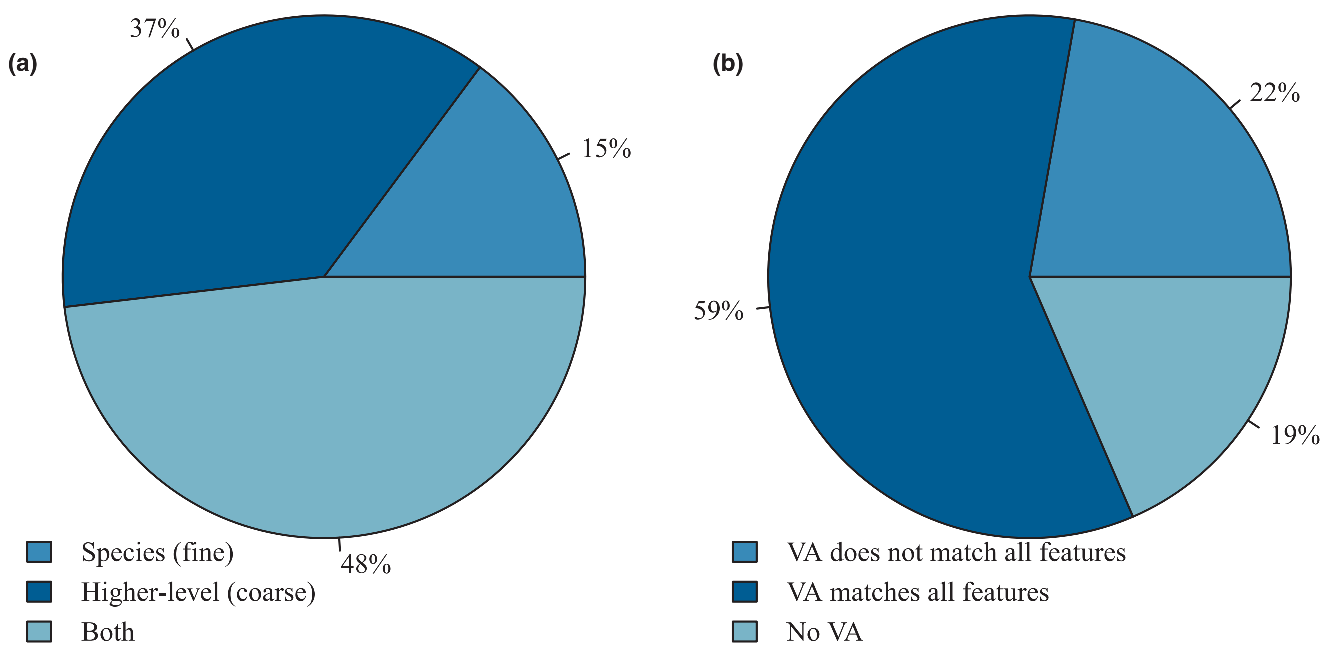

FIGURE 2 Overview of empirical case studies that considered climate change adaptation in the design of existing or future marine protected areas (MPAs; *n* = 27). (a) Conservation features prioritized for protection within the MPA, including species-based (fine), higher-level environmental or biological aggregations (coarse), or a combination of the two (both). (b) If a climate change vulnerability assessment (VA) was performed as part of the MPA planning process and if it matches all or not all conservation features. For further details see Appendix S2 [Colour figure can be viewed at wileyonlinelibrary.com]

where conditions are not changing or changing only slowly, have been prioritized for protection (Fredston-Hermann et al., 2018; Tingley et al., 2014). Others argue, however, that areas including the full range of projected climate change impacts should be considered to ensure the protection of the full spectrum of 'climate heterogeneity', in other words include areas projected to have different exposure to climate change (Gerber, Mancha-Cisneros, O'Connor, & Selig, 2014). Simulations of coral reef ecosystems have shown that as corals adapt to changing conditions, habitat diversity is the preferred adaptation strategy over climate refugia (Walsworth et al., 2019).

By protecting habitats experiencing the full range of climate projections, MPAs are best facilitating the ability of different species to adapt and evolve, or shift their distribution, particularly if connectivity is maintained between MPAs (Brock et al., 2012; Webster et al., 2017). For instance, Magris, Pressey, Mills, Vila-Nova, and Floeter (2017) prioritized a combination of refugia coral reefs and reefs exposed to warming temperatures for protection, while facilitating connectivity via source reefs (that export larvae to nearby habitats) and stepping stones (small habitat patches that species colonize to facilitate longer distance dispersal). Furthermore, if functional groups are protected across the full range of environmental conditions, ecosystem functions can be maintained as each trophic level has a role in regulating an ecosystem (McLeod, Salm, Green, & Almany, 2009; Simard et al., 2016). This has been incorporated into MPA conservation features by conserving herbivorous fish to increase coral reef resilience to climate change (Mumby, Wolff, Bozec, Chollett, & Halloran, 2014; Weeks & Jupiter, 2013). Protecting areas of high species diversity, genetic diversity and critical habitat areas have also been suggested as an important climate change conservation strategies (Brock et al., 2012; Fredston-Hermann et al., 2018), and were included in several design studies (Appendix S2).

Protecting species with crucial ecosystem roles, or of ecological concern, is an important biodiversity conservation goal in the face of climate change (Brock et al., 2012). When climate change was incorporated into MPA design with only species-based approaches (Appendix S2) these studies generally focused on protecting keystone species (Patrizzi & Dobrovolski, 2018) or used species-specific trait-based vulnerability to warming, such as coral reef thermal stress regimes (Magris, Heron, & Pressey, 2015; Mumby et al., 2011). The thermal stress regimes each denote different levels of projected coral stress, across various magnitudes of climate change exposure, to define a range of areas to protect across different climate futures. In mixed approaches (Appendix S2), individual species were included if they were threatened, endemic commercially or ecologically important, or were associated with a specific habitat area (e.g. Green et al., 2009; Lombard et al., 2007; Magris et al., 2017). Regardless of the type of conservation feature that was protected, similar conservation objectives were used in all case studies. All considered some type of climate change objective, also known as persistence targets, to ensure a conservation feature persists in the face of climate change (Appendix S2). Most (86%) of studies defined representation targets to be met within the MPA (e.g. 30% of the total habitat extent of a specific habitat). Many (63%) included socio-economic consideration such as minimizing loss to fishers, and some included objectives to maintain connectivity within an MPA network (26%).

3.2 | Vulnerability assessment: Testing for climate change vulnerability

Before climate change adaptation strategies can be incorporated into MPA design and management, the specific vulnerability of the conservation features to climate change must be assessed (Figure 1; Foden et al., 2019). Climate change vulnerability has three components: exposure, sensitivity and adaptive capacity (Dawson, Jackson, House, Prentice, & Mace, 2011). Exposure quantifies the amount of climate change expected to impact the conservation feature, for example, the rate and magnitude of sea surface temperature (SST) increases. Sensitivity is the dependence of a conservation feature on a given set of abiotic or biotic conditions, for example, some species can tolerate greater SST increases. Adaptive capacity is the ability of the conservation feature to deal with climate change through mechanisms such as phenotypic plasticity, evolutionary processes or range shifts. Climate change vulnerability has been examined in existing MPAs where it can inform management actions such as rezoning (Keller et al., 2009). It can also be included within the design phase of MPA planning during spatial prioritization to allow for the implementation of climate change adaptation techniques (Jones, Watson, Possingham, & Klein, 2016).

We examined how the vulnerability of MPAs to climate change has been assessed in the design phase of MPA planning (Figure 3; Appendix S2). Here we only focus on biological and not on the socio-economic response to climate change, but note that both be incorporated into the vulnerability assessment (Figure 1; Maxwell, Venter, Jones, & Watson, 2015). We found that 81% of case studies included a vulnerability assessment (Figure 2b). These were performed almost exclusively on corals (82%; Figure 3c). This meant that for almost a quarter of the case studies, not all conservation features within an MPA underwent a vulnerability assessment (Figure 2b). For instance, Magris et al. (2017) used thermal stress regimes for corals as a vulnerability assessment to prioritize refugia and disturbed reefs for protection. Coral reefs provide important biogenic habitat and can be considered a sentinel species, indicating broader changes in an MPA. Yet, no vulnerability assessment was performed for other conservation features such as threatened or endemic species. Different temperature tolerances between species and within a taxon (e.g., between coral species; Gibbin, Putnam, Gates, Nitschke, & Davy, 2015) result in species-specific climate vulnerability, and the inclusion of impacts across an entire ecosystem may suggest different areas to prioritize for protection (Rilov et al., 2019). Yet only a few studies exist on how to examine ecosystem wide climate change vulnerability within existing MPAs (e.g. Kay & Butenschön, 2018; Munguia-Vega et al., 2018; Queirós et al., 2016). For instance, Munguia-Vega et al. (2018) used a literature review to qualitatively synthesize ecosystem level climate change vulnerability across multiple studies for an MPA network in

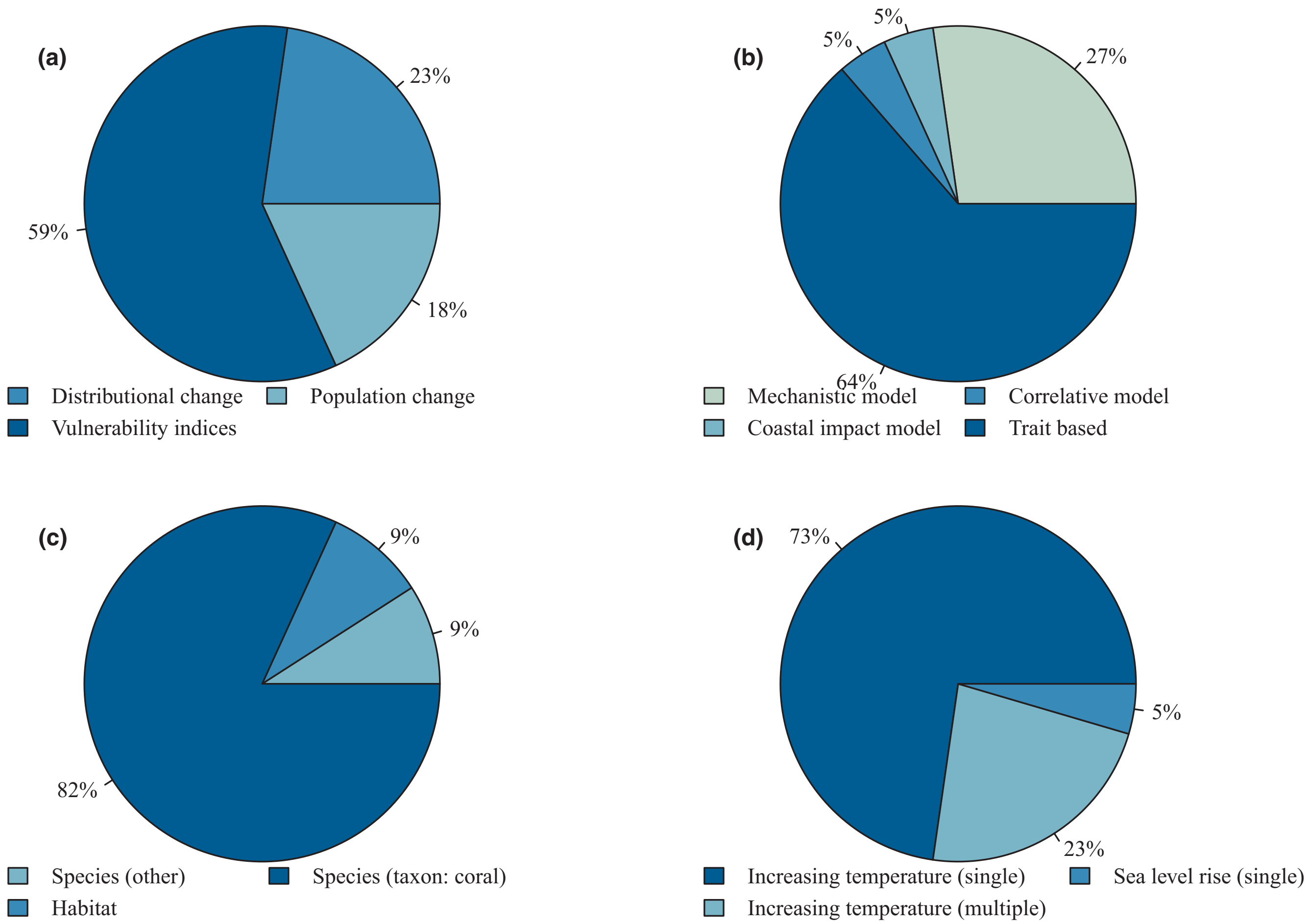

FIGURE 3 Empirical case studies that included a vulnerability assessment during the design of existing or future marine protected areas (n = 22). (a) The metric of how climate change will impact the conservation feature. (b) What type of model was used to assess the vulnerability. (c) What ecological resolution was used to examine the vulnerability. (d) What climate change threats were included in the assessment, and if the threat was examined in isolation (single) or in conjunction with other climate change stressors (multiple). For further details see Appendix S2 [Colour figure can be viewed at wileyonlinelibrary.com]

the Gulf of California. No case studies incorporated ecosystem wide climate change vulnerability into MPA design (Appendix S2).

Four main approaches have been used to assess a species' vulnerability to climate change: correlative, mechanistic, trait-based and combined approaches (Figure 3b) to model range shifts, extinction probability, population changes, and to create vulnerability indices (Figure 3a; Foden et al., 2019; Pacifici et al., 2015). Correlative and mechanistic models generally test for climate change exposure, while trait-based approaches test for sensitivity and adaptive capacity (Willis et al., 2015). Trait-based assessments have been widely used as many species can be assessed at once (Foden et al., 2019). We found that trait-based approaches were the most common method used to assess vulnerability in MPAs (Figure 3b), particularly those based on thermal stress regimes to identify coral bleaching risk. Thermal stress regimes use observed and sometimes future projected SST data to calculate metrics of acute (e.g. degree heating weeks) and chronic (e.g. rate of SST warming) stress to determine potential climate refugia (low exposure to thermal stress) and areas where corals may have high adaptive capacity due to previous or projected exposure to thermal stress (Chollett, Enríquez, & Mumby, 2014; Magris et al., 2015). Other trait-based methods included using susceptibility models to develop an exposure metric (Maina et al., 2015), or using thermal thresholds to examine distributional changes (Makino et al., 2014). Literature reviews and expert knowledge have also been used to qualitatively discuss vulnerability within the MPA or the results from the literature search have been used to make a quantifiable metric of a resilience indicator. For instance, Davies et al. (2016) used a literature review to identify the traits that may increase coral resilience to develop six, ranked resilience indicators that were included in MPA design.

With more knowledge, a species distribution model (SDM) can be used to explicitly test for future changes in habitat suitability (Foden et al., 2019). While SDMs were the most commonly used tool to incorporate climate change in a global review of spatial prioritization techniques (Jones et al., 2016) we found that only one study (Patrizzi & Dobrovolski, 2018) used SDMs to test for species distribution shifts with climate change within the context of MPA design (Figure 3a,b; Appendix S2). This study built SDMs for 17 threatened starfish species and their predicted current and future distributions were used to spatially prioritize areas for protection (Patrizzi & Dobrovolski, 2018). Other studies have used SDMs to examine climate change vulnerability within existing MPAs and their management (e.g., Jones et al., 2013). Yet the scarcity of SDMs used in designing MPAs is likely due to terrestrial bias in the global study (76%; Jones et al., 2016) and the greater use of SDMs in terrestrial compared to marine environments (Robinson et al., 2011). The most data-intensive and robust vulnerability approach uses process-based mechanistic models (Foden et al., 2019). We found that 27% of studies used mechanistic models to test for changes in coral per cent cover (Beger et al., 2015) and shifts in fish and invertebrate larval distribution (Álvarez-Romero et al., 2018).

In terms of climate change threats considered in the vulnerability assessments, we found that increasing temperature was by far the most common one (Figure 3d). Increasing temperatures were either examined in isolation (73% of studies) or in interaction with other climate-induced threats (23%). These interactions were most often examined with ocean acidification, changes in primary productivity or changes in UV radiation (Appendix S2). The interaction of multiple climate change stressors is important to include in vulnerability assessments, as predictions based on one stressor can be misleading (Worm & Lotze, 2016). Which threats to examine will be specific to the conservation goals of an MPA (Figure 1). For example, in tropical environments, increasing temperatures, rising sea level and decreasing pH will have negative impacts on coral reefs (McLeod et al., 2012). About 19% of the studies did not specify a specific climate change threat, and instead considered climate change adaptation in MPA design according to general resilience principles (Figure 2a).

3.3 | MPA design: Identify, select and implement climate change adaptation strategies

After a vulnerability assessment has been performed, specific adaptation strategies can be used in MPA design to minimize vulnerabilities (Figure 1). We reviewed the literature to extract climate change adaptation strategies that have been incorporated into MPA design (Figure 4; Appendix S2). Ideally, climate change considerations should be included early in the design process (Hopkins et al., 2016a). Furthermore, as there is often considerable uncertainty associated with climate change, conservation goals, adaptation strategies and management options must be robust or adaptable to different scenarios (Hopkins et al., 2016a) and include margins of error (Baron et al., 2009; McCook et al., 2009). The following sections define different adaptation strategies, explain how they were incorporated into MPA design and explore how they fit into the broader conservation literature.

3.3.1 | Increase MPA resilience

The earliest attempts to include climate change adaptation into MPA design were based on general guidelines to increase the resilience of coral reefs to climate change (McLeod et al., 2009).

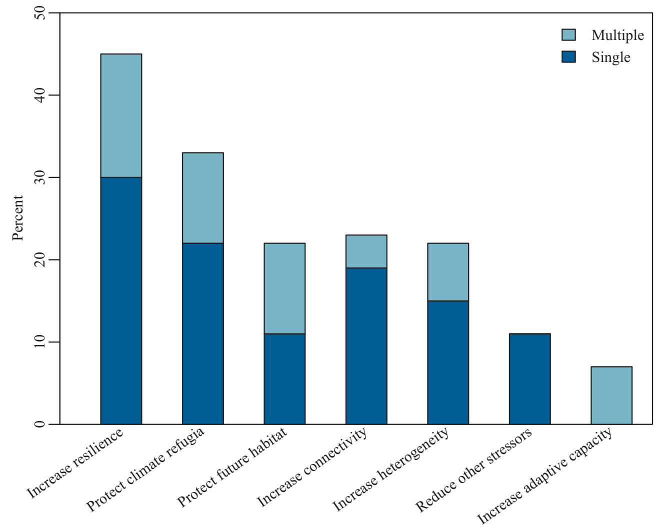

FIGURE 4 Climate change adaptation strategies for marine protected areas (MPAs). Shown are the common strategies employed relative to the total number of studies that considered climate change adaptation in the design of existing or future MPAs (new or redesign of existing; *n* = 27). Strategies were used in isolation (dark shade) or in conjunction with other strategies (light shade). For further details see Appendix S2 [Colour figure can be viewed at wileyonlinelibrary.com]

Resilience in this context is defined as the ability of an ecosystem to resist, recover or adapt to climate change while maintaining key ecosystem functions and services (Holling, 1973; Nyström & Folke, 2001). We found that 45% of studies used general resilience factors as the climate change adaptation strategy in MPA design (Figure 4). These resilience principles included recommendations on minimum MPA size, MPA shape, how to spread risk with representation and replication targets, how to protect critical habitat areas (ecologically important and climate refugia), maintain connectivity (for larval dispersal, connection of mobile species and interconnectivity of different habitat types), maintain ecosystem function, allow time for recovery, reduce other stressors and use ecosystem-based management (Green et al., 2014; Keller et al., 2009; McCook et al., 2009; McLeod et al., 2009). A recent review found 45 biological and physical attributes that contribute resilience to climate change across different ecological levels of organization (Timpane-Padgham, Beechie, & Klinger, 2017). As such, some studies have identified their own MPA-specific resilience features that are prioritized for protection. For example, representation targets were set in a proposed redesign of the Ningaloo Marine Park in Australia for structural complexity, water mixing, seaweed coverage, coral cover, proximity to human activities and minimum water depth as features that increase resilience to ensure adequate representation of areas that are most resistant or likely to recover from thermal disturbances (Davies et al., 2016).

These resilience principles are grounded in accepted design principles which are often applied outside the context of climate change (Roberts, Halpern, Palumbi, & Warner, 2001). But they have also been used in the design of a few MPA networks to specifically increase climate change resilience; for example in Kimbe Bay, Papua

New Guinea (Green et al., 2009). The design protected each conservation goal with a conservation objective based on three distinct replicates covering 20% of its total distribution (20% representation target). Fish spawning areas and turtle nesting sites were protected as critical habitat, and connectivity of shallow water habitats was incorporated by the automatic clustering of adjacent habitats. Due to data limitations they were unable to include more quantifiable methods of connectivity and used expert knowledge of coral bleaching vulnerability as a proxy for impacts of rising temperatures and coastal slope as a proxy for sea level rise. Similar approaches have been taken for MPA networks in Fiji (Weeks & Jupiter, 2013) and Indonesia (Mangubhai et al., 2015).

3.3.2 | Protect climate refugia

Another common adaptation measure is the protection of climate refugia, here defined as slower changing areas where species, habitats or ecosystems may be more likely to persist (Keppel et al., 2015; Schneider, 2018). Refugia occur from regional to small scales, while microclimates may provide refuges at scales of 10's of metres (Woodson et al., 2019). As there remains uncertainty around the effectiveness of MPAs in increasing ecosystem resilience to climate change, one argument for protecting refugia is that they might provide their full array of ecological benefits to the widest diversity of species as conditions are not changing, instead of only disturbance-tolerant species in a warming MPA (Côté & Darling, 2010). Protecting refugia may also be a way of 'buying time' to allow for species and ecosystems to adapt to changing conditions, despite their limited temporal (Keppel et al., 2015) and spatial (Ban, Alidina, Okey, Gregg, & Ban, 2016) scale of protection. Yet, they should not be the only climate future incorporated into MPA design (Tittensor et al., 2019).

We found that 33% of studies focused on protecting refugia as the key climate change adaptation strategy (Figure 4), for example, by including areas with cold-water upwelling to protect coral reefs from increasing temperatures (Perdanahardja & Lionata, 2017). However, the timing of cold-water upwelling events must also coincide with the timing of thermal stress, which may not always be the case (Chollett, Mumby, & Cortés, 2010). Using information about a range of current climate conditions, more quantifiable susceptibility models, or exposure metrics, can be generated to quantify current exposure to climate stress and prioritize areas with low exposure for protection. These can be based on several environmental data layers (Allnutt et al., 2012; Klein et al., 2013; Maina et al., 2015) or use information from SST only (Ban, Pressey, & Weeks, 2012). A key assumption with this approach is that areas with currently low exposure to thermal stress will continue to have low exposure into the future. To test if this assumption holds true, information about future projected climate conditions can be integrated. For example, coral bleaching risk up to 2100 has been examined based on where SST is projected to increase above a bleaching threshold to prioritize refuge areas for protection where the risk of bleaching was lowest (Game, Watts, et al., 2008; Levy & Ban, 2013). Ideally, future projected conditions are based on regionally downscaled output from earth system models (e.g. van Hooidonk, Maynard, Liu, & Lee, 2015), which alone often offer too coarse a spatial resolution for local management (Kwiatkowski, Halloran, Mumby, & Stephenson, 2014). Alternatively, historical satellite SST data can be used to understand patterns of local temperature variability over time and predict future refugial areas. However, this assumes that spatial patterns of temperature variability will persist into the future (Chollett et al., 2014).

3.3.3 | Protect future habitat

When projections exist for a species or habitat's future distribution, MPAs can be designed to prioritize those areas for protection that will either harbour key species or habitats in the future, or remain suitable for a certain time period (Jones et al., 2016; Soto, 2002). The key difference between protecting climate refugia and future habitat is that the latter can occur in an area with high climate change exposure. We found that 22% of studies prioritized future habitat for protection as the climate change adaptation strategy (Figure 4). For example, Runting, Wilson, and Rhodes (2013) prioritized areas where different wetland habitat types were expected to be found in the future, given projected sea level rise. Yet, many conservation processes require species presence in an MPA now, and not at a theoretical time in the future (Hopkins et al., 2016a). Therefore, most studies that focus on future habitat prioritize habitats that currently exist and are expected to continue to exist into the future. For example, a proposed redesign of an MPA network in Brazil found that if climate continues to warm, the most efficient MPA design would include both current and future distribution of threatened starfish species, based on SDMs (Patrizzi & Dobrovolski, 2018). Other approaches have modelled projected changes in coral cover to ensure it would remain at a suitable level within the MPA network over a specified time (Beger et al., 2015), or have incorporated connectivity metrics to prioritize current and future habitat (Makino et al., 2014, 2015).

3.3.4 | Increase connectivity

Increasing connectivity was the most commonly recommended climate change adaptation strategy for biodiversity management (Heller & Zavaleta, 2009). We found that 23% of studies increased connectivity as their adaptation strategy, tied with protecting future habitat and ~10% less than the protecting refugia (Figure 4). This in part may be due to the higher data requirements needed to accurately model connectivity (Friesen, Martone, Rubidge, Baggio, & Ban, 2019), whereas climate refugia can be categorized with only climate projections. Ensuring connectivity within an MPA network helps facilitate species persistence (McCook et al., 2009), and increases MPA benefits for the marine ecosystem (Carr et al., 2017; Olds et al., 2016). Climate change is expected to change connectivity in many different ways, such as by altering circulation patterns and stratification

(Gerber et al., 2014; Munday et al., 2009). Such changes in connectivity should be directly included in reserve design with ecologically justified statements rather than indirectly addressed through changes in MPA size (generally larger is better) or distance (closer; Magris, Pressey, Weeks, & Ban, 2014). Specific guidelines on how large an MPA should be will vary depending on the conservation goals (Carr et al., 2017). Ideally, both ecological (e.g. dispersal distances) and physical (e.g. currents) linkages would inform dynamic models of species transport and movement across all life stages under different climatic conditions, including source, sink, migration and stepping-stone areas as priorities for protection (Brock et al., 2012; McCook et al., 2009; Salm, Done, & McLeod, 2006). In practice, this is likely only possible for a few well-understood species.

Projected shifts in oceanographic currents for larval transport should be considered in MPA design (Foley et al., 2010) as they can impact dispersal distances, which necessitates MPAs being placed closer together to maintain connectivity (Gerber et al., 2014). To test this, Andrello, Mouillot, Somot, Thuiller, and Manel (2015) used a mechanistic model of larval transport driven by changes in current velocities to show that average larval dispersal distance would decrease in the Mediterranean Sea but connectivity within some MPAs would increase as new areas became suitable habitat. Other climate change impacts will also affect larval connectivity. Using a simulated 3°C increase in ocean temperature, planktonic larval duration was shown to decrease in the Gulf of California. This provided an ecological justification for the idea that larger, closer MPAs are required, instead of following general rules of thumb (Álvarez-Romero et al., 2018). Lastly, connectivity can be maintained by protecting climate (migration) corridors that allow species to track shifts in climate between MPAs (Beier, 2012), particularly if climate corridors follow local climate velocities (Fredston-Hermann et al., 2018). Yet, increasing connectivity can also interfere with adaptation if incoming genetic diversity reduces the prevalence of heat-resistant genotypes within a population (Mumby et al., 2011). In such cases, connectivity should be maintained across populations exposed to similar environmental conditions so as not to reduce genetic drift promoting adaptation to warming temperatures.

3.3.5 | Increase heterogeneity

Building on the protection of climate refugia, increasing heterogeneity aims to protect areas across the full range of climate change impacts including climate refugia, areas with high climate variability and high-exposure areas (Jones et al., 2016). This strategy adds the benefits of protecting climate refugia (discussed above) to those of protecting areas with greater climate variability which can increase the phenotypic plasticity of local populations (Boyd et al., 2016). Additionally, as climate change can drive rapid natural selection within disturbed populations, protecting high-exposure areas can promote local adaptation (Rilov et al., 2019). Furthermore, by protecting both low exposure areas where non-disturbance-tolerant species are afforded protection, and high exposure areas where protection facilitates adaptation with the potential for recovery after climate-driven events, the likelihood that healthy ecosystems can persist is increased (Game, McDonald-Madden, Puotinen, & Possingham, 2008). If connectivity is maintained across the full spectrum of climate heterogeneity, then the MPA network is facilitating adaptation at different spatial, temporal and taxonomic scales, a strategy known as 'adaptation networks' or increasing adaptive capacity (Webster et al., 2017). For example, Mumby et al. (2011) used thermal stress regimes to define hypothesized future coral reef health and linked these with larval dispersal predictions to prioritize reefs for protection that promote high genetic adaptation and phenotypic acclimation potential.

We found that 22% of studies focused on protecting areas across a gradient of climate heterogeneity as the climate change adaptation strategy in MPA design (Figure 4). Generally, different management strategies and representation targets are set across different levels of climate change exposure. Using a conceptual model of low and high climate change exposure, fishing pressure and biodiversity value, Allnutt et al. (2012) assigned different management actions across areas of high and low values of each metric. Magris et al. (2015) defined different representation targets for MPA network design for nine different combinations of exposure to thermal stress. For instance, 100% representation targets were set both for areas with low observed and future rates of exposure, providing thermal refugia now and into the future, and areas with high observed and future exposure, protecting potentially disturbance-tolerant species with high resistance to warming.

3.3.6 | Reduce other stressors

MPA managers can do little to reduce the direct climate change impacts in MPAs (but see Macgregor & van Dijk, 2014; Mawdsley, O'Malley, & Ojima, 2009; West et al., 2009). Yet management actions can be taken to reduce other stressors and minimize cumulative impacts (Gurney, Melbourne-Thomas, Geronimo, Aliño, & Johnson, 2013), thereby increasing the resilience of marine ecosystems to climate change impacts (Mcleod et al., 2019). We found that 11% of studies focused on reducing other stressors as the climate change adaptation strategy in MPA design (Figure 4). To do so, information on different land-based, fishing and climate change stressors can be used to inform habitat condition to prioritize habitats where stress is low and habitat condition is assumed to be high (Klein et al., 2013). Other examples include explicitly linking land-use and climate change scenarios to prioritize protecting land areas upstream from MPAs to reduce the impact of land-based stressors (Delevaux et al., 2018, 2019).

3.3.7 | Other methods

While the above-mentioned adaptation strategies have been incorporated into some MPA designs (Appendix S2), others ideas exist in the literature that have yet to be documented in published applications, least as published in the scientific literature (Heller & Zavaleta, 2009; Rilov et al., 2019). Of particular interest are dynamic MPAs, which can move in space and time. Dynamic MPAs could be used to rotate protection across MPAs in coral reefs to protect herbivorous fish which can increase ecosystem resilience (Game, Bode, McDonald-Madden, Grantham, & Possingham, 2009). Dynamic MPAs could also track changing environmental conditions by tracking shifts of SST fronts which often harbour aggregations of vulnerable marine predators (Hannah, 2008), or move with species as their range shifts in response to climate change (Hobday, 2011). Dynamic MPAs could be used in conjunction with permanent MPAs to create flexible networks which draw on the benefits of permanent and dynamic MPAs (D'Aloia et al., 2019; Tittensor et al., 2019).

3.4 | MPA management: Managing for climate change

Effective management is critical to the success of any MPA, even without the added impacts of climate change (Gill et al., 2017). Ecosystem-based management was initially proposed as a central resilience principle for MPA networks incorporating climate change adaptation (McLeod et al., 2009). A global meta-analysis found that with proper management, partially protected areas promote greater fish abundance and biomass than unprotected areas, and this benefit was enhanced when placed adjacent to a marine reserve (Zupan et al., 2018). As such it has been proposed that MPA networks be built around core no-take marine reserves managed in conjunction with partially protected MPAs or OECMs and managed within a wider seascape in which fisheries and other ocean uses are managed appropriately (e.g. invasive species, pollution; Keller et al., 2009; Wenzel et al., 2016). Recently there has been a shift to resilience-based management, which builds on ecosystem-based management by acknowledging that humans are a driver of change in marine ecosystems, to identify and prioritize management actions to promote ecosystem resilience and facilitate adaptation (reviewed in Mcleod et al., 2019).

Due to the global scale of climate change, management for climate change impacts should be coordinated across the entire MPA network, with regional management focusing on smaller scale impacts such as land-based pollution (Mach et al., 2017) and transboundary partnerships to facilitate range-shifting species (Hannah, 2010). Management may best build synergies by coordinating centralized governance and local community governance that includes input from a diverse stakeholders with different capacities to promote climate change adaptation (Ma, 2018; Tuda & Machumu, 2019). Climate change should also be incorporated into management plans with varying scenarios accounting for uncertainty (Hannah et al., 2002). Management actions that target mitigation, repair (e.g. assisted evolution) and societal adaptation (e.g. to loss of coastal protection) will also play a role (Comte & Pendleton, 2018; Rogers et al., 2015).

To increase management effectiveness, adaptive management is one of the most widely cited climate change adaptation strategies (Heller & Zavaleta, 2009), and an important component of resilience-based management (Mcleod et al., 2019). We found that only one of the case studies (~4%) had used adaptive management, but as a caveat we did not review all existing MPA management plans; thus, adaptative management may be more prevalent. Adaptive management uses new information to iteratively update management goals and methods either passively from past experiences or actively through experimentation with carefully designed monitoring (Ban et al., 2011). As such adaptive management can be used in MPAs to continually respond to ongoing climate change impacts. This can address uncertainty surrounding climate change impacts in conservation planning, as plans can be continually updated (Ban et al., 2011; Mcleod et al., 2019). Updates to plans can include rezoning (Keller et al., 2009) or re-delineating MPA network boundaries (Weeks & Jupiter, 2013). Adaptive management can help to correct any errors made during the initial planning process (Magris et al., 2014). It can increase the clarity of management actions if a diverse group of stakeholders is included throughout the process to promote support and compliance within an MPA (Mcleod et al., 2019).

In order for adaptive management to be effective, monitoring programmes targeting multiple indicators for ecological and social effectiveness in MPAs are required (Carr et al., 2017; Mcleod et al., 2019). Indicators can be based on climate-driven ecological thresholds that are indicative of phase shifts, providing early warning signs to inform where management intervention should focus (Johnson & Holbrook, 2014). Indicators can also track other climate-driven changes such as species range shifts, alterations in community assemblages groups, reductions in sentinel species coverage (e.g. seagrass) or changes in resilience (Maynard, Marshall, Johnson, & Harman, 2010; Otero, Garrabou, & Vargas, 2013). The chosen indicators will be specific to the geographic region and conservation goals an MPA has (Carr et al., 2017; Mcleod et al., 2019). For instance, if an MPA network goal is to promote connectivity, monitoring could examine the transport of juveniles from nursery areas to other habitats as an indicator of MPA effectiveness (Carr et al., 2017). Monitoring programmes should include targeted (standardized) and surveillance (observational) monitoring over the long term to understand changes in MPA environmental and ecological conditions, as well as short-term studies to understand specific processes within MPAs (Rannow et al., 2014; Salm et al., 2006). To be effective, monitoring programmes need to be designed at the appropriate spatial and temporal scale (Baron et al., 2009; Carr et al., 2017). They should also include human drivers that can affect a species/ecosystems vulnerability within an MPA (Mcleod et al., 2019). For instance, physical barriers to protect against sea level rise can have indirect negative impacts on marine ecosystems ability to migrate and adapt in response to sea level rise and other climate impacts (Maxwell et al., 2015).

4 | BARRIERS TO CLIMATE CHANGE ADAPTATION

Reviewing studies which had conducted interviews with MPA managers and other individuals involved in the planning and implementation process (Cvitanovic, Marshall, Wilson, Dobbs, & Hobday, 2014; Hagerman & Satterfield, 2014; Hopkins et al., 2016a) offers insight into the perceived barriers for embracing climate change adaptation in marine conservation planning (Figure 5). Despite recognizing a need to act with current knowledge, in full awareness of uncertainty (Hagerman & Satterfield, 2014; Simard et al., 2016), a lack of scientific information is often listed as a major barrier to climate change adaptation (Cvitanovic et al., 2014; Hagerman & Satterfield, 2014; Hopkins et al., 2016a). Missing information includes an understanding of synergistic impacts of climate change and other stressors in MPAs. There are concerns that by focusing on climate change adaptation strategies, more immediate drivers of change might be sidelined (Hagerman & Satterfield, 2014). A second limitation is missing environmental and biological climate change impact data at a relevant scale to management as most climate change projections are based on global climate models. There is a recognized need for greater dialogue between academics and policymakers (Petes, Howard, Helmuth, & Fly, 2014). Interestingly, although MPA managers recognize the importance of peer-reviewed science to inform decision-making, it is not always thought to be less biased than other information sources (Cvitanovic et al., 2014), and is sometimes valued and used less than data collected by government staff (Lemieux, Groulx, Bocking, & Beechey, 2018). The third source

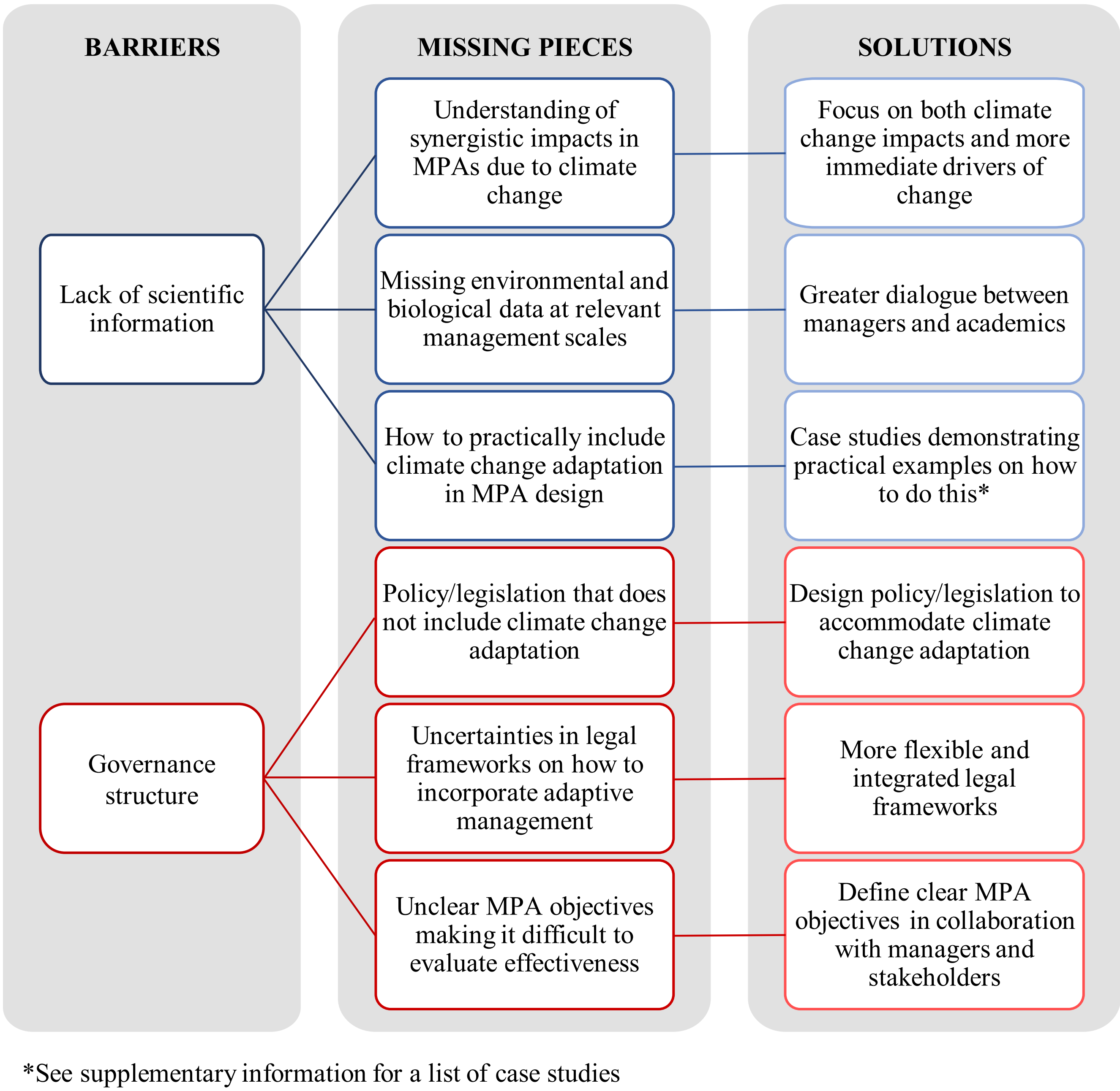

FIGURE 5 Barriers to climate change adaptation. Perceived general barriers, specific missing pieces and potential solutions to implementing climate change adaptation in marine protected areas (MPAs) were identified by reviewing interview-based studies with MPA managers and other individuals involved in the MPA planning and implementation process [Colour figure can be viewed at wileyonlinelibrary.com]

of limited scientific information is a lack of thorough understanding of how adaptation can be practically incorporated into marine conservation planning and management (Cvitanovic et al., 2014; Hagerman & Satterfield, 2014; Hopkins et al., 2016a). MPA managers value peer-reviewed research based on case studies that provide relevant and realistic examples of how climate change adaptation can be incorporated under current policy constraints (Cvitanovic et al., 2014). Here we provide a list of case studies that demonstrate examples of incorporating climate change adaptation into MPA design (Appendix S2).

The second most common barrier is based in governance structures (Figure 5; Cvitanovic et al., 2014; Hagerman & Satterfield, 2014; Hopkins et al., 2016a). This includes cases where policy frameworks and related legislation are not designed to accommodate climate change adaptation. For example, recent updates to MPA policy documents for the European Union do not discuss climate change adaptation (Russel, den Uyl, & de Vito, 2018). Scotland's Marine Act gives reference to how climate change mitigation can be incorporated but does not address adaptation (Hopkins, Bailey, & Potts, 2016b).

Another related barrier concerns uncertainties in legal and regulatory frameworks. Uncertainties in how to incorporate adaptation in management, and rigid government/policy structures have limited the use of adaptive management in MPAs, and this will likely continue (Cvitanovic et al., 2014; Hagerman & Satterfield, 2014; Hopkins et al., 2016a). Legislation and policy structures will need to become much more flexible, and be integrated across different planning and management structures to allow for successful adaptation across the global network of MPAs (Cliquet, 2014; Hopkins et al., 2016a; Spalding et al., 2016). This change has already begun: climate change adaptation is considered in Australia's Marine Park Act (Johnson & Holbrook, 2014; Yates, Clarke, & Thurstan, 2019) and several US policy initiatives are beginning to incorporate climate change adaptation (Petes et al., 2014). Furthermore, theoretical frameworks have been developed which demonstrate how conservation policy could include climate change adaptation (McDonald et al., 2019). Yet, there is still a long way to go to embrace flexible climate-smart planning and management. For instance, dynamic MPAs are a often-cited climate change adaptation strategy in the scientific literature (D'Aloia et al., 2019), but are currently thought to be politically unfeasible in many jurisdictions (Hopkins et al., 2016a; Tittensor et al., 2019).

A third barrier based in governance structures is a mismatch between MPA objectives and definitions of success from regulators and stakeholders' perspectives (Cvitanovic et al., 2014; Hagerman & Satterfield, 2014; Hopkins et al., 2016a). Very few MPAs provide clear objectives that directly relate to climate change (Hopkins et al., 2016a). Unclear objectives make it difficult to evaluate the effectiveness of an MPA with continued climate change which can skew stakeholder perception of success (Hopkins et al., 2016a), although this problem is not specific to climate change objectives (Yates et al., 2019). Clear objectives are needed to ensure the monitoring required for adaptive management is at its most effective (Hopkins et al., 2016a), particularly since the ability to link management actions to objectives is a central tenet of CSC (Stein et al., 2014).

5 | RESEARCH GAPS

In the following, based on our above review, we highlight key research gaps in climate change adaptation for marine conservation planning:

1. *Focus on a variety of ecosystem types across a range of latitudes*. To date almost all studies that consider climate change adaptation have focused on conservation planning for coral reef MPAs. Coral reefs are important ecosystems that are highly vulnerable to climate change (Hoegh-Guldberg et al., 2007). Yet, future work should also focus on developing climate-adaptive MPA designs for more temperate and polar habitats, dominated by other ecosystems or habitat-forming species, such as kelp or seagrass. For instance, the concept of using thermal stress regimes to define the full range of climate heterogeneity is easily transferrable to other biogenic habitats, particularly for climate-sensitive species such as kelp (Wernberg et al., 2016).
2. *Focus on pelagic and deep-sea habitats*. The dominance of corals also meant most research has focused on climate change adaptation in coastal habitats. Climate change impacts will vary in pelagic and deep-sea habitats, which may require new thinking on how adaptation technique should be incorporated into MPAs.
3. *Focus on multiple climate change stressors*. Most vulnerability assessments and corresponding adaptation methods focus primarily on the impact of increasing temperature. While temperature is the most understood impact, increasing temperature will interact with other climate and non-climatic stressors in MPAs potentially resulting in synergistic impacts (Hewitt, Ellis, & Thrush, 2016).
4. *Examine the dichotomy between adaptation strategy recommendations*. Polarizing advice has been provided in the scientific literature by either protecting only climate refugia or protecting the whole range of climate futures (increase heterogeneity), with the former focused on protecting the status quo, and the latter focused on facilitating adaptation. As such:
5. *Gather empirical evidence for the effectiveness of different adaptation strategies*. So far, very few existing MPAs have incorporated climate change adaptation strategies (Tittensor et al., 2019). Therefore, in most cases it is too early to tell which adaptation strategies are the most effective. Experimental research into climate-adaptive MPAs, as well as terrestrial PAs, can help determine which adaptation strategies are the most effective at protecting biodiversity in the face of climate change.

6 | CONCLUSION

Our review provides a comprehensive synthesis of planning frameworks, case studies, adaptation strategies and management actions that can be used to incorporate climate change adaptation into the design and management of MPAs. As there is a vast amount of research on this topic, we can only summarize the main themes, but we have compiled a database of relevant papers to provide further guidance (Appendix S3). This is compiled from the primary literature and does not include all grey literature reports. To address this issue, it has been recommended to create a centralized catalogue of all case studies where climate change adaption has been incorporated into MPA design and management (Tittensor et al., 2019). From the onset of MPA planning, clear conservation goals should be defined, based on both species-based (fine-filter) and higher level (coarse-filter) conservation features. Vulnerability assessments for all conservation features and multiple climate change impacts can provide insight into how species and communities may be impacted, and which specific climate change adaptation strategies should be incorporated into MPA design. MPAs should be closely monitored with relevant indicators and managed adaptively in response to monitoring results. Incorporating climate change adaptation strategies across every stage of the planning process maximizes the likelihood that MPAs will effectively protect marine biodiversity in a changing climate. The outlined conservation planning process, if implemented in existing and future MPAs and networks across the global seascape, could guide a more coordinated effort across nations to protect an increasing number of species and ecosystems (e.g. 30% by 2030) in the face of continued climate change.

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SUPPORTING INFORMATION

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Climate change adaptation in aquaculture

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Abstract

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

Key words: adaptation, aquaculture, climate change, research directions, systematic literature review.

Introduction

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

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

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

Methods

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

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

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

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

Table 1 Inclusion and exclusion criteria for document selection

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

Results

Descriptive results

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

Table 2 Definitions of selected variables/terms

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

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

Studies on climate change adaptation in the context of aquaculture are written by authors of both global south and global north countries, while the studies are conducted primarily in the global south except for Australia (Fig. 2). Most of the studies (57%) are initiated by five countries: United States (8), Australia (5), Thailand (5), Vietnam (4) and UK (4) (Table S2). Interestingly, 30% of the studies are produced by four institutions: Chiang Mai University (Thailand), University of Arkansas at Pine Bluff (USA), CSIRO-The Commonwealth Scientific and Industrial Research Organisation (Australia) and University of Leeds (UK). As seen in Figure 2, the country where the highest number of case studies was carried is Vietnam (11). Interestingly, four of those case studies are done by authors from Vietnam. Following that is Bangladesh, with seven case studies, of which three are written by authors from the United States and Thailand, with five case studies written entirely by authors from Thailand. Small and vulnerable Pacific islands have also been the subject of studies. A total of six case studies have been done in Vanuatu, Fiji and the Solomon Islands.

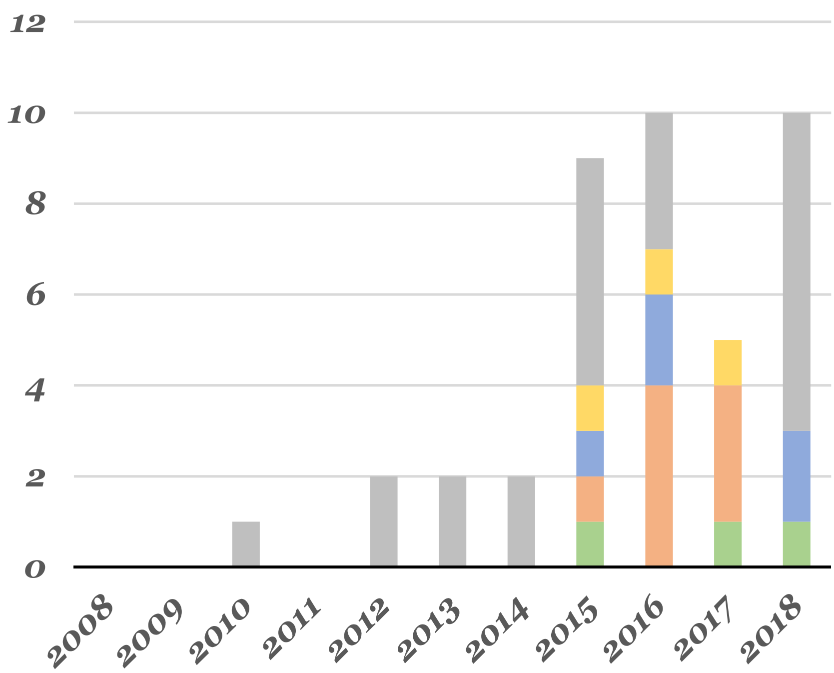

Figure 1 Publications at the intersection of climate change, adaptation and aquaculture per journal per year from 2008 to 2018. (■), Other; (■), Ocean and coastal management; (■), Regional environmental change; (■), Marine policy; (■), Environmental development and sustainability.

Climate change has mixed impacts on aquaculture

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

Theoretical approach towards studying climate adaptations in aquaculture

Many studies (over 50%) have adapted integrated approaches that combine various conceptual approaches (e.g. combining an economic approach with marine protected areas) to study adaptation in an aquaculture setting (Dey *et al.* 2016a; Table S3). The most common (27%) conceptual approach used to study aquaculture is the 'systems approach' (Berkes *et al.* 2003), supplemented with the scholarship areas of social–ecological systems (Berkes *et al.* 1998), resilience (Folke 2016), ecosystem-based management (Long *et al.* 2015), knowledge systems (Berkes 2012) and integrated farming systems (Bosma *et al.* 2012). Only two studies use the vulnerability approach to study adaptations in an aquaculture setting (Arimi 2014; Orchard *et al.* 2016). Developed countries (United Kingdom, Sweden, Canada and Spain) lead the majority of such studies to assess aquaculture systems in Asian countries such as Vietnam and Bangladesh (Galaz *et al.* 2012; Orchard *et al.* 2015; Khan *et al.* 2018). Publications from the United States incorporate a number of national-level studies aimed at Pacific islands (Fiji, the Solomon Islands, Timor-Leste and Vanuatu), looking at the economic impacts of climate change in aquaculture (Rosegrant *et al.* 2016; Dey *et al.* 2016a; Dey *et al.* 2016b). Sustainability and livelihood is another approach often employed to study aquaculture in

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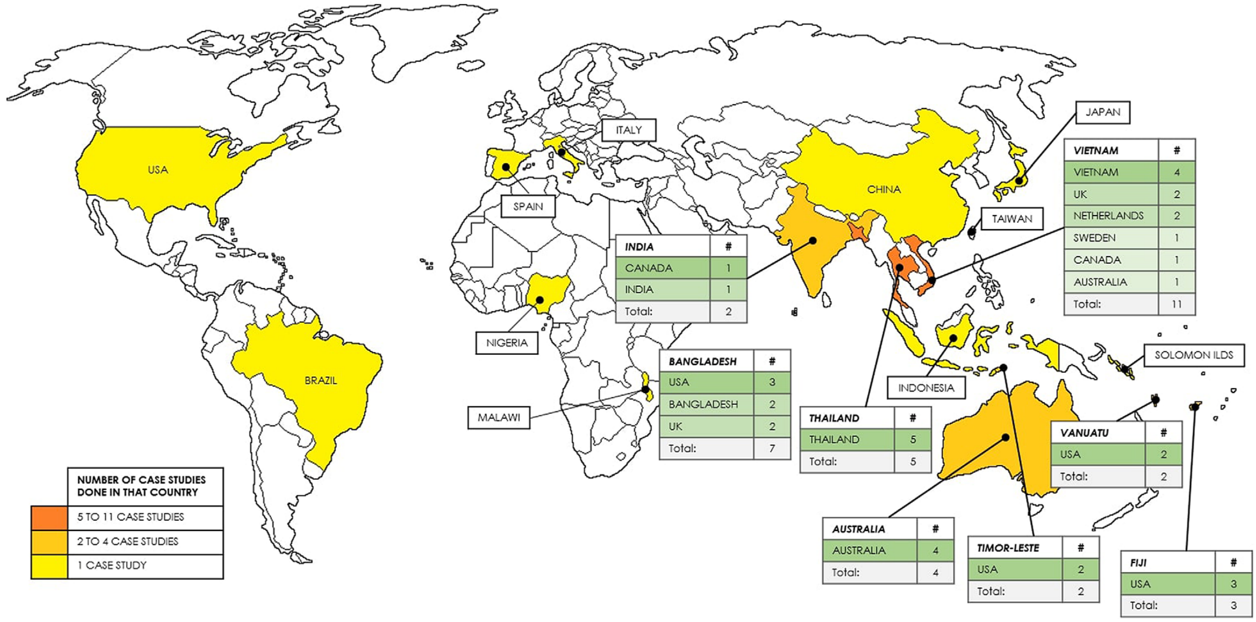

Figure 2 Map showing research destinations for case studies and the country of the first-affiliated author of the case study.

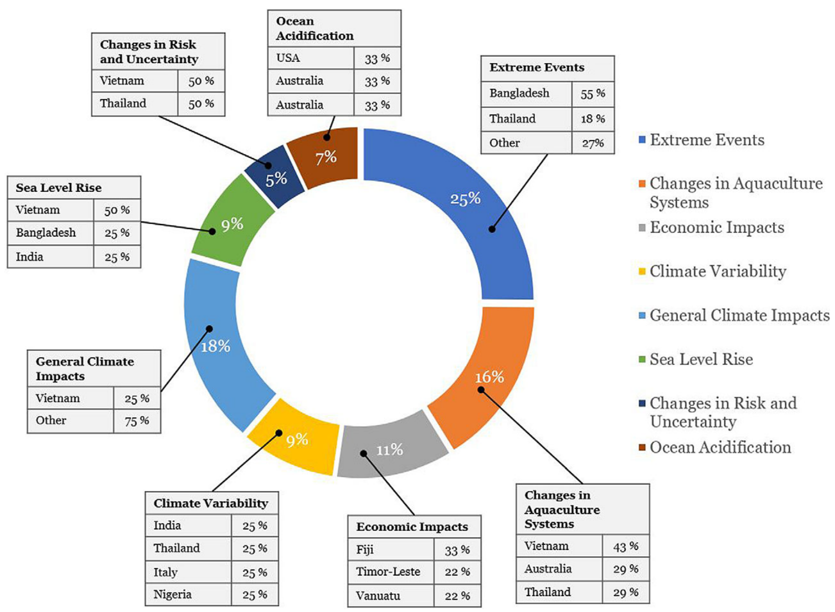

Figure 3 Climate change impacts studied in selected papers, by percentage, with top study locations. (■), Extreme events; (■), Changes in aquaculture systems; (■), Economic impacts; (■), Climate variability; (■), General climate impacts; (■), Sea level rise; (■), Changes in risk and uncertainity; (■), Ocean acidification

the development context (e.g. Malawi, Bangladesh and Vietnam; Nguyen *et al.* 2017; Hossain *et al.* 2018; Limuwa *et al.* 2018). Most of the studies that assessed local aquaculture by using adaptive capacity, resource management approaches (e.g. co-management and adaptive management), risk and uncertainty, and human perceptions of climate change adaptation are led by the same country (Arimi 2014; van Putten *et al.* 2014; Frisch *et al.* 2015; Lim-Camacho *et al.* 2015; Spillman *et al.* 2015; Ho *et al.* 2016; Bunting *et al.* 2017; Nguyen *et al.* 2017; Hossain *et al.* 2018; Lebel & Lebel 2018; Lebel *et al.* 2018a; Lebel *et al.* 2018b).

Types of targeted aquaculture

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

Coping mechanisms in aquaculture

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

Adaptive strategies in aquaculture

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

Management approaches in aquaculture

Apart from adaptive strategies, studies identified four key management approaches for climate impacts adopted in aquaculture resource management and in other areas such as adaptation planning, community-based management, adaptive management and government support (Table S5). The first approach is regional-level 'adaptation planning' related to aspects of aquaculture resource management (mostly shrimp aquaculture) studied in Vietnam, Bangladesh, Australia and Thailand (Bosma *et al.* 2012; Lim-Camacho *et al.* 2015; Lebel et al. 2016; Bunting *et al.* 2017). The second key management approach is regional 'community-based adaptation' (or community-based management), employed in particular against climate change impacts such as ocean acidification in coastal aquaculture (Frisch *et al.* 2015), more frequent intense precipitation in shrimp aquaculture (Bunting *et al.* 2017) and floods, droughts, sea-level

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

Response type	Response/strategy	Scale/level	Form
Common adaptive responses (for specific climate impacts)			
No regret	Provide supplementary aeration as appropriate (weather-related stress/variations)	Farm	Technical
	Harvest fish early to reduce losses (extreme weather event)	Farm	Technical
	Frequently monitor water conditions and fish behaviour during high-stress periods (temperature variations, unexpected weather changes)	Farm	Information
	Keeping the pond's water outlet valve open during the raining season (raining seasons)	Farm	Technical
	Share rearing knowledge in fish farming groups and networks (in general)	Community	Institutional
	Adopt good disease management practices to reduce risks (raining seasons)	Farm/ community	Technical
	Adopt good feed management practices to reduce risks from climate-related stresses (unexpected weather changes)	Farm	Technical
Low regret	Shift stocking dates and adjust stocking density (floods and droughts)	Farm	Technical
	Buy fingerlings at a nearby site to prevent heat stress due to transportation (heatwaves)	Farm	Technical
	Use groundwater to pump (refill) ponds (droughts)	Farm	Technical
	Adjust water infrastructure (stocking tanks) to regulate supply for aquaculture (droughts)	Farm	Technical
	Seek compensation assistance following disaster-related losses (extreme climate events)	Community	Institutional
	Prepare shade roof over hatchery tanks or cages (or grow aquatic weeds in ponds for shelter) (heatwaves)	Farm	Technical
	Strengthen cages so that they are less likely to be damaged (floods, extreme climate events)	Farm	Technical
	Enter into contract farming arrangements (e.g. leases) (in general)	Farm	Financial
	Stock and harvest multiple fish to reduce risk or switch species reared (floods, droughts, climate-change-influenced disease outbreaks)	Farm	Technical
	Dip ice bags in pond/hatchery to reduce water temperature (heatwaves)	Farm	Technical
	Engage in frequent pond water exchange (temperature variations)	Farm	Technical
	Plant fruit trees on pond dikes and vegetation on pond slopes (temperature variations)	Farm	Technical
Common adaptive strategies			
Future benefit strategies	Protect and restore ecosystems for flood protection, water storage and water quality services	Regional	Management
	Provide broad range of higher thermal tolerance breeding	National	Technical
	Introduce new technology at the farm level to improve water productivity through research and development	National	Technical
	Diversify into other business/income sources to subsidise risk reduction investments	Community/ regional	Institutional
	Increase savings to buffer household from losses and still make risk reduction investments	Community	Financial
	Engage in community-based watershed management	Community/ regional	Management
	Engage in research and development to improve climate risk information systems and accessibility	National	Institutional
	Install rainwater harvesting tanks and use rainwater for fish culture and pond-dike cropping	Community	Technical
Easier-early strategies	Engage in zone production so that aquaculture has sufficient water (volume/quality)	Regional	Management
	Support integrated water resource management in which aquaculture stake is recognised	Community/ national	Management
	Engage in on-farm value-added processing	Community	Technical
	Reuse waste and integrate resources into the farm to reduce input costs and dependencies on input suppliers	Community	Management
	Establish early-warning systems to seek information about floods, droughts and heatwaves	National/ regional	Institutional
	Establish mutual or weather-indexed insurance for aquaculture	National	Financial
	Develop new export markets and strengthen existing markets for farmed fish products, to create higher farm prices	National	Marketing
	Develop standards to improve climate- and water-related risk management	National	Management
Upfront strategies	Construct large-scale water storage and infrastructure development to take into account aquaculture uses of water	National	Infrastructural
	Install water treatment equipment in storage ponds with recirculating technology	Community	Technical
	Provide a protective flood dike around aquaculture ponds	Community	Technical
	Avoid prone areas and shift production site to a lower-risk location	Community	Technical
	Seek opportunities for floodplain aquaculture	Community	Technical

rise and sea surface temperature changes (Ahmed *et al.* 2014). Third, 'adaptive management' is documented as an approach for adapting to the implications of climate uncertainties in the context of inland and coastal aquaculture systems in Italy, Vietnam and Malawi (Canu *et al.* 2010; Pham 2017; Limuwa *et al.* 2018). Fourth, we identified 'government support' and attention at the community and regional levels as an approach for dealing with the impacts of climate change (Paprocki & Cons 2014; Spillman *et al.* 2015; Rodríguez-Rodríguez & Ramudo 2017).

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

Policy contributions

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

Discussion

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

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

We identified three categories of responding to the implications of climate change impacts on the global aquaculture setting: (i) coping mechanisms, (ii) adaptive strategies and (iii) management approaches for adaptation. First,

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

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

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

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

Directions for future research

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

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

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

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

The conceptual approaches used vary among selected publications; particularly, we can see that the type of approach used varies by continent. Most publications combine several theoretical approaches to produce a novel conceptual approach. This is explained by the fact that research in social aspects of climate change adaptation in aquaculture is interdisciplinary by nature and that, to understand the complexity of adaptation responses in the social dimension, multiple approaches must be employed (e.g. social–ecological systems resilience, ecosystem management; Kelly *et al.* 2019). The lack of studies using the vulnerability and political ecology approaches may indicate a limited focus on power and dispossession in studies (Veuthey & Gerber

2012). Currently, authors from developed countries employ the system approach the most, mainly to study Asian and Pacific aquaculture, whereas authors from developing countries mostly study themselves and use the sustainability and livelihoods approach to uncover how livelihood (mostly of the poor) and the environment are interlinked. Consistency and/or comparisons between methods could be taken into consideration in future research.

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

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

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Supporting Information

Additional supporting information may be found online in the Supporting Information section at the end of the article.

Table S1. Definitions of terms used for search engine web of knowledge.

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

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

Table S4. Definitions of types of coping mechanisms and adaptive strategies (building on Lebel & Lebel 2018).

Table S5. Management approaches taken in aquaculture.

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

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

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