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The quantifying, mapping, and risk analysis of human-related stressors in the high seas

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Abstract

Objectives: Marine biodiversity and ecosystem services in the high seas are threatened by numerous stress factors caused by human activities, including global shipping, high-sea fishing, marine plastic pollution, and anthropogenic climate change. Socioeconomic factors are one of the criteria for the establishment of area-based management tools in the high seas for marine biodiversity conservation beyond national jurisdiction. The aim of the work is to propose a spatiotemporal approach to identify risks from marine human activities and recommendations for high seas governance. **Methods:** Data related to human activities from 2014 to 2022 were used to calculate the distribution and changes of human-related stressors, and the risk to marine biodiversity in the high seas caused by human activities. **Results:** The North Atlantic, Philippine Sea, Arabian Sea, Bay of Bengal, and East Central Atlantic show high and increasing intensities of human-related stressors, and are therefore particularly at need for the protection and conservation of marine biodiversity. Risks from human activities vary within the marine areas that are prioritized for biodiversity protection. The study recommends that the designation of high seas protected areas should take into account the types of risks to which the different marine areas are exposed, and that the high seas protected areas should be established gradually. At the same time, appropriate management measures should be formulated according to the intensity of human activities in the different marine areas. **Conclusions:** Quantifying and classifying the risk from human-related stressors could help identify solution for the protection and conservation and facilitate the marine spatial planning, establishment area based management tools, including marine protected areas in the high seas.

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Keywords
Risk assessment, marine conservation, marine plastic pollution, climate change, marine protection

Introduction

The high seas are an area beyond national jurisdictions, which covers almost two-thirds of the global ocean. The high seas play essential roles such as sequestering carbon dioxide and provide important habitats for marine ecosystems,[1] and oceanic highways for marine species migration.[2,3] Since the 1950s, human activities have expanded to the high seas, owing to technological innovations and an increasing demand for deep-sea resources.[4,5] More than 80% of the world's trade flow is carried across the high seas,[6] accounting for trillions of dollars in trade.[7] The economic value of high seas fisheries is approximately $7.6 billion per year.[8] However, the expanding of long-line and deep-sea fisheries,[9] international shipping,[10] marine plastic pollution,[11,12] and ocean acidification caused by anthropogenic climate change,[13] have led to threats to marine biodiversity.[14]

The conservation and management of high seas is a collective responsibility of all countries.[15] Since 2012, recognizing the need for high-sea biodiversity conservation,[14] the United Nations adopted an agreement for the "conservation and sustainable use of marine biodiversity of the areas beyond national jurisdiction" (hereinafter the BBNJ Agreement) in 2023.[16] The development of area-based management tools (ABMTs), including marine protected areas (MPAs) to protect and conserve at least 30% of the oceans by 2030 become a historic agreement to which nations committed in the "Kunming-Montreal Global Biodiversity Framework" of the Convention on Biological Diversity in 2022.[17] Economic and social factors are one of the indicative criteria for the identification of ABMTs,[16] and the marine systematic conservation planning.[18,19] The effective delineation of ABMTs in the high seas requires quantification of the distribution and risks of human activities.

Studies quantifying and mapping threats from human activities at a global scale have focused on different areas, including lands,[20–25] coastal areas,[26] and the oceans,[13,27–29] using different scales of measurement and various approaches for normalization. In studies that focused on marine and coastal areas, Halpern et al. calculated and mapped human activities impacts on the oceans based on fisheries, climate change, and land-based activities in 2008 and 2015.[28,30] O'Hara et al. intersected the spatial distribution of 21,267 marine species with 13 anthropogenic stressors to evaluate the impact risk of human activities in 2023.[29] Allan et al. evaluated the footprint of human activities in coastal areas based on 10 major terrestrial stressors and 10 marine stressors and analyzed the factors affecting human activity at the national scale in 2023.[26] Elliott et al. quantified human footprints based on multisectoral and trans-boundary impacts using the Drivers Activities Pressures State Impacts Responses model in 2020.[27] Other studies on the impact of human activities have focused on sea areas including the Mediterranean Sea,[31] Canadian[32] and Icelandic[33] coastal waters, and the North Sea.[34]

However, no studies have tracked the trends in human-related stressors in the high seas or identified the risks concerning the intensity and trends of human-related stressors. International shipping and fishing are important high-sea human activities. Climate change[35] and marine plastic pollution[36,37] are also stressors for high-seas biodiversity. The entanglement and ingestion of plastic harms marine species[11,38,39]; the amount of marine plastic floating is increasing annually.[40,41] Anthropogenic climate change also poses a major threat,[42] resulting in declines of marine biomass and fishery production.[43] To address gaps in knowledge, we quantified and mapped the distribution and trends of human-related stressors in the high seas based on four factors: shipping, fishing, marine debris, and climate change trends. The results provide a reference for future governance of the high seas.

Methods

Data sources and interpretation of the indicators

International shipping and high-sea fishing. In this study, we used the automatic identification system (AIS) data to quantify the stress caused by international shipping and fishing in the high seas. Originally, AIS data were used to enhance shipping collision avoidance and improve shipping radar functions, traffic management and report. Moreover, they also provide additional information, and improve communication between ships.[44,45] As required by the International Maritime Organization, cargo ships of over 300 tonnes are required to be equipped with an AIS system, providing the basis for shipping activity analysis using AIS data.[46] Currently, because of its strong availability and extensive information coverage, AIS data are widely used as a data source for research on ship activities,[46,47] including the activities of high-sea fishing vessels,[48] and for mapping fishing grounds[49–51] (Figure 1).

AIS data of ships from 2014 to 2022 were used to map the distribution of international trade transport and high-sea shipping. For this study, three categories of vessels, namely, bulk carriers, container ships, and oil tankers, which play the main role in international maritime trade,[6] were selected to represent the activities of global maritime trade. The

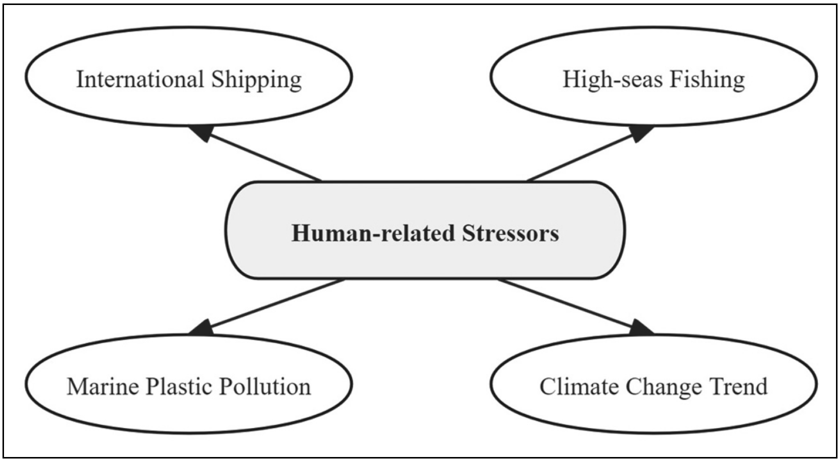

Figure 1. Factors of human-related stressors in the high seas.

AIS data were obtained from the public service website Shipxy (http://www.shipxy.com), which contains both shore-based and space-based data and provides a comprehensive picture of vessel activity in the high seas.[52] The data includes ship type, vessel speed, position, course, Maritime Mobile Service Identity, time, number of vessels, and shipping deadweight. For the distribution of high-sea fisheries, vessel speed is generally used to distinguish between fishing and non-fishing behaviors.[49,53] Global Fishing Watch has also begun to use AIS data to analyze fishing activities.[54] Following the methodology used in Global Fishing Watch by Alzorriz et al.,[55] this study used four knots as a speed criterion to distinguish between the fishing and cruising hours of vessels. We screened AIS data for fishing vessels below four knots as a basis for calculating. AIS data were cleaned and processed according to the method described by Fiorini et al.[56]

Marine plastic pollution. Plastic pollution in the high seas is mainly accumulates in garbage patches within ocean gyres,[57] and is carried and accumulated by ocean currents.[58] The work use the estimation by Kaandorp et al. that the amount of plastic waste marine environments is increasing at an annual a rate of 4%.[36] Plastic waste in the high seas is influenced by ocean circulation, and waste discharged into the ocean is concentrated in several areas forming garbage patches that are relatively fixed.[59] Considering that the annual increase in plastic discharge into the sea is approximately 4%, in this work, we estimated that the distribution of global marine plastic pollution increased equally from 2016 to 2022 at a growth rate of 4% per year,[36] and used the density grids of marine plastic distribution in 2014 from the study of Clark et al.[11] as a baseline.

Climate change. Sea surface temperature (SST) is an essential climatic variable that describes the influence on climate dynamics.[54] Fluctuations in SST are an important factor influencing the abundance of marine species in the high seas.[60,61] In this study, we used annual SST data from the European Space Agency Climate Change Initiative[62] to calculate the SST trends and map the extent of ocean stressors caused by climate change,[63] as a faster rate of climate change has been shown to have more negative impacts on marine biodiversity and ecosystem services.[64] SST data from 2008 to 2022 were used to calculate SST trends every 7 years[62,65] (e.g. the trend in SST for 2014 was calculated from the annual SST from 2008 to 2014).

Data analysis

Intensity analysis of human activities and climate change. First, all vector datasets were projected before converting the data into raster format. The study used the "Extract in Mask" function to convert all data into a uniform range layer (resolution $0.2° \times 0.2°$) with high seas layers as a base to facilitate further processing and calculation of the data. High-sea layers were downloaded from "Marine Regions."[66] The layers of shipping and fishing activities were created by using the "Density Function" in ArcGIS (v10.5)[67] with a resolution of $0.2° \times 0.2°$ based on a nearest neighbor routine. We normalized each of the human activity threat data layers concerning the maximum score of each stressor such their maximum value was one (after this normalization, stressors that existed everywhere did not have a minimum value of zero). The grid layers of shipping, fishing, SST trends, and marine plastic distribution were projected using the Mollweide projection with WGS84 datum. For each map, we summed the intensity of the different factors for each year in all cells and normalized the results of mapping to facilitate comparison of human-related stressors.

Spatiotemporal trend analysis. The Mann–Kendall (MK) monotonic trend analysis method was used in this study to quantitatively calculate time-series changes in SST and intensity of human activities in the high seas from 2014 to 2022. The MK test is widely used to access trends in time series data.[68–70] It has the advantage of handling missing values and partial outliers.[71–73] The MK test (S) showed a linear or nonlinear trend in the data series, which was calculated based on the test statistic S as follows. S indicates the sum of the differences of the values x, and $sgn(x)$ is a signum function that indicate the value −1, +1 and 0, according to the positive and negative of x.

$$\mathrm{S} = \sum_{\mathrm{I}=1}^{\mathrm{n}-1} \sum_{\mathrm{j}=\mathrm{i}+1}^{\mathrm{n}} \mathrm{sgn}(\mathrm{x(i)} - \mathrm{x(j)})$$

while

$$\begin{cases} if\ x > 0,\ \ sgn(x) = 1 \\ sgn(0) = 0 \\ if\ x < 0,\ \ sgn(x) = -1 \end{cases}$$

The positive or negative values of S correspondingly reflects to upward or downward trends, respectively.[73–75] To obtain a more accurate result, the variance of S VAR(S) was calculated as

$$\mathrm{VAR(S)} = \frac{\mathrm{n(n-1)(2n+5)}}{18}$$

where n is the number of data points. Then the Kendall standardized test statistic Z was then calculated by the following equation:

$$\mathrm{Z} = \begin{cases} \dfrac{\mathrm{S}-1}{\sqrt{\mathrm{VAR(S)}}},\ \ S > 0 \\ 0,\ \ S = 0 \\ \dfrac{\mathrm{S}+1}{\sqrt{\mathrm{VAR(S)}}},\ \ S < 0 \end{cases}$$

where Z > 0 and Z < 0 refers to increasing and decreasing trends, respectively.[70] The results of this analysis indicated the status of human activity risks in the context of increasing or decreasing trends. All data handling was carried out using R "trend" package.[76] We used 2022 as the base year for the trend calculations in this study.

Risk analysis. The intensity of human activities and climate change has created a risk to the protection and conservation of marine biodiversity, and temporal changes in human activities and climate change stressors may increase or decrease the risk to marine species.[28] In line with the intensity and variability of the risk of human activities in the high seas, we proposed a spatiotemporal approach to characterize the risk of human activities.

This study categorized the risk of marine anthropogenic activities with reference to the classification of global PM2.5 pollution as proposed by Lim et al.[77] The six classifications are "High Risk," "Risk," "Stabilization," "Deep Stabilization," "Safety," and "High Safety." Firstly, the intensity of human activity was divided evenly into three categories, namely high, medium, and low. Trends in the intensity of human activity were classified as either increasing or decreasing. Using data from 2022 as a baseline, the two categorized layers were overlaid to obtain six categories of risk-rated areas.

High Risk regions are marine areas with a combination of high intensity and increasing trends in human activity and climate change, whereas, Risk regions refer to sea areas with medium intensity and increasing trends in human activity. The criteria used to classify of the other four types of marine areas were similar (Figure 2). Marine areas in Stabilization refer to regions with a combination of medium intensity and a decreasing trend in human activities, whereas, Deep Stabilization refers to regions with high intensity and a decreasing trend in human activities. Safety regions refer to marine areas with low intensity but increasing trends in human activities and climate change, whereas, High Safety regions are sea areas with both low intensity and decreasing trends in human activities and climate change. We used the R packages "trend" and "raster" for calculations and ArcGIS (v10.5) to visualize the results.

Data visualization. After classifying the risks in the high seas, spatial analyses were used to disaggregate the statistics for the data at different risk levels. The distribution data of Important Marine Mammal Areas (IMMAs)[78] and Important Bird and Biodiversity Areas (IBAs)[79] were converted to a raster format and overlaid with the risk classification result. All results were visualized using ArcGIS (v10.5). The shapefiles of land boundaries[80] and Exclusive Economic Zone[81] were from the open source website.

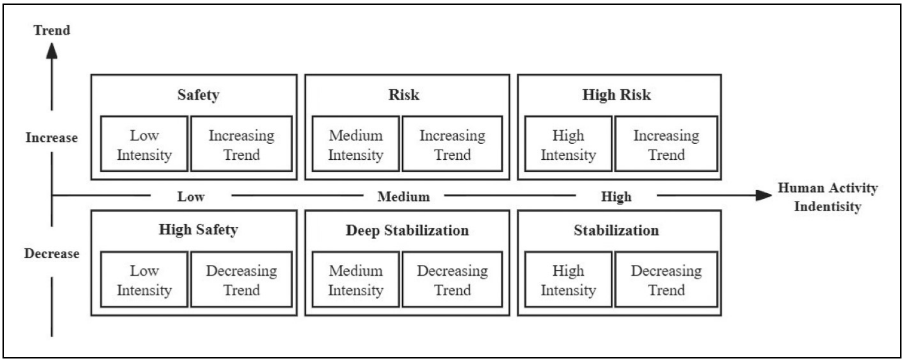

Figure 2. Classifications of the human-related stressors risks on the high seas from 2014 to 2022.

Results

Changing intensities of human activities on the high sea

Regions with high-intensity of human activities vary from year to year based on intensity assessments. The global distribution of high human-related pressures over the last decade indicates a high risks in the high seas. Sea areas with higher intensities of human-related pressures are generally spatially distributed along the main shipping routes of the Indian Ocean, Cape of Good Hope in southern Africa, Northeast Pacific, and Northwest Atlantic, with intensities above 0.83. Regions such as the Southeast Pacific and Southeast Indian Ocean have relatively low intensities of human-related environmental pressures (less than 0.17 from 2014 to 2022) (Figure 3).

A monotonic MK trend analysis of human-related stressors intensity from 2014 to 2022 was used to identify areas with increasing or decreasing concentrations. There was a clear increase in the western and central Pacific, Philippine Sea, Bay of Bengal, and Arabian Sea, as well as in the Northeast and mid-Atlantic regions of the high seas, with MK values >0.5 (more than 50%, extreme increase). Human activities and climate change in the high-sea regions, such as the eastern Pacific and Northwest

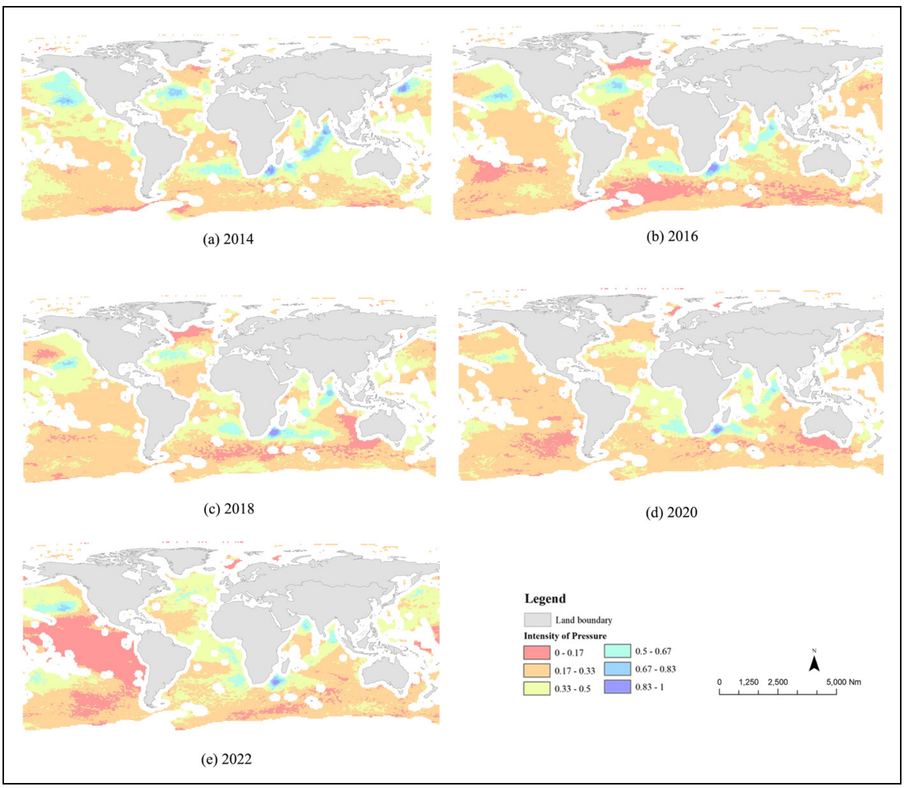

Figure 3. Distribution of the normalized intensity of human activities and climate change in the high seas from 2014 to 2022 (per 2-year period).

Atlantic, generally show a decreasing trend, with MK values < −0.5 (more than 50%, extreme decrease). Overall, 39% of the total high sea area showed an upward trend, while 61% showed a downward trend (Figure 4).

Spatiotemporal classification and risk assessment of human-related pressures on the high seas

According to the calculation, the high-risk areas which represent areas of high and increasing human-related pressures are mainly located in the North Pacific, the Philippine Sea and the central and southern of the Pacific Ocean, the Arabian Sea and the Bay of Bengal of the Indian Ocean, as well as the North Atlantic and South-East Atlantic Oceans. The Indian Ocean shipping lane area and the Northwest Atlantic are in Stabilization Status, indicating areas of high and decreasing human-related pressures. The south Atlantic and the north-central Atlantic are at Risk status, with medium and increasing human-related pressures, and the other areas are in a state of Deep Stabilization and High Safety Status. The marine areas within Deep Stabilization were widespread in the Indian Ocean, indicating that stable changes are underway (Figure 5).

The risk assessment results varied from one sea area to another. Overall, the largest areas were in the High Safety category, with roughly equal proportions of areas in the High Risk, Risk, and Deep Stabilization categories, and the smallest areas in the Safety category. The largest proportion of High Risk and Risk areas is in the Atlantic

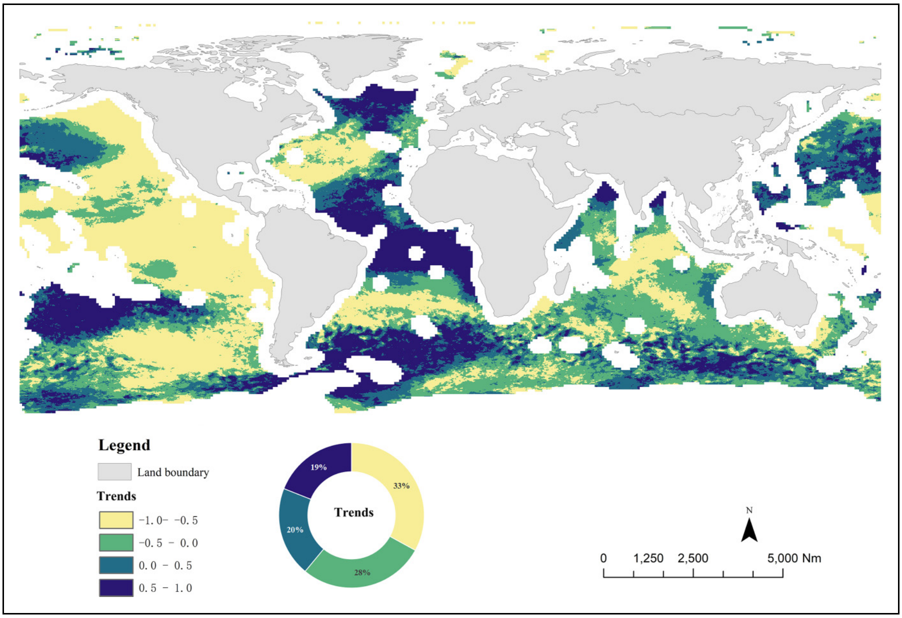

Figure 4. Mann-Kendal trends of normalized intensity of human-related stressors on the high seas from 2014 to 2022.

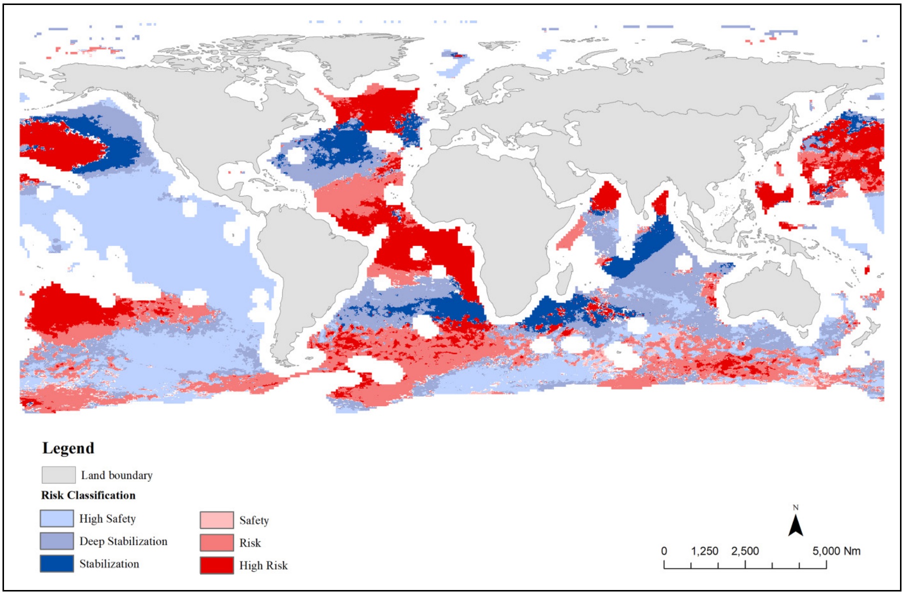

Figure 5. Risk classification distributions of human-related stressors on the high seas in 2022.

Ocean, while the Indian and Pacific Oceans have larger proportion of High Safety, Deep Stabilization, and Stabilization statuses, with the Indian Ocean having the largest proportion of areas in Deep Stabilization. Overall, the Atlantic region shows the highest risk to marine biodiversity from human activities, followed by the Indian Ocean, the Pacific had the lowest relative risk to marine biodiversity from human activities (Figure 6). These spatiotemporal results will facilitate the identification of marine areas at High Risk status for marine biodiversity conservation, taking into account the increasing or decreasing trends, as well as the intensity of human activities and climate change.

Drivers influencing global risk classifications on the high seas

Trends in the exposure to various human-related stressors vary from one marine area to another. The factors causing this variation include the development of international regulations and influence of the global economy.

The distribution of global high-sea trade routes is essentially relatively stable in space and time, and the high intensity of international shipping activities is concentrated in shipping route areas. Owing to the impact of COVID-19 postpandemic trends from 2019, the war in Ukraine, and tightening global supply chains over the past 2 years, global seaborne trade volume has decreased marginally by 0.4% in 2022. The overall trend of shipping activity in key route areas, such as the northern Indian Ocean has declined to some extent. Consequently, the routes in these regions are in a state of high stability risk with high intensity and an overall downward trend. This may change in the future as the global economy recovers and develops, particularly, with the development of foreign trade in China, an important global shipping country.[6]

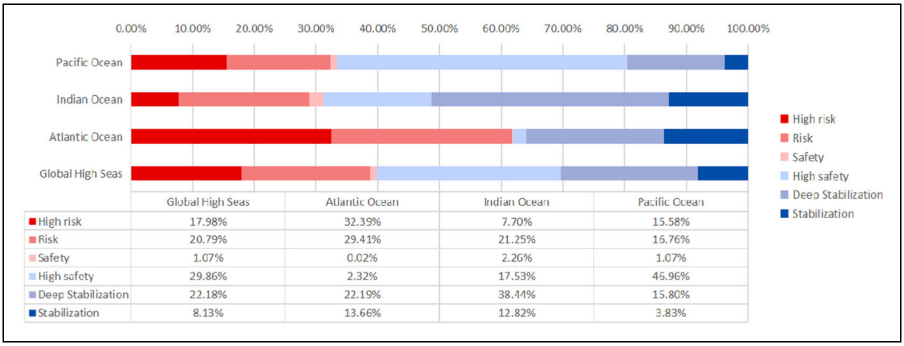

Figure 6. Proportions of different risk categories in the Pacific, Indian, and Atlantic oceans.

As far as high-sea fisheries are concerned, the changes in their activity vary from region to region. The intensity of high-sea fishery activities in the western and central Pacific and the eastern and central Atlantic has increased annually. In particular, catches of tribe Thunnini and skipjack tuna (*Katsuwonus pelamis*), has increased significantly in the western and central Pacific. China is the world's largest marine fishery, but catches have declined annually from 2015 to 2022, with the policy of reducing fishing to continue in the 14th Five-Year Plan (2021–2025),[82] the intensity of fishing activities near China is expected to continue to decline in the coming years. This is related to the risk categorized in sea areas such as the western and central Pacific and the eastern central Atlantic.

Marine plastic debris pollution is an important human-related issue that threatens the safety of marine mammals and other marine species, particularly through the risk of entanglement and ingestion.[12] The North Pacific, North Atlantic, South Pacific, South Atlantic, and Southern Indian oceans are five oceanic garbage patches,[59] over time, the amount of plastic accumulating in these waters has increased, posing a risk to marine mammals, marine reptiles, and other marine species. Recently, with the development of the International Legally Binding Instrument to end plastic pollution, global regulations have been proposed to address marine plastic pollution.[83] If the rate of increase in plastic litter in the oceans can be slowed, and at the same time, salvage and other methods implemented in areas where plastic litter has accumulated (e.g. the "Ocean Clean System"), it may be possible to reduce the marine risk caused by plastic pollution in the future.

The threat posed by climate change to the oceans is global. The threat posed by climate change has increased, particularly in the northern and southern mid-latitude waters of the Atlantic Ocean. Therefore, there is a need to reduce the impacts of climate change, including through carbon reduction on ships. In addition, climate change mitigation cannot be focused solely on human activities in the marine sector, this requires global coordination across sectors and industries.

Discussion

Protection of marine species based on risk classification results

Mapping and quantifying the stressors of human activity and climate change are fundamental to understanding the risks of marine protection and conservation in the high seas.

This study considered the application of human activity stressors in the design and management of MPAs. To identify the hotspots that need to be protected by marine mammal and seabird specifications, IMMAs have been described by the International Union for Conservation of Nature, and the marine IBAs have been identified by BirdLife International. IMMAs and marine IBAs beyond national jurisdictions can be considered priority areas for marine conservation in the high seas. Descriptions of IMMAs and marine IBAs are based on the distribution data of marine mammals and seabird species, and they are generally selected according to criteria and thresholds such as species or population vulnerability, species distribution and abundance, activities of key life cycle stages and special attributes, and expertise from expert seminars,[84,85] without considering human activities such as global shipping, high-sea fishing, and marine plastic pollution.

Comparative analysis revealed a significant difference in the potential social and economic risks of human activities between the IMMA and marine IBA regions. The proportions of high-risk areas in IMMAs and marine IBAs were 12.14% and 29.62%, respectively, with 36.67% and 21.09% at the Risk level and, 21.9% and 6.64% at the Deep Stabilization status, respectively; over 20% of areas were at the High safety level. As shown in Figure 7, there are significant differences in the impacts of risks from human-related pressures in marine areas that also require protection.

At present, the establishment and management of MPAs are associated with high monitoring and administrative costs,[86] as such, more cost-efficient[87] and effective MPA management will be needed in the future.[88] Blind and overly large-scale MPAs with high ambition are difficult to monitor effectively,[89] leading to the emergence of "paper parks."[90] It is recommended that different types of areas be given priority in the designation of future protected areas in the high seas. For areas with a high risk to marine biodiversity in the high seas, MPAs should be designated as early as possible, and resources should be concentrated to monitor and implement stringent management measures. Areas that are in a Safe condition and where the risk of human activities is relatively low can be exempted from designation as priority protection areas to

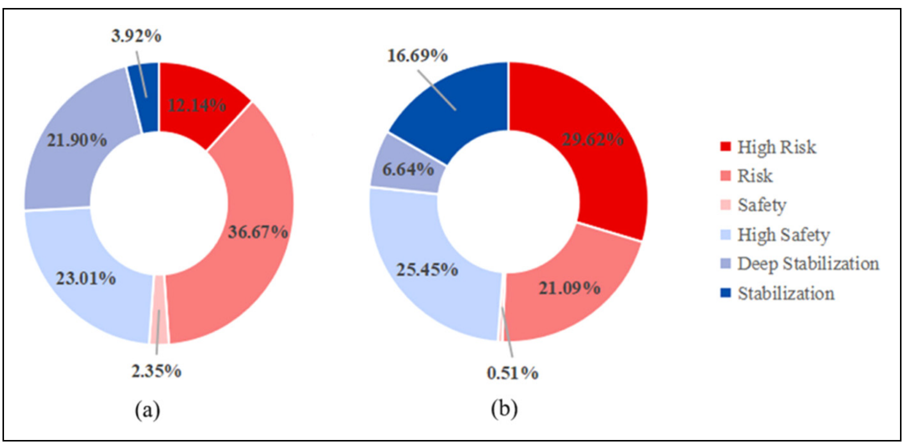

Figure 7. Proportions of existing important marine mammal areas (a) and marine important bird and biodiversity areas (b) in different risk categories.

reduce the administrative costs of MPAs and improve the actual protective effect in high-sea marine ecosystems. The same applies to marine spatial planning (MSP) in the high seas, which is performed to determine the balance between human activities and environmental protection.[91] Economic and social aspects must be considered in MSP.[92] Consequently, studies on human-related stressors in the high seas are also useful for the development of MSP.

Limitations

This study has some limitations and uncertainties that should be addressed in future studies. The data used in this study were all from open sources. Although the latest available data were used, data such as the spatial distribution of plastics are relatively outdated. While this study estimates trends in marine plastic pollution, it is understood that this may not fully reflect the true spatial distribution of marine plastic litter. In addition, although the AIS data have recently been widely used for research, they were not originally developed for research use, and there are gaps and uncertainties in some cases.[45,93] For example, some small vessels that do not carry an AIS system,[94] some AIS coverage is lacking,[95] and some vessels lag in AIS reception.[93] The known and common gaps in AIS data may lead to an underestimation of overall activity.[95]

Conclusions

Marine socioeconomic factors are among the criteria that determine the designation of MPAs and the development of MSP in the high seas. In this study, human-related pressures on high-sea ecosystems from shipping, high-sea fishing, marine plastic pollution, and climate change, as well as the intensity and trends of these pressures, were used to delineate risk categories in different high-sea areas. The intensity of activity in the North Pacific, Arabian Sea, and Southern Central Atlantic are high and show an increasing trend. We propose using the intensity of human activities and climate change in different areas as a reference for prioritizing the establishment of future high-sea MPAs. This will make the designation of MPAs more effective and lead to the development of more targeted management measures. This study proposes an analytical framework for assessing the risk of human activities in the high seas that incorporates the intensity and trends of human activities.

Author contributions

Chang Zhao put forward the overall research ideas and framework, responsible for data analysis, the drafting and revision of the paper; Miaozhuang Zheng is responsible for data curation and Visualization; Yuejing Ge is responsible for the revision of the paper.

Consent

There are no human participants in this article and informed consent is not required.

Declaration of conflicting interests

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Ethical considerations

Not applicable.

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