PREDICTING FUTURE OCEANS

CLIMATE CHANGE, OCEANS & FISHERIES

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The Nippon Foundation - University of British Columbia

NEREUS PROGRAM

Predicting Future Oceans

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About the Nereus Program:

The Nereus Program is an interdisciplinary ocean research initiative established in 2011 by the Nippon Foundation and the University of British Columbia. It is a partnership of eight institutions: the Nippon Foundation, the University of British Columbia, the University of Cambridge, Duke University, Princeton University, Stockholm University, United Nations Environmental Program-World Conservation Monitoring Centre and Utrecht University. The program is built on three core objectives: to conduct collaborative research across the natural and social sciences to better understand the future of global oceans; to develop a network of experts that can engage in discussion of complex and multifaceted questions surrounding ocean sustainability; and to transfer these concepts to practical solutions in global policy forums.

About this report:

There is a growing concern among marine scientists over the impacts of global environmental changes, specifically climate change, ocean acidification, and the loss of biodiversity, on the state of our future oceans and their capacity to produce seafood. Given the scale of these environmental changes and their implications for international ocean governance, it is imperative that all stakeholders involved have access to the latest scientific knowledge and understanding of the relationships between oceans, marine ecosystems and fisheries at the global level.

The objective of this report is, therefore, to share scientific knowledge about the challenges and potential solutions for the sustainability of future oceans. The primary focus of the report is on the interactions between CO_2 emissions, oceans and the world's fisheries. It aims to provide a wider audience with a concise overview of what's happening in the oceans and with fish right now—and what will be happening in the future.

This report consists of seven sections, each representing a key statement on future oceans. In each section we start with a general summary of the current scientific understandings followed by the latest findings from selected studies of the Nereus Program addressing these issues. Contents of this report are based on the scientific views and opinions of the members of the Nereus Program, all of whom are engaged in innovative research concerning marine systems and ocean governance.

A full list of publications, as well as supplementary materials on topics discussed in this report, can be accessed at: www.nereusprogram.org.

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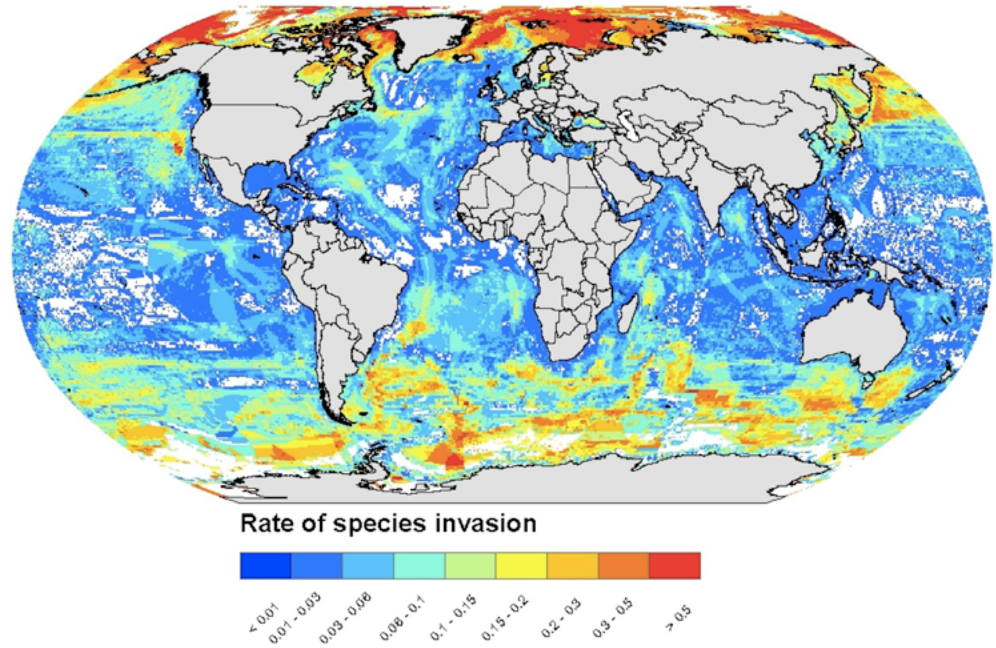

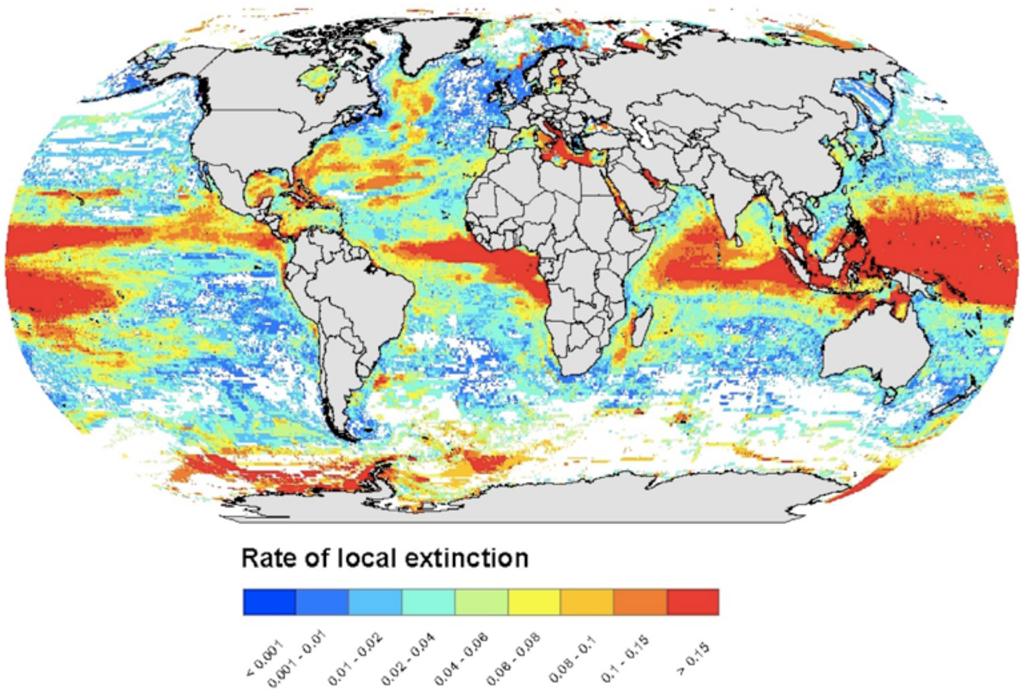

Distributions of marine fish species are expected to shift as climate change alters ocean conditions. The figures above are projections of species invasions and local extinctions by 2050 under the IPCC's scenario representing "business as usual" in CO_2 emissions. (Source: Jones and Cheung 2015)

Climate Change, Future Oceans and Fisheries

Changes in sea temperature disrupt movements of water, distributions of marine organisms, and structures of ecosystems. Moreover, as the chemistry of the Earth's atmosphere is altered through continued CO_2 emissions, so too will there be demonstrable changes in the chemistry of the oceans. Evidence of increased ocean acidification and decreasing oxygen, both of which are critical factors that influence marine life and biodiversity, are mounting. Naturally, changes in the oceans will have major repercussions on their capacity to support marine life and, ultimately, fisheries.

In the newly released Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), the addition of chapters dedicated exclusively to ocean-climate issues marks the emergence of a consensus of this linkage between climate change, oceans and fisheries. Following this lead by the IPCC, the international institutions responsible for ocean governance must, therefore, function within the context of the global changes driven by CO_2 emissions.

To improve ocean governance in the future, we need to further develop and improve access to scientific understandings of the relationship between the climate and oceans. Furthermore, researchers must continue their efforts to develop a more holistic understanding of the dynamics between oceans and more direct human-induced stressors such as marine pollution and overexploitation by fisheries that are likely to intensify as the oceans become more impacted by climate change. As we look toward the future of our oceans and fisheries, this knowledge must translate into public engagement and action – from the local to the global level.

The following seven key statements highlight the pathways and challenges facing the future of global oceans and fisheries. In the final section of the report, we propose strategies for attaining ocean sustainability.

Seven Key Statements for Future Oceans:

1. Due to CO_2 emissions, changes in global ocean properties – particularly temperatures, acidity and oxygen levels – are occuring at a scale unprecedented in the last several thousands of years.

2. Climate change is expected to affect the oceans' biological productivity–from phytoplankton to the top predators.

3. Climate change has already been affecting global marine ecosystems and fisheries, with further impacts expected given current trends in CO_2 emissions.

4. Fishing exerts significant pressure on marine ecosystems globally – altering biodiversity and food web structures – and affects the ability of the international community to meet its sustainability goals.

5. The impacts of climate change interact with the existing problems of overfishing and habitat destruction, driven largely by excess fishing fleets, coastal development and market expansion.

6. Aquaculture is developing rapidly, with the potential to supersede marine capture fish supply. Yet, the full understanding of its impact, including its long-term ecological and social sustainability, is unclear.

7. Sustainable fisheries in the future require the further development and strengthening of international fisheries law, as well as the overarching international framework for ocean governance.

1. Due to CO_2 emissions, changes in global ocean properties – particularly temperatures, acidity and oxygen levels – are occuring at a scale unprecedented in the last several thousands of years.

Current scientific understanding

As the global climate becomes warmer due to an increase in the concentration of greenhouse gases (GHGs) in the atmosphere (such as CO_2), the ocean's temperature is also expected to rise. The average sea surface temperature is projected to increase by a range of 2.0 – 3.5° C by the end of the century if the current GHG emissions rate continues.

Furthermore, because of water's natural capacity to absorb heat, combined with global ocean circulation patterns that transfer warm surface water across the entire ocean basin, the projected warming is likely to continue even if CO_2 emissions are brought under control.

In addition to serving as a heat sink, the oceans also act as a carbon sink by removing CO_2 from the atmosphere. Through this, the oceans can play a vital role in lessening the magnitude of temperature change in the atmosphere. However, this service comes at a cost as increased CO_2 in the water acidifies the ocean (ocean acidification). As the water becomes more acidic, it causes problems for some marine life, particularly those that form calcium-based shells (such as corals, crustaceans and shellfish). Under high CO_2 emissions scenarios, the acidity of the world's oceans, as measured by pH, is likely to decrease by 0.33 units by the end of the century, a rate that is unprecedented over the past millions of years.

With the melting of ice caps in sub-polar regions and the dilution of the surface water, stratification (formation of water layers with different properties, such as salinity, that act as barriers to water mixing) between warm, light surface water and cooler, denser deep ocean water is expected to intensify. Moreover, this stratification of ocean water is expected to limit the transfer of nutrients critical for marine life from the deep ocean to the surface, as well as the diffusion of oxygen from the surface to the deep ocean.

What is the Policy Strategy to pursue?

BRINGING CO_2 EMISSIONS UNDER CONTROL will reduce the rate and magnitude of climate change, ocean acidification and other related changes in ocean properties.

For risks that remain under this strategy, please see the summary table at the end of this report.

Highlights from Nereus research

Frölicher and colleagues demonstrated that ocean acidification is expected to emerge much earlier in the 21st century than other ocean properties such as temperature and oxygen. They evaluated the emergence of CO_2 emission-driven patterns in four key properties: warming, acidification, deoxygenation and disturbance to biological productivity. Frölicher and colleagues used Large Initial-Condition Ensemble Simulations (LICES) with a comprehensive Earth System Model (ESM) based on a historical trajectory from 1950 and projected the future change under various CO_2 emission scenarios up to 2100.

The authors also found that there are regional differences in the changes in the patterns of oceanographic conditions. For example, in tropical areas, changes in sea surface temperature emerge early; yet, oxygen concentration in subsurface water emerges much later. Conversely, the change in subsurface oxygen concentration emerges much earlier in the Southern Ocean. When examining projections for all four properties together, the patterns of CO_2 emission-driven changes emerge in 41% of the global ocean from 2005 to 2014 and 63% from 2075 to 2084. The combined changes in properties emerge much more prominently in the Southern Ocean, North Pacific, and Atlantic by the end of the century, but remain relatively low over the tropics and the South Pacific.

In terms of impact on marine ecosystems, there is a pressing concern in the tropics where coral reefs are susceptible to warming and acidification — the two conditions that are projected to emerge earliest in the area. More generally, in regions where these changes in ocean properties emerge most strongly, marine ecosystems may be pushed beyond their natural capability to cope.

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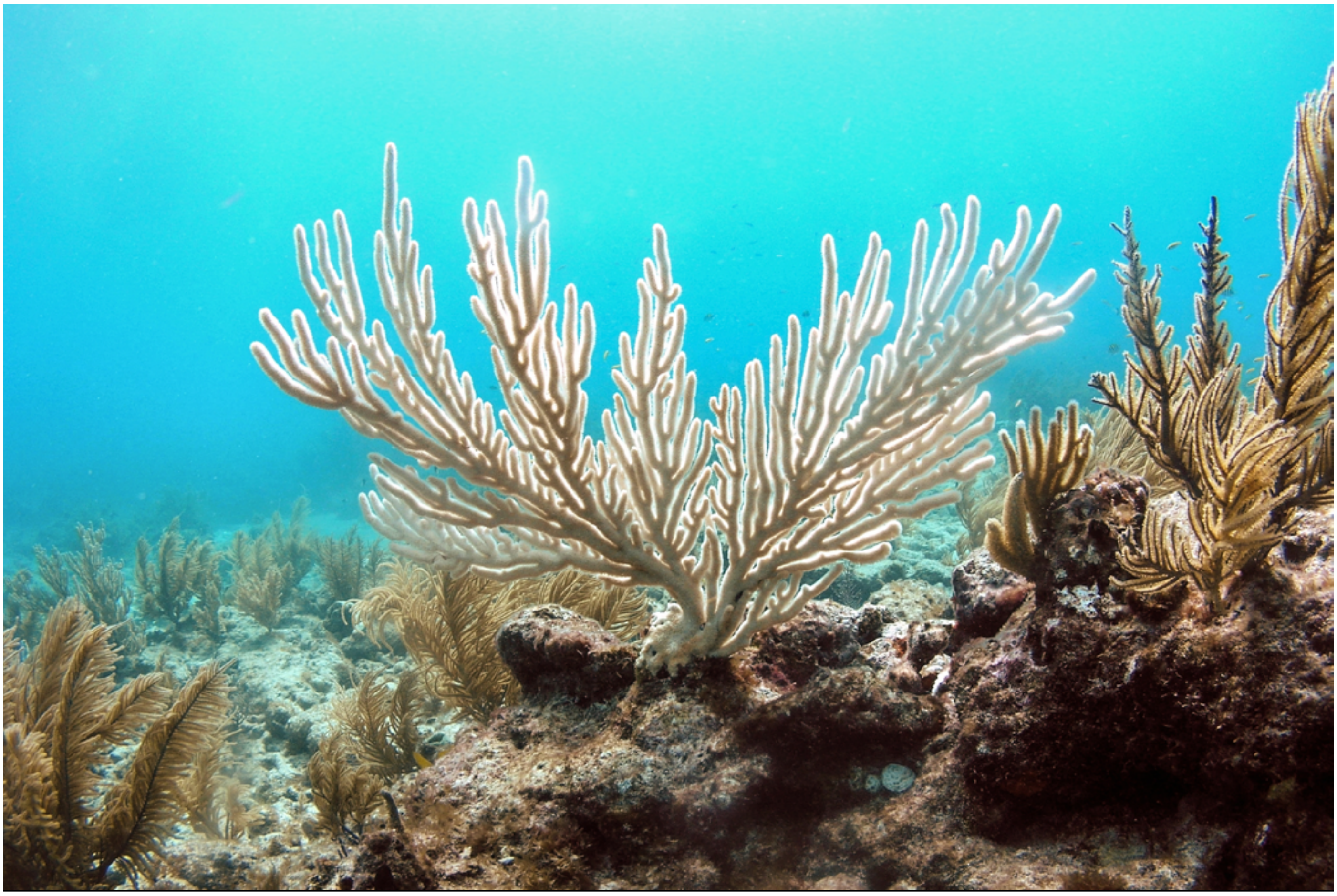

2. Climate change is expected to affect the oceans' biological productivity – from phytoplankton to the top predators.

Current scientific understanding

The impact of climate change on marine biological productivity will vary geographically, due to the physiological condition, the habitat structure, and the composition of the species that occur in these areas. The projected changes in phytoplankton production will ultimately affect the growth and survival of animals that feed on these phytoplanktons, as well as the fisheries that depend on the production of a variety of fishes and invertebrates.

Climate change is projected to intensify the stratification of ocean layers (formation of water layers with different properties, such as salinity, that act as barriers to water mixing) and reduce the transfer of nutrients from the deep ocean to the surface. In nutrient limited regions of the low and mid-latitudes, this reduced transfer of nutrients from the deep ocean will decrease biological productivity, specifically phytoplankton production, on the surface. In temperate and sub-polar waters, which are nutrient rich but receive less light exposure than tropical waters, the reduction in sea ice coverage and sea water mixing may promote longer growing seasons and phytoplankton production.

On a regional level, the impacts of climate change on marine biological productivity may be more distinct and influenced by local conditions. For example, in some areas, the heating patterns between land mass and sea surface may be more pronounced and result in stronger wind currents, intensified upwelling of deep sea water to the surface, and greater phytoplankton production.

What are the Policy Strategies to pursue?

BRINGING CO_2 EMISSIONS UNDER CONTROL will reduce the rate and magnitude of climate change, ocean acidification and other related changes in ocean properties.

MAINTAINING BIODIVERSITY, HABITAT AND ECOSYSTEM STRUCTURE will protect the capacity of marine ecosystems to adapt to impacts from all human-induced stressors and enhance ecosystem services to human societies.

For risks that remain under this strategy, please see the summary table at the end of this report.

Highlights from Nereus research

To understand the relative effects of primary production and fishing effort on the productivity of commercially important fish stocks, McOwen and colleagues assessed the historical trends of global fisheries catch among Large Marine Ecosystems — regions of the world's oceans from the coast to seaward boundaries of continental shelves that are characterized by distinct biophysical conditions. They showed that the bottom-up (i.e. environmental conditions) and top-down (i.e. fishing) effects vary consistently with the characteristics and exploitation status of the ecosystems. Specifically, the bottom-up effects drive catches from productive, overfished regions while top-down effects appear more influential in relatively unproductive and under-exploited waters. The authors conclude that their findings can be attributed to differences in species compositions and oceanographic properties of regions, together with variations in fishing practices and management effectiveness.

To further understand the importance of bottom-up effects on fish stocks, Kearney, Stock and Sarmiento developed an ecological model that incorporates the relationship between environmental conditions, phytoplankton, fish and other marine animals. Using the Eastern Subarctic Pacific system as a case study, the authors investigated the interactions between primary production (phytoplanktons), fishes, and other marine predators. They found that organisms do not necessarily increase in proportion to increased primary production as a result of complex predatory interactions within the ecosystem. Stock and colleagues also came to a similar conclusion in their global assessment of planktonic ecosystems. They found that the effects of the oceanographic changes on primary production can be both amplified and attenuated for organisms higher in the food chain.

Rykaczewski and colleagues considered the hypothesis that increased CO_2 emissions would intensify the upwelling (vertical water movement from deep to the surface) of some coastal systems, such as the Humboldt Current off Peru. These coastal upwelling systems support some of the largest fisheries globally, as they bring nutrients to surface water, and the intensified upwelling may increase fisheries' yield in the region. Rykaczewski and colleagues analyzed existing studies on wind-upwelling relationships around the world and found a strong correlation between winds and upwelling intensity in the California, Benguela, and Humboldt systems. However, they observed an opposite relationship in the Iberian system and no relationship in the Canary system. The authors also found that the signals of upwelling intensification are more commonly observed at high latitude areas within each system. Thus, the study provides some support for the hypothesis that CO_2 emission affects coastal upwelling systems.

The projection of future fisheries production under a range of climate change scenarios will require further understanding of the relationships between oceanography, primary production and fisheries. At the same time, the uncertainties associated with these interactions must be better understood and, when possible, quantified. Applying an ecosystem model based on sizes of marine organisms, Watson, Stock and Sarmiento demonstrated the importance of accounting for the movement of organisms in the oceans when projecting their biomass and responses to human-induced stressors. Sarmiento and Rykaczewski, with colleagues, showed how inconsistencies in underlying datasets could affect the detection of trends and patterns in ocean primary productivity. As such, they argued for continuous satellite-based records to be maintained in order to improve the models for climate change detections.

As for the uncertainties associated with the modeling of climate change impacts, the Nereus Program is currently undertaking a comprehensive assemblage of existing ocean ecosystems and fisheries models to facilitate improvements in quantifying uncertainties in future projections.

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3. Climate change has already been affecting global marine ecosystems and fisheries, with further impacts expected given current trends in CO_2 emissions.

Current scientific understanding

In addition to food web interactions between phytoplankton, fish and other marine animals, climate change is expected to affect the structure of marine ecosystems and fisheries catch. Fish and invertebrates (e.g. crustaceans and shellfish) are sensitive to water temperature and oxygen concentration for their survival and each organism has a range of ocean conditions that they can tolerate. When they are exposed to conditions outside these ranges, their body functions, such as growth and reproduction, can be negatively impacted and, in extreme cases, they could die.

Given the observed and projected changes in ocean conditions, specifically the water temperature, acidity and oxygen concentration, marine species are becoming increasingly exposed to conditions beyond their tolerance level. On an individual level, some organisms may show decreased growth and body size. On a species level, some species may change in distribution by moving to areas more favourable to their survival. All of this results in shifts in community composition and trophic interactions within ecosystems. In addition, the losses of ecologically important habitats (such as coral reef systems) are also exacerbating the changes in ecosystem structure and species distribution.

The biological and ecological responses of marine species to climate change and ocean acidification can be observed in the fisheries through changes in diversity, composition, distribution, and the quality and quantity of the catch. This type of change is expected to continue and will have major implications for future fisheries yields.

What are the Policy Strategies to pursue?

BRINGING CO_2 EMISSIONS UNDER CONTROL will reduce the rate and magnitude of climate change, ocean acidification and other related changes in ocean properties.

MAINTAINING BIODIVERSITY, HABITAT AND ECOSYSTEM STRUCTURE will protect the capacity of marine ecosystems to adapt to impacts from all human-induced stressors and enhance ecosystem services to human societies.

DIVERSIFYING THE "TOOLKIT" FOR FISHERIES MANAGEMENT will ensure that fisheries management has the capacity to implement a diverse range of strategies to address the increased uncertainties in the marine ecosystems arising from multiple human-induced stressors and the impacts of climate change.

For risks that remain under this strategy, please see the summary table at the end of this report

Highlights from Nereus research

A study led by Cheung and Pauly showed that the effects of climate change have been visible in the catches of the world's marine fisheries since the 1970s. Similarly, Pinsky, Sarmiento, and colleagues, found that marine organisms are changing their distribution at a rate and direction that corresponds to local temperature gradients. Moreover, Jones and Cheung projected that the global redistribution of marine species toward cooler waters of the polar regions and into deeper waters will continue to 2050.

Additionally, changes in ocean biogeochemical characteristics, such as ocean warming, decreased oxygen availability and increased acidity, caused by climate change are predicted to affect both physiology and ecology of marine fishes. These effects include shifts in their geographical distribution, age of maturity, body size and natural survival. Cheung, Sarmien-to, Frölicher, Lam and Pauly, with colleagues, used computer simulation models that incorporated the relationships between water temperature, oxygen content and growth of fish to examine biological and ecological responses of over 600 species under various climate change scenarios. They found that maximum weight in fish communities is expected to shrink, on average, by 14–24% globally from 2000 to 2050 under a high CO_2 emission scenario as a re-sult of both redistribution of fish and increased con-straints on growth. Decreases in growth and body size are expected to reduce the overall productivity of fish populations—and fisheries catch—as well as affect the ecosystem dynamics in these areas.

Cheung and colleagues, in their contribution to the Fifth Assessment Report of the Inter-governmental Panel on Climate Change in 2014, highlight that the impacts of climate change on fish stocks and fisheries are uneven. Specifically, the tropics will experience a high rate of local species extinction, decreases in catch potential, and a significant decrease in the size of fish. Coastal communities in the tropics are highly dependent on fisheries and, therefore, their food security and livelihood could be heavily affected by climate change.

However, there are coastal communities that are predicted to benefit from the CO_2 emission-driven changes in marine fisheries over the short term. A study by Lam, Cheung and Sumaila, using a bio-economic model, found the potential gains in the Arctic communities. While increases in water temperature and biological productivity and decreased sea ice coverage are expected to yield higher fisheries production, the authors also cautioned that ocean acidification will add a substantial degree of uncertainty to the change in fisheries potential in the region.

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4. Fishing exerts significant pressures on marine ecosystems globally – altering biodiversity and food web structures – and affects the ability of the international community to meet its sustainability goals.

Current scientific understanding

Fisheries affect both the productivity and abundance of marine fish stocks. Excessive fishing pressure has and continues to deplete fish stocks to levels that are less productive and not sustainable. Today, 28 percent of the global fish stocks are considered to be biologically unsustainable (i.e. overfished). The implications of overfishing can reverberate across marine ecosystems by affecting other organisms with which an exploited fish species interacts, both directly (e.g. predator-prey interactions) and indirectly (e.g. trophic cascade).

In particular, large predatory species that are inherently vulnerable to fishing due to individual biological characteristics (e.g. slow growth) have been significantly depleted across a number of marine ecosystems. Consequently, these marine ecosystems are increasingly dominated by smaller, fast-growing organisms that occupy lower levels of the food chain. While some short-term and local benefits may arise from the restructuring of marine food webs (e.g. increasing fisheries yield of smaller prey species), the long-term effects of continued overfishing will be the loss of marine biodiversity. Moreover, some species may play an important function in marine ecosystems and the depletion or local extinction of these keystone species — via overexploitation — may result in greater ecosystem-wide disruptions.

Recognizing the vulnerability of marine ecosystems to human-induced stressors, including fisheries, the international community has made a series of commitments to ensure the sustainable use of marine living resources. Yet, given the current trends in biodiversity and fisheries status, the targets set out by many international bodies are unlikely to be met.

What are the Policy Strategies to pursue?

MAINTAINING BIODIVERSITY, HABITAT AND ECOSYSTEM STRUCTURE will protect the capacity of marine ecosystems to adapt to impacts from all human-induced stressors and enhance ecosystem services to human societies.

DIVERSIFYING THE "TOOLKIT" FOR FISHERIES MANAGEMENT will ensure that fisheries management has the capacity to implement a diverse range of strategies to address the increased uncertainties in the marine ecosystems arising from multiple human-induced stressors and the impacts of climate change.

For risks that remain under this strategy, please see the summary table at the end of this report.

Highlights from Nereus research

A global meta-analysis of ecological models by Christensen, Pauly and colleagues showed that the biomass of large predatory fish has declined by two-thirds across the world's oceans over the past 100 years. Their study also found that the rate of decline in their biomass is accelerating, with over half of this decline having occurred within the last 40 years. At the same time, the populations of prey species were shown to be increasing in abundance as they face reduced predation pressure. The authors concluded that, on a global scale, the predator-prey dynamics of marine ecosystems have shifted significantly in a manner consistent with the concept of "fishing down marine food webs."

Some species play a pivotal role in the dynamics of marine ecosystems and the overexploitation of these keystone species can result in significant transformations of ecosystem structure. Valls and Christensen, with a colleague, defined these keystone species as predators with the ability to disproportionately influence food web structures. The authors examined existing ecological models to identify and evaluate the roles of such species and concluded that fishing frequently disrupts the ecological functions that these species serve.

Given the historical and projected trends in the management of the world's oceans, the international community is unlikely to meet some of its conservation and sustainable development goals. For example, Cheung, Christensen and colleagues assessed the progress towards realizing the Aichi Targets, twenty biodiversity-related objectives that were developed in 2010 under the framework of the Convention on Biological Diversity. The authors concluded that the objectives associated with sustainable fisheries are unlikely to be attained by the 2020 deadline. Though progresses toward the rebuilding of overexploited fish stocks has been made in many developed countries, the proportion of stocks considered to be within ecologically sustainable limits is likely to decline unless there is a significant shift in the current global trajectory.

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5. The impacts of climate change interact with the existing problems of overfishing and habitat destruction, driven largely by excess fishing fleets and catching power, coastal development and market expansion.

Current scientific understanding

As global fishing capacity — both in terms of the number of vessels and technology available — expands and an increasing number of fish stocks become fully or over-exploited, the prospect for further growth in the world's marine fisheries production is diminished. Meanwhile, the intensification of other ocean and coastal activities, including offshore mining, coastal development and renewable energy generation, is likely to continue and may result in potential conflicts with marine fisheries. These developments may also place coastal ecosystems and habitats under greater strain.

Seafood is now one of the most widely traded food commodities in the world, with the seafood industry increasingly becoming highly integrated and globalized. The consequences of large-scale stock collapses may, therefore, have significant implications throughout the global fisheries economy. Climate change impacts on ocean ecosystems, by reducing their productivity and biodiversity, will intensify the effects of these fisheries-driven pressures. The conflict between the economic objectives of commercial fisheries and conservation targets, particularly with regards to protection of vulnerable species, will continue.

What are the Policy Strategies to pursue?

DIVERSIFYING THE "TOOLKIT" FOR FISHERIES MANAGEMENT will ensure that fisheries management has the capacity to implement a diverse range of strategies to address the increased uncertainties in the marine ecosystems arising from multiple human-induced stressors and the impacts of climate change.

ADOPTING ECONOMIC SYSTEMS THAT SUPPORT SUSTAINABLE PRACTICE will create a market model that is capable of recognizing and rapidly responding to the effects of all human-induced stressors on the oceans.

For risks that remain under this strategy, please see the summary table at the end of this report.

Highlights from Nereus research

The historical catch reconstruction work conducted by the *Sea Around Us* Project reveals that the scale of fishing activities over the past 60 years may be significantly larger than previously thought. This finding suggests that the world's marine ecosystems have been under considerably more pressure from exploitation by fisheries. Thus, the impacts on the marine systems may intensify when compounded with those of climate change. A study by Cheung and Sumaila applied bio-economic analyses to identify areas where fisheries are most economically and biological susceptible to over-exploitation. The authors found that vulnerability of fish stocks is inherently high on the northeastern coast of Canada, the Pacific coast of Mexico, the Peruvian coast, the southern and southeastern coast of Africa, in the South Pacific, and in the Antarctic.

Swartz, Folke and Österblom, with colleagues, examined the relationship between the fish abundance, fisheries catch (i.e. supply) and the price consumers pay at the retail market in globally integrated supply chain systems. The authors concluded that the signals of stock overexploitation are rarely captured in the price. Thus, the decline in the fish population does not necessarily translate into an increase in price for that fish and may not raise public awareness for overexploitation.

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6. Aquaculture is developing rapidly, with the potential to supersede marine capture fish supply. Yet, the full understanding of its impacts, including its long-term ecological and social sustainability, remains unclear.

Current scientific understanding

Aquaculture currently supplies almost half of the total fish and shellfish consumed directly by humans. On a global scale, aquaculture offers the potential to reduce the vulnerability of the global food system, acting as a buffer by presenting alternative sources for animal proteins and other micronutrients for human consumption.

Nonetheless, aquaculture remains an emerging industry and requires further development of responsible management and best business practice as well as strategic environmental planning and sustainability assessment.

The key concerns over the unregulated expansion of aquaculture include: the use of wild fish as feeds and stock, discharge of pollutants, impacts on local ecology, habitat degradation, and lack of transparency. However, technological improvements in farming practices and the strengthening of local management capacities are lessening some of these impacts.

What are the Policy Strategies to pursue?

ADOPTING ECONOMIC SYSTEMS THAT SUPPORT SUSTAINABLE PRACTICE will create a market model that is capable of recognizing and rapidly responding the effects of all human-induced stressors on the oceans.

ENHANCING COOPERATION AND COORDINATION BETWEEN INTERNATIONAL FISHERIES REGULATION AND REGULATION OF OTHER MARITIME ACTIVITIES will address challenges to managing and responding to global environmental changes by increasing the coordination between existing global and regional regulatory frameworks.

ENSURING EQUITABLE DISTRIBUTION AND ACCESS FOR FISHING IN VULNERABLE COMMUNITIES will safeguard the rights of coastal communities that are vulnerable to the impacts of ocean changes driven by human-induced stressors. This includes more equitable distribution of access to the world's fish stocks.

For risks that remain under this strategy, please see the summary table at the end of this report.

Highlights from Nereus research

Metian, Boustay, and colleagues, found that aquaculture practices involving large predatory fish (e.g. blue-fin tuna), are highly dependent on marine capture fisheries to supply the protein and lipids required for growing these fish. Furthermore, they argued that some mariculture (i.e. aquaculture in the marine environment) currently contribute only a small proportion to the total fish production in volume, but will soon play a major economic role in the global seafood supply due to their high commodity value. Capture-based tuna farming is a form of aquaculture that requires stocking of juveniles from wild fish stocks. The authors highlighted concerns related to the governance of the operations as they expand, including the lack of reporting standards, its impacts on wild stock and the risk of over-development in absence of robust management measures.

As for the socioeconomic impacts of aquaculture, Metian and colleagues found that the development of aquaculture may have contributed to the improvement of food security in Asia, but has had little role in Africa to date. This is due to the fact that the fish farmed may not correspond with local demand or may not be available locally as they are exported.

In the first review of the Chinese aquaculture industry, the largest contributor of farmed fish to the global supply, Metian and colleagues found that it is increasingly utilizing feeds based on fish from wild stocks. The authors warned that such practice is unsustainable and called for reduced dependency on wild fish stocks, suggesting byproducts from seafood processing as a potential alternative.

Aquaculture has a limited ability to add resilience to global food systems, which are the entire food production operation on both land and sea. This is because aquaculture relies on wild fish as well as terrestrial crops that are consumed directly among low income households. Metian, Folke and Österblom, with colleagues, found that the increased use of food crops in aquaculture may lead to a surge in price levels and availability for low-income households. Therefore, the cost to develop the production system on a larger scale can be a burden on this particular sector of society. The authors identified that there are opportunities for aquaculture to enhance food security, but outcomes will depend on whether government policies can provide appropriate incentives for resource efficiency, equity, and environmental protection.

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7. Sustainable fisheries in the future require the further development and strengthening of international fisheries law, as well as the overarching international framework for ocean governance.

Current scientific understanding

Given the current and projected intensification of human-induced environmental stressors and their expected impacts on the world's oceans and ecosystems, there is an urgent need for the further strengthening of international fisheries law and global ocean governance frameworks.

Specifically, the universal support for and operationalization of the more comprehensive ecosystem approach to fisheries management is required.

Moreover, benefits from fisheries and burdens from implementation of various conservation measures must be fairly and equitably distributed across relevant states and stakeholders. This type of effort must be complemented by reforms in the overarching framework of global ocean governance, including greater cooperation and coordination among fisheries management authorities, as well as with agencies involved in regulating other maritime activities.

What are the Policy Strategies to pursue?

ENHANCING COOPERATION AND COORDINATION BETWEEN INTERNATIONAL FISHERIES REGULATION AND REGULATION OF OTHER MARITIME ACTIVITIES will address challenges to managing and responding to global environmental changes by increasing the coordination between existing global and regional regulatory frameworks.

ENSURING EQUITABLE DISTRIBUTION AND ACCESS FOR FISHING IN VULNERABLE COMMUNITIES will safeguard the rights of coastal communities that are vulnerable to the impacts of ocean changes driven by human-induced stressors. This includes more equitable distribution of access to the world's fish stocks.

For risks that remain under this strategy, please see the summary table at the end of this report.

Highlights from Nereus research

With improvements in the projections of future ocean changes and marine productivity, the fisheries status, seafood availability and security, there is a demand for better understanding of how governance can influence the future outcomes of global oceans and related socio-economic impacts. In light of this, Nereus Program researchers (led by Österblom) have constructed a conceptual model that focuses on the complexity and dynamic interactions between the natural and social systems that dictate human exploitation of the marine environment.

Merrie, with other Nereus Program researchers, examined the historical development of commercial uses of the high seas (e.g. fisheries, shipping), concluding that potential conflicts between various users of marine space may occur unexpectedly and may have unexpected cumulative environmental impacts on ecosystems.

Furthermore, Ota, with Hanich, assessed the framework of the regional fisheries management organizations (RFMOs), specifically the management of international tuna resources under the Western and Central Pacific Fisheries Commission (WCPFC). Their analysis focused on the distribution of benefits and burdens associated with various fisheries conservation and management measures and found

that, in many cases, the costs of conservation are often disproportionately distributed across stakeholders. Ota and Hanich explored approaches to attaining more equitable distribution of costs and benefits in multi-national fisheries.

In discussing the management of illegal, unreported and unregulated (IUU) fisheries in the Southern Ocean, Österblom and Folke highlighted the emergence of informal groups and networks between both state actors (national and inter-governmental) and non-state actors (fishing industries and environmental NGOs). They concluded that the stewardship of regional marine resources is highly dependent on four features: actors, networks, organization and institutions.

At a more localized tier of management, Dunn, Boustany and Halpin co-authored a study laying out the concept of dynamic ocean management, in which management measures are directly tied to ecological conditions of the ocean and are updated in real-time. Dynamic ocean management is more capable of addressing shifting species distributions under climate change and should achieve management goals more efficiently than traditional static measures.

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LOOKING TO THE FUTURE

Based on the current trajectory of human-induced impacts on the environment, it is clear that we are pushing the oceans and marine ecosystems to unprecedented limits. Environmental changes in ocean properties — caused or influenced by climate change and ocean acidification — as well as other human drivers, have led to an array of ecological responses, from shifts in the composition of the ocean's phytoplankton to changing distributions of fish species.

Pressures on our oceans from human activities are intensifying, due to the expected rise in the demand for global seafood brought on by an expanding global population, further economic developments, and shifts in our food preferences. Therefore, responsible, ecosystem-based and precautionary management of fisheries resources is paramount to ensure that seafood remains an important component in global food systems.

The oceans in the past will not be the same as the oceans in the future. They are expected to change at a rate and magnitude that are unprecedented in human history, and empirical relationships between oceans, fish and fisheries observed in the past may differ from future dynamics. We need to improve our ability to anticipate and respond to future ocean changes by exploring the evolving nature in both ecological and socio-economic systems.

The Nereus Program will continue to highlight the pressing need to understand the mechanisms underpinning the functioning of physical, ecological, social, legal and governance systems in its future research. Specifically, the overarching interdisciplinary research themes for the next phase of the Nereus Program will address the following:

- The predictions of future global oceans and fisheries
- Biological and societal adaptation to climate change and ocean acidification
- Adjustments to international fisheries law
- The overarching framework for ocean governance to meet current and emerging changes
- The challenges small-scale and culturally important fisheries face under climate change

Finally, as an attempt to apply our knowledge to responsible, ecosystem-based and precautionary management, we have identified six strategies that can be used to address immediate challenges to the sustainability of marine living resources, with a particular emphasis on fisheries. These six strategies are also topics that require further research to fully appreciate their importance and influence in contributing to the sustainability of the future oceans:

Strategies	Stressors being addressed	Scope of risk reduction
1. BRINGING CO_2 EMISSIONS UNDER CONTROL	Reduce the rate and magnitude of climate change, ocean acidification and other related changes in ocean properties.	Based on current understanding of the oceans and available technology, emission reductions will be most effective in mitigating the risks associated with climate change and ocean acidification. However, due to past CO_2 emissions, the effects of climate change on the oceans will continue to be visible in the short to medium term (up to 40 years), particularly in sensitive regions and systems.

2. MAINTAINING BIODIVERSITY, HABITAT AND ECOSYSTEM STRUCTURE	Protect the capacity of marine ecosystems to adapt to impacts from all human-induced stressors and enhance ecosystem services to human societies.	Marine ecosystems have some intrinsic ability to absorb stressors. Therefore, the risk of impacts from climate and non-climate change related stressors, such as fishing and habitat modification, can be reduced through protection and enhancement of this ability. For example, this can be done by maintaining biodiversity and preserving ecosystem structure. However, there is a limit to how much these ecosystems can endure. The risks will not be fully eliminated, particularly if the global-scale stressors, such as climate change, are not sufficiently mitigated.
3. DIVERSIFYING THE "TOOLKIT" FOR FISHERIES MANAGEMENT	Ensure that fisheries management has the capacity to implement a diverse range of strategies to address the increased uncertainties in the marine ecosystems arising from multiple human-induced stressors and the impacts of climate change.	Ecosystem-based management recognizes a full array of interactions within an ecosystem, including human impacts. By incorporating such strategies, the risk of direct exploitation and habitat destruction on ecosystems can be reduced. However, without sufficient CO_2 emission control, the threats from climate change and ocean acidification remain.
4. ADOPTING ECONOMIC SYSTEMS THAT SUPPORT SUSTAINABLE PRACTICE	Create a market model that is capable of recognizing and rapidly responding to the effects of all human-induced stressors on the oceans.	The risk from human-induced stressors can be minimized by creating incentives for sustainable use, such as fisheries, and greater opportunities for public actions. This approach can be applied at both regional and global levels.
5. ENHANCING COOPERATION AND COORDINATION BETWEEN INTERNATIONAL FISHERIES REGULATION AND REGULATION OF OTHER MARITIME ACTIVITIES	Address challenges to managing and responding to global environmental changes by increasing the coordination between existing global and regional regulatory frameworks.	The risk from multiple human-induced stressors can be reduced by narrowing the gaps in ocean governance through more holistic approaches such as ecosystem-based management. However, this approach needs to be paired with local strategies that consider regional impacts.
6. ENSURING EQUITABLE DISTRIBUTION AND ACCESS FOR FISHING IN VULNERABLE COMMUNITIES,	Safeguard the rights of coastal communities that are vulnerable to the impacts of ocean changes driven by human-induced stressors. This includes more equitable distribution of access to the world's fish stocks.	Risk will be reduced by providing economic opportunity and food security, but not fully eliminated, especially for those politically and economically marginalized coastal communities in both developed and developing countries, including indigenous communities and communities in extreme poverty.

IMAGE ATTRIBUTIONS

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