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Integrating climate change in ocean planning

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The acceleration of global warming and increased vulnerability of marine social-ecological systems affect the benefits provided by the ocean. Spatial planning of marine areas is vital to balance multiple human demands and ensure a healthy ocean, while supporting global ocean goals. To thrive in a changing ocean though, marine spatial planning (MSP) must effectively integrate climate change. By reviewing existing literature on MSP and climate change, we explore the links between them and with ocean sustainability, highlight management challenges, and identify potential pathways to guide action towards the effective integration of climate impacts in MSP.

The sustainable use and conservation of the world ocean and its resources represent one of the 17 global goals set to 'transform our world' in the context of the United Nations (UN) 2030 Agenda for Sustainable Development[1]. Although such global agreement on promoting sustainability in the ocean is relatively recent, protecting marine ecosystems has been in the international agenda for decades[2,3], with numerous actions, approaches, frameworks and plans being developed and implemented to support it. These include the ecosystem approach, with its origins in the UN Convention on Biological Diversity[4], ecosystem-based management (EBM) that grew out of the ecosystem approach[5], the integrated management concept that stemmed from Chapter 17 of the Agenda 21[6], or international treaties such as the UN Convention on the Law of the Sea (UNCLOS)[2].

Concomitant to these developments, and incorporating many of these concepts (for example, the ecosystem approach and integrated management; Box 1), in the 1990s a management process commonly known as marine spatial planning (MSP) emerged and has spread widely in the last 15 years[7]. No single definition exists for MSP; it takes many forms and names depending on context (Box 1). However, it can be generally outlined as the analysis and allocation of the spatial and temporal distribution of human uses in the ocean, with the goal of minimizing conflicts and fostering compatibility among such uses, as well as between human uses and the environment[8]. MSP has the potential to balance multiple—and often conflicting—human demands and to protect the environment in a spatially explicit way[8,9]. Therefore it is increasingly recognized as a vital process to achieve global ocean governance goals[10,11], in particular the UN Sustainable Development Goal (SDG) 14, Life Below Water[1]. MSP has gained momentum globally, and marine spatial plans are currently under development in about 70 countries, from high to low latitudes and across all ocean basins (except for the Southern Ocean)[7] (Fig. 1). About half of all coastal countries, comprising more than half of the surface area of the world's exclusive economic zones (EEZs), have ongoing MSP initiatives, although most of them are in early stages of development (only 25 countries have marine spatial plans that are already implemented or at least government approved; Fig. 1)[7].

MSP will likely keep expanding in the coming decade as new countries start to discuss the development of ocean planning initiatives, especially in Africa and South America. For example, the European Union (EU) funded Paddle project ('Planning in a liquid world with tropical stakes'; www-iuem.univ-brest.fr/paddle) explores opportunities and limits of MSP in Brazil, Senegal and Cabo Verde, although government-led initiatives are not yet in place. MSP in international waters is also being increasingly discussed[12,13], and in early 2019, the European Commission and UNESCO's Intergovernmental Oceanographic Commission (IOC) jointly launched the MSPglobal program (www.mspglobal2030.org) with the intention to support the effective implementation of marine spatial plans worldwide.

Several conceptual and practical challenges limit the efficacy of MSP development and implementation[14]. For example, ensuring ecosystem conservation through MSP is rarely straightforward because the importance of protecting marine ecosystems is often overlooked by economic and/or political short-term goals and objectives, often insensitive to environmental impacts[15,16]. In addition, improving social justice and the inclusion of social aspects in ocean policy and planning is key for successful ocean management[17], but social complexities make it difficult to even attain a single definition of what the 'social dimension of MSP' is[18].

Besides these challenges to MSP, anthropogenic climate change creates an additional, overarching and imminent one[19–21]. Climate change is one of the Earth-system processes that has already crossed its boundary for a safety operating space (both globally and for the ocean)[22,23], and a great challenge to humankind[24]. International treaties have long dealt with setting a path to address it, the current goal being to hold warming below 1.5–2 °C[25,26]. However, even if the most optimistic scenarios are met (which may not be feasible[26,27] in face of continuously rising emissions), our planet, and particularly

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Box 1 | MSP-related definitions

What is marine spatial planning (MSP)?
No single definition exists for MSP; it takes many forms and names depending on context. Still, the most commonly used one is from the IOC-UNESCO guide[8], where MSP is defined as "a public process of analyzing and allocating the spatial and temporal distribution of human activities in marine areas to achieve ecological, economic, and social objectives that are usually specified through a political process". According to the same reference, effective MSP is ecosystem-based, integrated (across sectors, agencies and levels of government), area-based, adaptive, strategic (that is, focused on the long term), and participatory (with active involvement of stakeholders). MSP development also includes a number of key steps that are linked through many feedback loops, rather than a linear process:

1. Identifying need and establishing authority;
2. Obtaining financial support;
3. Organizing the planning process;
4. Organizing stakeholder participation;
5. Defining and analysing existing conditions;
6. Defining and analysing future conditions;
7. Preparing and approving the spatial management plan;
8. Implementing and enforcing the spatial management plan;
9. Monitoring and evaluating performance; and
10. Adapting the process (revision).

MSP is not an end in itself, but a practical way to create and establish a more rational use of the ocean space and the interactions among ocean uses, to balance demands for development with the need to protect the environment, and to deliver social and economic outcomes (msp.ioc-unesco.org).
In the EU, MSP is commonly referred to as maritime (over 'marine') spatial planning. Although the definition is similar[58], to some authors the linguistic choice of 'maritime' goes beyond semantics, translating a deeper focus on blue growth and the development of the ocean economy[3] (and a shift from an ecosystem approach focused on ensuring environmental health).
Marine spatial management or sea-use management are also used by some authors as equivalent terms to MSP[8,9,123]. Although MSP is commonly characterized as 'just planning', in reality MSP is about marine spatial management[124]. This includes three main phases of management: planning and analysis to support the development of a management plan; implementation of the management measures of the plan; and monitoring and evaluation of the marine spatial plan performance, that results in changes and adaptation of the plan over time[8,124].

What MSP is not.
Ocean zoning. Zoning is a key part of MSP, but zoning is not planning[8]. It is only one tool to implement the goals of a marine spatial plan[124]. Ocean zoning is a set of regulations and maps that specify prohibitions on, or permission for, ocean uses in a given management area[9]. Ultimately, if zones are created without a planning vision, or consideration of other ocean uses, the result is often a chaotic pattern of overlapping and conflicting zones[124].

Marine conservation planning or marine protected area planning. According to the International Union for Conservation of Nature (IUCN), marine protected areas are areas that have been reserved by laws or other means to protect part of or all the enclosed marine environment. While conservation planning focuses on fulfilling protection or conservation goals, MSP is multi-objective planning. Indeed, a network of marine protected areas might be one outcome of MSP, but the latter seeks to integrate and balance economic, social and environmental objectives through an integrated management plan[124].

Ecosystem-based management. A management framework that integrates biological, social and economic factors into a comprehensive strategy aimed at protecting and enhancing the sustainability, diversity and productivity of natural resources. Sometimes it is used interchangeably with 'ecosystem approach'[4,5].

Integrated coastal management or integrated coastal zone management. A process that is focused on the management of coastal areas using an integrated approach in an attempt to achieve sustainability. This concept was born during the Earth Summit of Rio de Janeiro in 1992[6]. Contrary to MSP that usually focuses on large marine areas (from coastal to open-ocean regions), coastal zone management tends to be more focused on the land–sea interface[125].

our ocean[28], will still experience considerable change. As ocean warming keeps accelerating[29] and the vulnerability of marine organisms keeps increasing[30], the benefits provided by the ocean will keep changing and cause change in the way human populations have access to, and use the ocean[31,32]. In a planet with over 7.7 billion people[33], almost half of which inhabiting areas close to the coast, these changes will have multiple implications for human well-being and prosperity[31].

A number of studies from around the world address the nexus between climate change and MSP at varying lengths (from brief references to full discussions) and spatial scales (local to global; Fig. 2). Missing from these discussions, however, is a coherent and clear set of messages and guidelines on how to integrate climate change in MSP. Alongside—or perhaps also because of—the scattered nature of these discussions, in practice few marine spatial plans include climate change considerations in their general planning framework (for example, identifying the need to prevent climate impacts in ocean uses and ecosystems)[3,20]. Even fewer consider adaptation and mitigation to climate change as a planning objective for which specific actions are put in place[3,20]. There is thus a pressing need for a more in-depth, thorough conversation[11] both within the scientific community and with policymakers, lawmakers, planners and managers to strengthen the integration of climate change into MSP.

In this Review, we analyse and synthesize information from over 150 scientific references published since 2008, selected through a qualitative systematic review, that include both MSP and climate change in their contents (see Supplementary Table 4 and Supplementary Methods). Three main topics emerge from the analysis: (1) MSP as a solution to mitigate climate impacts and support UN SDGs 13 and 14; (2) integration of climate change in MSP; and (3) potential pathways for MSP adaptation to a changing climate. We explore the MSP–climate change–ocean sustainability nexus (Fig. 3), emphasizing the importance of understanding connections, synergies and trade-offs to finding new solutions and pathways to respond to ocean sustainability challenges[34–36]. Advancing the discussion on this topic will contribute to further thinking and debate, and to the social and political recognition of its key importance.

Climate change–MSP–ocean sustainability nexus

The general pathways that link climate change effects, MSP and ocean sustainability are depicted in Fig. 3. Climate-related drivers of change (for example, primary ones such as ocean warming or acidification, and secondary ones such as deoxygenation or sea level

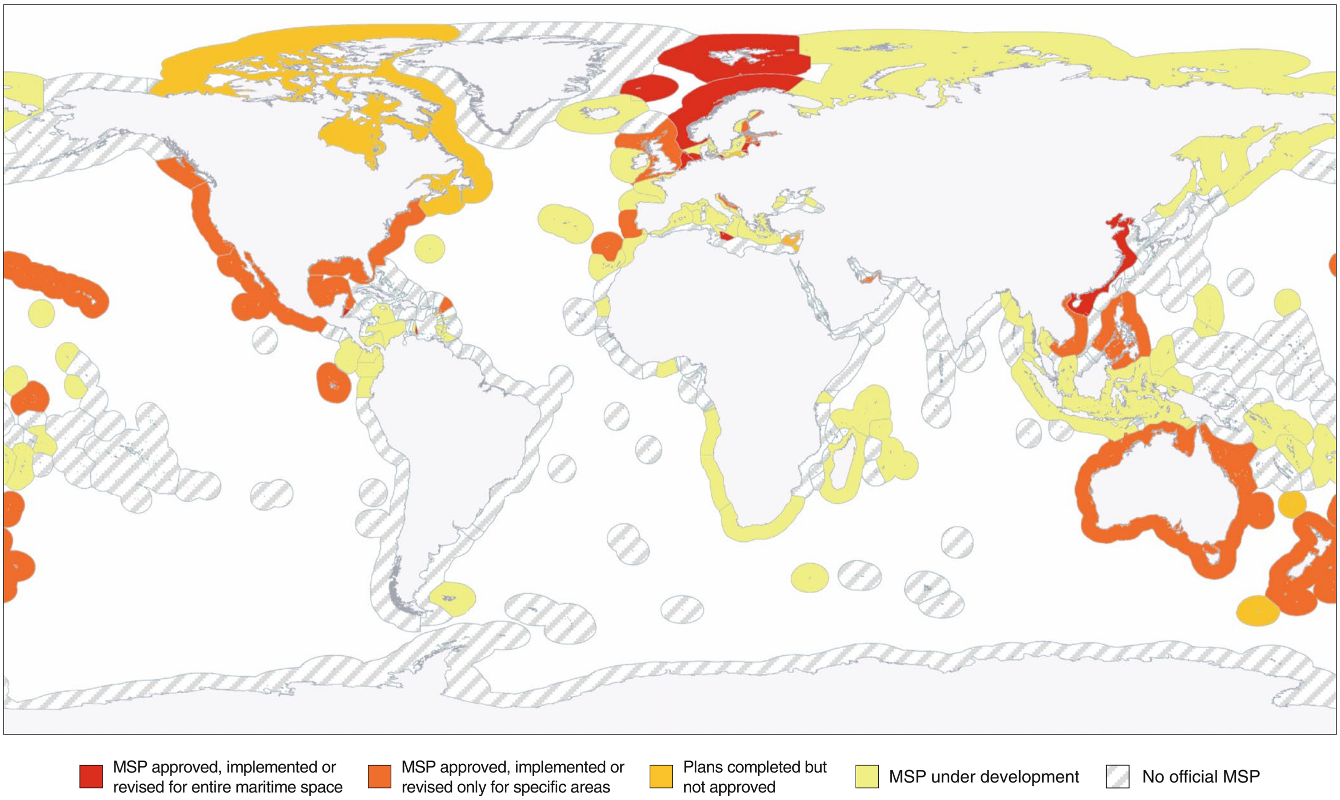

Fig. 1 | Global status of MSP development in 2019. EEZs of countries where: marine spatial plans are approved by government or implemented for the entire marine space (red); marine spatial plans are approved or implemented only for a specific area within the EEZ, such as a province, municipality, state or marine reserve (dark orange); marine spatial plans are fully developed but not approved by government (orange); marine spatial plans are still under development (yellow); no formal MSP initiatives are being carried out (grey). From the 70 countries/territories with ongoing MSP initiatives, only 25 countries have marine spatial plans in place—either partially or for the entire maritime space (see Supplementary Tables 1 and 2 and Supplementary Methods). The latter include 15 nations with plans effectively implemented, and 10 nations with plans approved by government. Only seven countries (Australia, Belgium, China, Germany, Netherlands, Norway and United States) have undertaken one or more revision processes, and now have second- or third-generation marine spatial plans.

rise[21]) are altering physical, chemical and biological conditions in the ocean, affecting the composition of entire ecosystems, including their spatial structure and functioning[28] (Fig. 3, arrow 1). Such changes in biotic and abiotic conditions alter the delivery of marine ecosystem services (MES), that is, the benefits to human societies derived from nature, both in terms of their spatial-temporal distribution and intensity[37,38] (Fig. 3, arrow 2). Changes in MES will in turn affect dependent human uses of the ocean (for example, fisheries, aquaculture and tourism; Fig. 3, arrow 3), both directly and indirectly[31,38], at multiple scales and to varying degrees. This applies equally to maritime activities and uses related to the 'blue economy' and to marine conservation[39]. Changes in ocean conditions will also directly affect ocean uses, even if they do not rely on MES (Fig. 3, arrow 4). For example, shipping, renewable energy and seabed mining can be affected as a result of increased frequency of extreme weather events that will intensify danger at sea (damaging infrastructures and limiting human operations), or changes in circulation patterns of winds and currents[40,41].

Not all ocean uses will be affected in the same way, some being globally more sensitive to a changing ocean than others[21]. There will also be considerable regional variation, because as climate impacts vary from place to place the same ocean use will be differently affected depending on geographical context[21] (for example, fish production is expected to increase at high latitudes and decrease at low and mid-latitudes, thus fisheries' vulnerability to climate change will not be the same worldwide[42]).

From a spatial management perspective, a changing ocean implies that human uses will experience spatial-temporal change (through local decrease or increase, or relocation[21]). Ocean users may adjust to non-stationary marine resources by moving accordingly (for example, fisheries and marine conservation[43,44]), or may take advantage of new spatial opportunities to expanding to new areas (for example, the loss of large extensions of sea ice will open new areas for fossil fuel and renewable energy development in Arctic latitudes[41], and shipping patterns will be globally modified due to the opening of new navigable routes near the poles[45,46]) (Fig. 4). However, ocean uses may also decrease their intensity due to spatial-related limitations (for example, when fish stocks move into or beyond national jurisdiction and fisheries cannot change their focus[43]). Accompanying these changes, there will be potential new conflicts among uses (for example, uses that move to areas already occupied), new conflicts between uses and the environment (for example, exploitation of previously inaccessible areas of high ecological value[47] and new cumulative environmental impacts[48]), and new legal issues (for example, changing jurisdictions and ocean activities that require use permits[32]). MSP will need to work with these new conflicts and issues—which are at the core of MSP processes[8,9]—and still meet multiple ecological, economic and social objectives in an increasingly crowded and human-pressured ocean[48,49] (Fig. 3, arrow 5).

While MSP will be affected by a changing ocean, MSP initiatives that are designed and implemented with explicit climate-related

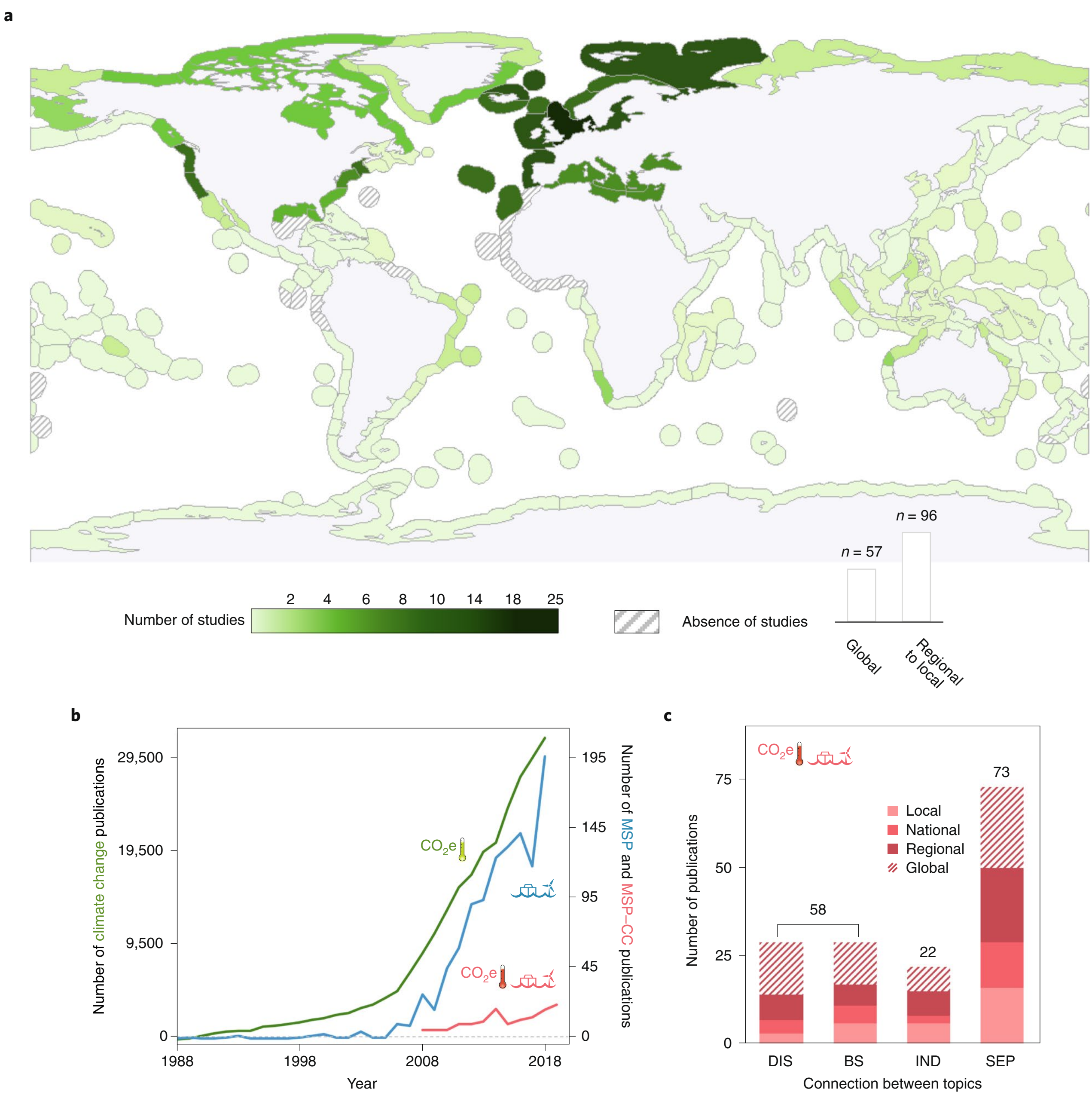

Fig. 2 | Overview of climate change and MSP literature. a, Geographic distribution of studies that simultaneously address MSP and climate change ($n = 153$), by marine ecoregion[122]. Most studies pertain to Europe ($n = 38$) and North America ($n = 28$), the two regions that also enclose a higher number of MSP initiatives[7]. Global studies are not included in the figure as they apply to all ecoregions equally. **b**, Publication trends for climate change (green) and MSP studies (blue) have increased through time, particularly in the last decade. The number of studies that simultaneously address MSP and climate change (MSP–CC, red) also follows an increasing trend, although at a much smaller scale (for 2008–2019, these studies represent 13% of the publications on MSP, and 0.06% of the publications on climate change). **c**, Overview of concepts from publications of the MSP–CC subset (red) in **b**. While most studies refer to both topics separately (SEP) or through an indirect discussion (IND), 58 references establish a direct connection between MSP and climate change. Often, such connection is made by a brief statement (BS) relating both topics, while in other cases authors provide a more detailed discussion (DIS)—at varying lengths and spatial scales. See Supplementary Methods, Supplementary Tables 3–5 and Supplementary Figs. 1 and 2 for details.

objectives can also notably contribute to minimize climate impacts[21,32,50,51] (Fig. 3, arrow 6), support climate adaptation and mitigation actions (Fig. 3, arrows 7a and 7b), and further promote the sustainable use and conservation of the ocean (Fig. 3, arrows 8a and 8b)[1].

Some studies emphasize that the challenge of climate change requires integrated, cross-sectoral approaches to manage ocean use[50]. Climate adaptation planning cannot be developed on a sector-by-sector basis (for example, for fisheries, tourism and conservation) because adaptation actions that are effective against one issue might be maladaptive to another[52]. There is a need to plan holistically instead (SDG target 14.2[1])—which, by definition, MSP can provide for[51–53].

Alongside, it is critical to ensure healthy, well-functioning, resilient marine ecosystems (SDG target 14.2[1]) in a climate change era[32], as these are expected to better adjust to changing conditions and continue providing the goods and services needed to maintain human well-being[9]. MSP can foster such resilience[32,51] by reducing

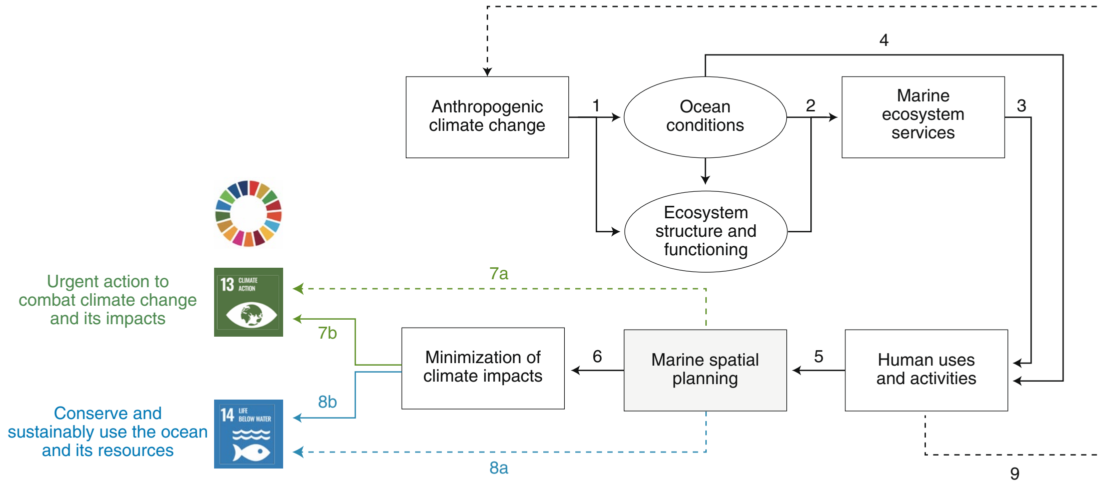

Fig. 3 | Conceptual model of the nexus among MSP, climate change and ocean sustainability, and direct relationships to UN SDGs. Climate-induced changes in ocean conditions and in marine ecosystems structure and functioning will lead to changes in the distribution and intensity of ocean-related human uses. Such redistribution of uses will lead to new potential use–use and use–environment conflicts, together with legal issues, which are at the core of MSP processes. MSP needs to be able to incorporate these challenges and dynamics to support the implementation of global sustainability goals[28]. The link between MSP and SDG 14, Life Below Water[1], is unequivocal as by definition MSP is all about promoting the conservation and sustainable use of the ocean. If properly considering the climate dimension, MSP can also play an important role in supporting climate adaptation and mitigation, and the implementation of SDG 13, Climate Action[1]. See detailed pathways, specific SDG targets and corresponding flux numbers in the main text. SDG icons are used with UN permission (www.un.org/sustainabledevelopment; the content of this publication has not been approved by the UN and does not reflect the views of the UN or its officials or Member States).

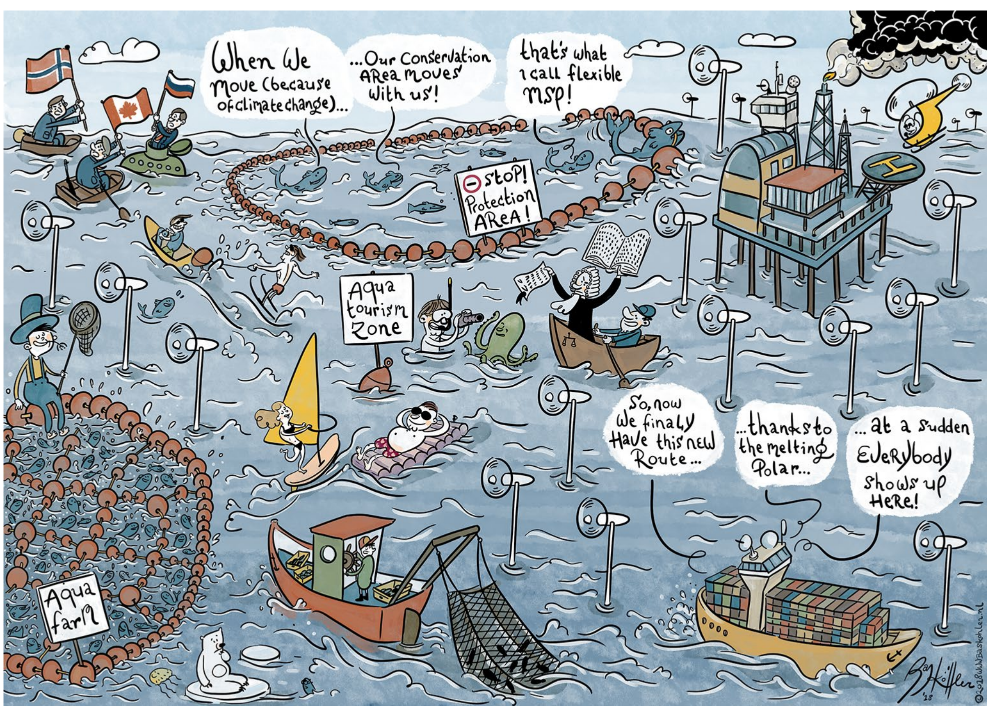

Fig. 4 | A crowded ocean under a changing climate. This cartoon illustrates the challenge of meeting multiple objectives in an increasingly crowded and changing ocean—a challenge MSP will have to deal with. There is a clear reference to the Arctic Ocean, where previously inaccessible areas are becoming available for human exploitation due to reductions in sea-ice cover, and where spatial management challenges are expected to be great[12,45,47]. There is also a clear reference to spatially dynamic marine protected areas that move with their target species[44,118]. Cartoon created by visual artist Bas Kohler (www.baskohler.nl).

non-climate stressors and pressures (for example, pollution, overfishing and habitat loss—SDG targets 14.1, 14.2 and 14.4[1]) through spatial management actions, or by ensuring effective protection of critical marine areas and climate refugia[3,8] (SDG target 14.6[1]). MSP can also promote social-economic resilience to climate change (SDG targets 13.1 and 13.3[1]), for example by involving coastal stakeholders and communities in the planning process, using local knowledge to identify new management actions and solutions, and anticipating (and avoiding) new conflicts between uses[8,51]—all of which are essential to empower human populations and increase their adaptive capacity[51].

However, it is important to bear in mind that promoting ecological resilience is more difficult when marine spatial plans do not have at their core a conservation foundation (for example, when prioritizing blue growth without a clear compromise with achieving healthy functioning of ecosystems)[15,16], or that resilience-based management does not always achieve expected results (for example, protection of coral reefs in the Great Barrier Reef)[54,55]. Some studies emphasize that only effective climate mitigation actions can fully protect ocean ecosystems from climate impacts, which goes far beyond the MSP realm (as of other area-based management processes), requiring different, more global solutions[32,39,55] (for example, global policies and treaties).

Nonetheless, there are those who advocate that MSP can contribute to reducing greenhouse gas (GHG) emissions (SDG target 13.2[1]). Expectations are that renewable energy infrastructures will become commonplace in the ocean over the next decades, and that certain ocean areas may be assigned to carbon capture and storage[56]—either because of national or international commitments to deliver a higher percentage of energy from renewable sources (to reduce GHG emissions)[25,57] or because of non-climate goals related to promoting maritime economies growth[58]. MSP can support this expansion by promoting the appropriate allocation of areas to both the installation of renewable energy developments (for example, offshore winds, waves and currents)[59] and blue carbon capture and storage[57,60] (for example, areas for the conservation of blue carbon ecosystems; www.thebluecarboninitiative.org); or by decreasing conflicts and fostering compatibilities with other activities, and helping stakeholders and policymakers to perceive the advantages of having these uses in place[8].

MSP can also contribute to climate mitigation by prioritizing the allocation of space (or facilitating the attribution of permits to the use of such space) to ocean uses and activities that choose to use new eco-efficient technologies and power sources that tend to zero emissions (for example, fuel-efficient shipping, electric engines, solar and wind power)—this way counteracting the normal contribution of such uses (for example, shipping, fisheries or tourism) to accelerating GHG emissions (Fig. 3, arrow 9)[61,62]. More pervasively, MSP can limit the available space for polluting activities that do not engage in decreasing the rate of GHG emissions.

Depending on how MSP considers the climate dimension, these pathways that link MSP to UN SDGs and targets may, or may not, unfold. It is then critical to understand how marine planners, managers, policymakers and lawmakers can incorporate uncertain 'future' dynamics in MSP initiatives (particularly at the national level), monitor to see how rapidly changes are happening, and mitigate impacts through adaptive planning and management.

Integrating the climate dimension into planning

Effective ocean management and governance must acknowledge that marine species move in response to shifting climate, changing in time and space even if at imperceptible speeds[31,32,44]. Marine spatial plans are no different. As MSP operates in a changing ocean, properly addressing and integrating climate effects is vital[50,63,64] to keep plans viable, relevant and useful in the long term[21,32]. However, climate change is often neglected as a factor in MSP processes. A recent study highlights that only three EU member states (Netherlands, United Kingdom and Sweden) have marine spatial plans that consider climate adaptation and mitigation as one of their objectives, sometimes also including climate impacts as a management concern in MSP monitoring and evaluation stages[3]. All other member states largely disregard climate change in their MSP documents[3]. Although there are more MSP processes around the world that also recognize a changing climate as a threat or challenge—for example, Rhode Island in the United States, Abu Dhabi in the United Arab Emirates, or Seychelles (msp.ioc-unesco.org)—this lack of integration seems to be the overall trend[20]. This means that, in practice, climate-related impacts end up being largely ignored by marine planners, managers and policymakers[3].

Some authors suggest that such lack of integration is because MSP conceptually arose without any reference to a changing climate[32] and planning future ocean use is a somewhat recent concept[47]. Yet, the decade-old MSP guide by IOC-UNESCO identifies the analysis of future conditions as one of the 'key steps' to developing MSP[8]—and in line with it many authors acknowledge that MSP is all about the future[11], a way to look forward and to guide human action[8,9,47] toward a vision for tomorrow's ocean[20].

To others, climate change is not properly considered in MSP because the majority of marine management approaches, MSP included, are largely static and do not take into account the dynamic nature of the ocean and its uses[44,65]. Marine spatial plans are static 'images' with little or no margin for dynamics[20]. Even when considering the future (for example, scenario building), this is commonly done by using static predictions (for example, habitat maps of a single time stamp)[20] rather than by considering ocean dynamics (for example, including the latter when building scenarios at 10–30 years).

Another appointed reason for the lack of integration of climate change in MSP is that, in practice, planning and management often end up being reactive, that is, responding to problems only as they arise[19,66]. This can occur for a variety of reasons. When developing MSP and in a context where resources tend to be limited, proactively considering climate impacts may represent additional initial costs[8,51] to develop scenario analysis, vulnerability assessments or modelling tools[19,67]. Also, there can be resistance to including climate change in MSP, either because this requires new skills in the planning team[51], because of a tendency for humans to avoid behavioural change until impacts strongly affect well-being[19], or due to reluctance justified on the uncertainty of future climate predictions[20].

A final reason for the lack of integration of climate change as a major driver for dynamic MSP relates to nation-specific institutional (jurisdictional) frameworks and to power allocation and power relations. These hinder effective adaptation of governance systems[65,68]—which calls for a transformation in the management system in parallel (or at least, in response) to changes in the system being managed, for example through a transition management approach[68,69].

Still, different methodologies and approaches can be used to support the integration of climate impacts in marine spatial plans. The main ones are tackled in the following subsections.

Visioning and scenario analysis. Scenario analysis has been identified as the most promising approach to inform MSP adaptation to future evolving conditions[20]. Spatial scenarios are not plans; they are future visions that provide insights into how a MSP management area could look, for example in 10–20 years[70,71]. There will always be multiple alternative futures. In each of them human uses will be differently distributed in space and time depending on the socio-political options underlying management and governance decisions[8,20] (for example, prioritizing marine conservation, blue growth or cultural aspects). Scenarios are built using different approaches (for example, qualitative and quantitative) and combining methods to presenting alternative 'storylines' on how the future may unfold. Discussing these storylines allows for a better understanding on how different development pathways can affect the future (under different assumptions about drivers of change and their impacts)[71,72]. Scenario-building processes can be exploratory ('what can be done?'), normative ('what must be done to achieve a desired future?') or predictive ('what is the most likely situation?'). By using results from modelling and mapping tools to explore the consequences of different planning and management decisions, visioning and scenario analysis provide a pathway to integrate climate impacts in MSP practice. However, coupling climate-related impacts and socio-political factors is needed to properly reflect the complexity of social-ecological systems, because governance decisions are sometimes more important in determining outcomes than climate impacts alone[73].

Representing a shared vision and explicitly incorporating it with quantitative, analytical tools is not always straightforward. There are examples of MSP processes that successfully include spatial scenarios (for example, Belgium, Netherlands, Sweden and Abu Dhabi[3,74]; msp.ioc-unesco.org). However, others show that there is a need to bridge the gap between the will to represent future use and climate change impacts, and the ability to do it (for example, Belize and St. Kitts and Nevis)[75,76]. The Symphony tool is a specific example of a tool developed to support strategic planning in Swedish MSP, and that now includes climate change projections (for example, temperature, salinity and ice-cover)[74]. Another example is the ACCESS MSP scenario tool that incorporates climate considerations in the Arctic region, although not corresponding to a legally binding MSP initiative[47]. Other types of decision support tools such as Marxan (systematic conservation planning tool)[77,78], InVEST (integrated valuation of ecosystem services and trade-offs tool)[75], or the Bayesian Belief Network–GIS modelling framework[79] can be used to explore the consequences and threats associated to different spatial management decisions—such analysis being essential to produce knowledge for planning under a changing ocean. Nevertheless, it is argued that there are few examples of studies using such decision support tools in climate change contexts, and only for near-term scenarios[20].

Modelling and mapping change. Modelling tools have been widely used to estimate near- and long-term alterations in marine ecosystems and human uses resulting from climate change—such as changes in fisheries[42,73], aquaculture[80], shipping[46] or biodiversity distribution[31]. Several authors maintain that estimating and mapping these changes in ecosystem services over space and time—and in human activities that rely on such services—is essential for MSP design under a changing ocean[51,63,81–83]. And new modelling and mapping tools can represent a step forward in ensuring this knowledge integration[64,67,79].

Some studies refer to using global change projections (based on different Intergovernmental Panel on Climate Change (IPCC) emission scenarios)[26,28] together with predictive species distribution models (long-term projections from an ensemble of ecosystem models). These are used to identify changes in the distribution and extent of priority marine habitats[81] or 'hotspots' of change[83] (areas with substantial and directional change of ecosystem components). Global change projections for sea surface temperature, pH, dissolved oxygen and sea surface height[26] (under different Representative Concentration Pathways (RCPs)—RCP8.5 to RCP3-PD) have been applied, for example, to estimate future changes in the spatial-temporal distribution of coral reefs[53], fish stocks and fisheries[53,84], sea-ice cover[50], or regionally differentiated changes in sea level[8]. A number of studies also emphasize the importance of mapping species assemblages (mostly benthic communities) and ecological boundaries[64,85,86] in providing baselines against which to measure future impacts.

It is important to bear in mind, however, that predicting future climate conditions and their impacts on marine social-ecological systems includes a certain level of uncertainty[20,50]. Using abiotic shift models to predict species range alterations, and mapping ecological boundaries is also not sufficient to fully incorporate climate impacts in MSP. Further predictions, at more local scales, on how human activities are expected to increase, decrease or relocate as a result of environmental change[21] (Fig. 4) are, for example, key to inform 'climate-smart' or 'climate ready' marine spatial plans.

Still, a range of new, useful tools will become available (contributing to advances in the field) as remote sensing, new monitoring technologies, and global systems for collecting and sharing data are refined[56].

Risk and vulnerability analysis. Spatial assessments of exposure, vulnerability (either social, economic, cultural, ecological, or a mix of them) and risk have been identified as part of the solution to 'climate-proof' MSP[11,21,83]. In addition to identifying spatial-temporal changes in marine ecosystems and human uses, MSP requires knowledge on where the consequences of such changes are most significant[11,53,63]. That is, where marine social-ecological systems are more vulnerable (susceptible and predisposed to harm), exposed (present in places that can be adversely affected), and where the probability of hazardous events (for example, sea-level rise and extreme events) is higher[87,88]. This allows for the identification of key problematic areas[88], where adaptation actions will be most needed[85,89].

These spatial assessments can, however, be challenging. There are multiple and overlapping definitions for each of these concepts (risk, vulnerability and exposure) and a myriad of corresponding assessment methodologies and frameworks[90]. The selection of a particular one is thus a complex, subjective process. As MSP initiatives take place at different spatial scales around the world (from local to national/regional levels)[7] and climate impacts do not affect all locations, economic sectors and groups of people equally, there will never be a one-size solution to fit all cases[11,21]. Global analyses[21] must, therefore, be deepened and applied at a scale that is relevant to MSP (not only within the implementation area of the plan, but also considering its surroundings to allow for the identification of relevant sources of influence[8]). We must start building a deep understanding of the vulnerability and exposure of social-ecological systems in MSP management areas. For example, what ocean uses are present (or are expected in the future)? What is their socioeconomic importance? What drivers of change are expected to affect them, and to what extent? These analyses will bring to the forefront important social-ecological linkages and methodological limitations that will require further investment in the future[11,63].

Adaptive management

MSP is continually iterative and adaptive by nature[8,56], because planning (if developed properly) has no endpoint and needs to be consistently adjusted over time[19,20,52]. In the particular context of a changing climate the need to ensure dynamic, flexible and adaptive MSP solutions is even more urgently needed[20,21,32,83]. No single MSP initiative will be able to anticipate all potential future impacts from climate change and other human stressors[19]. Attempting to plan for all cases[91] would imply a major use of resources (for example, time, human and financial) with no guarantee of success because of the high uncertainty involved (even with continually refined forecasts and using the best predictive tools)[28,63,67,92]. Finding the pathways to truly develop dynamic and flexible MSP can be complex—given the variety of issues, challenges or opportunities that need to be dealt with, under a diversity of geographical contexts and settings. However, a number of management approaches have been identified as having potential to support the management of ocean uses under change. These include dynamic ocean management[44,93,94], anticipatory zoning[32,82,95], just-in-time planning[21,91], or anticipatory bidding for use rights (a combination of dynamic ocean management and anticipatory zoning)[32] (Table 1).

Such approaches fall under adaptive management, which is conceptually embedded in the MSP framework[8,56]. Adaptive management allows MSP to be modified by changing its goals and objectives, by altering desired outcomes, or by modifying management actions[56]. However, challenges to implementing adaptive management need to be addressed, such as the ability to incorporate change in governance and jurisdictional frameworks[96,97]. Despite the key

Table 1 | Pathways to support the inclusion of climate change in MSP

Approach	Solution / good practice	Description	Real examples
1. Integrating climate change impacts in MSP policies and plans	1.1. Recognizing climate change as a threat or challenge	This is the underlying premise for MSP to be able to effectively address and incorporate the climate change dimension and thrive in a dynamic and uncertain future[21]. Several MSP plans and policies recognize climate change in their objectives, but often in a very general, vague way without really integrating it through specific measures or actions.	*Marine spatial plans*. The Netherlands, United Kingdom and Sweden consider adaptation and mitigation to climate change as one objective of their plans for which specific actions are put in place[3]. Portugal and Malta plans only mention climate change as a challenge in general, while for example Germany, Belgium and Latvia mention it in the planning objectives or measures[3]. MSP initiatives in Morocco, Indonesia, Jamaica, Panama and United Arab Emirates also mention climate change (msp.ioc-unesco.org). *MSP policies*. The EU MSP Directive (the major MSP policy in the EU) stresses that marine spatial plans are to contribute to resilience to climate change impacts, taking into consideration climate-induced long-term changes[58]. Yet, the challenge of a changing climate is not addressed in the procedural steps that member states are actually expected to establish to contribute to the Directive objectives (that is, its 'minimum requirements')[58]. No potential pathway on how to put these concepts into practice is thus identified.
	1.2. Including climate change in spatial-use scenarios and visioning processes	When defining and analysing future conditions for MSP[8], future sea-use scenarios are to be developed and analysed. This includes projecting current trends in spatial and temporal needs of both existing human uses and new demands for ocean space, and identifying and selecting alternative futures. Climate change can be included in these scenarios, anticipating related conflicts and opportunities[8], and allowing for more informed planning and decision-making[63,83]. In some MSP initiatives specific scenarios for climate change are developed.	For MSP in the Netherlands, three alternative spatial-use scenarios were developed, being integrated with alternative sea level rise scenarios[8]. Climate change scenarios (optimistic and catastrophic) were developed by stakeholders when establishing visions for MSP in the western tropical Pacific Ocean[111]. The spatial vision experiment of Flanders Bays (Belgium) aimed to ensure protection against sea level rise[3].
	1.3. Using modelling and mapping tools	Modelling and mapping tools can be used to support scenarios and visioning processes. Modelling and mapping changes in ecosystem services and related human activities over space and time is essential for MSP design under a changing ocean[51,63,81]. Several mapping and modelling tools can be used, from more sectoral (for example, aquaculture, shipping and renewable energy)[46,79,80] to more comprehensive ones[47,74].	The Symphony tool, developed for Swedish MSP, is used to test scenarios and support climate-adapted strategic planning, and includes cumulative impacts mapping and climate change projections (temperature, salinity and ice-cover)[74]. The ACCESS ArcGIS online MSP tool, developed for the Arctic Ocean to store, manage, interrogate and access regulatory and spatial-temporal information to support MSP, specifically incorporates climate considerations[47]. Analysis of the distribution of hotspots of ecological change and ocean uses in the northeast Atlantic Ocean is identified as part of a climate-ready solution for MSP[83]. Maps produced with Marxan and Zonation are used to analyse exposure to climate change in the west coast of Madagascar and support MSP[78].
	1.4. Climate-related vulnerability and risk analyses	Results from vulnerability and risk analyses can also be used to support MSP scenarios and visioning processes. Existing tools and frameworks to assess risk and vulnerability of marine social-ecological systems to climate change tend to follow a sectoral approach (for example, assessments for fisheries, aquaculture, shipping and conservation). Yet, integrated approaches to be used specifically in the context of MSP are under development.	Social-ecological vulnerability of small-scale fisheries in Moorea (French Polynesia) was analysed to inform and optimize national MSP[112]. Cumulative risk of human activities was assessed in two MSP areas in the United States – northeast Atlantic and mid-Atlantic planning regions[113]. Vulnerability of marine habitats' capacity to deliver ecosystem services was evaluated using a climate scenario, together with its potential to inform MSP in Portugal[114]. A preliminary approach was developed to analyse the vulnerability of MSP and the blue economy to climate change in European coastal countries[115].

contined

Table 1 | Pathways to support the inclusion of climate change in MSP (Continued)

Approach	Solution / good practice	Description	Real examples
2. Promoting adaptation to climate-related change	2.1. Dynamic ocean management	Planning approach intended to reduce conflicts between dynamic resources and human activities on the move. Using near real-time data (for example, from remote sensing) it allows for the designation of management areas whose boundaries change in space and time in response to shifts in ocean resources and ocean uses[93,94]. In addition to providing flexibility, this approach promotes increased adequacy and efficiency in ocean use by supporting the development of human activities in more appropriate places, thus narrowing their spatial-temporal requirements[44]. Potential for MSP is well established[44], yet real applications tend to be more sectoral (for example, fisheries and conservation).	Dynamic solutions are used for fisheries management in the United States (New England, California and Hawaii) and Australia[44,93,94,116]; for marine mammal protection in the east coast of United States[44] and Canada[117]; and for offshore aquaculture operations in Tasmania[32]. Potential for mobile protected areas in the High Seas to support resilience to climate change effects was recently highlighted[118].
	2.2. Anticipatory zoning	A priori allocation of areas to particular ocean uses in the future—or to their exclusion—in anticipation of climate change effects[32,82,95]. This has the potential to be used as a precautionary legal tool (protecting and preserving the ecological integrity of most sensitive ecosystems)[32]. It fosters flexibility by allowing responsible entities to make decisions before ocean uses are in place, thus avoiding political and legal problems, anticipating conflicts and prioritizing ocean uses before costly infrastructure investments are made[32].	Areas were closed to human uses (for example, commercial fishing) in the Arctic Ocean in anticipation of sea-ice loss, using the status of marine protected areas or special protected areas[32,47]. Preferred sand extraction zones were established in the Netherlands to support climate adaptation, namely the protection of low-lying coastline against sea level rise[8].
	2.3. Adaptive management	Based on the concept of learning by doing, and on adjusting actions and strategies according to obtained results, adaptive management is conceptually embedded in the MSP framework[8,56]. The need for adaptability in MSP relates to moving marine ecosystems (that change their distribution and extent over time and space)[81,119]; social systems being dynamic (with changes in policies, management practices, economic conditions, societal and stakeholders' interests and expectations, existing human uses, and new demands for ocean space)[8,9,20,50,56,84,100,120]; and new knowledge becoming available or scientific and technological advances[11,19,20,120]. Adaptive management largely relies on two main steps, identified as vital for MSP adaptability[8,9,19,20,50,56,66,120,121]: performance monitoring and evaluation; and revision. Monitoring allows managers to measure results and evaluate if goals and objectives are being met[52,53,100]—without it, success cannot be distinguished from failure[56]. The process must then be revised on a periodic basis[21,51,120] and modified to overcome limitations[19].	Only seven nations with implemented marine spatial plans have undertaken one or more revision processes (Australia, Belgium, China, Germany, the Netherlands, Norway and United States[7]; msp.ioc-unesco.org), thus effectively completing the adaptive management cycle.
	2.4. Just-in-time planning	A planning approach that instead of using statutory long-term plans, uses planning laws and rules referring to qualitative relations between different activities and factors within a system[91]. Contrarily to traditional practices, this approach does not try to anticipate every possible situation, and there are no 'future complete pictures' to be accomplished[91].	Originally discussed in the context of urban planning[91], the potential of just-in-time planning for MSP was already highlighted in the scientific literature[21].

importance of an adaptive approach to MSP being widely recognized (and even identified as "the single most important weapon in our armoury" to achieve effective, efficient and equitable ocean management[9]), this is rarely operationalized[20]. For some, this is the consequence of little research on MSP monitoring and evaluation effectiveness[56], short implementation times and limited experience of marine spatial plans that have been implemented and revised[20,98] (see Fig. 1 caption). The know-how expected from a global endorsement of MSP (www.mspglobal2030.org) in coming years should, however, contribute considerably to overcome these limitations[98]. More importantly, ensuring political commitment, willpower and institutional (legal) ability[97,99] to continue adjusting MSP initiatives as they evolve will be essential[8,12,100].

Surfing the waves of change

There are still uncertainties regarding the extent and magnitude of how global climate change will modify the ocean in years to come[28]. It is certain though, that the ocean and its uses will undergo change[28]. In such a future, only by finding ways to continually adapt to uncertain changes will we achieve effective, efficient and equitable ocean governance—and MSP processes can be pivotal. Different areas of the world, experiencing different social-ecological realities, will require different solutions to both integrate climate impacts in MSP and ensure dynamic solutions.

This Review assembles some key ideas and guidelines towards climate readiness. Similar to other natural resource management areas such as agriculture or biodiversity conservation[101,102], MSP must become 'climate-ready'. The first step is to build evidence at multiple scales on the pathways through which climate impacts on marine social-ecological systems will challenge ocean planning. Identifying in advance potential places in which human activities and infrastructure are more vulnerable and exposed to climate impacts is key to target proper climate adaptation actions. It is also vital to recognize the differences among human communities' capacity to cope, respond or adapt to climate challenges[103], and that such differences will affect the ability to achieve an equitable, inclusive and sustainable use of the ocean[17].

Second, we need to better understand the robustness of different management approaches under climate uncertainty[48,101], particularly their ability to transform, adapt and integrate change[65,104]. Table 1 provides a glimpse on 'what works where' so far, but as MSP continues to spread globally, countries with ongoing initiatives must evaluate which dynamic solutions suit them better and why. MSP must be flexible while simultaneously providing predictability and stability for ocean users. A growing body of literature on adaptive law and governance[65,68,99,104–106] addresses these issues (together with broader legal impediments to effective ocean management) and can provide pathways to support dynamic MSP solutions (for example, overcoming legal obstacles to integrating dynamic and adaptive management in planning). It is also critical to deepen the analysis on adaptive governance[68,104] and understand the key social-ecological relationships on which it depends (despite existing examples on sea basin scales[105], sector approaches[106] or the contribution of a specific component[99], a common vision to guide action remains to be established). Alongside, a regular revision mechanism (for marine spatial plans and MSP policies)[19–21] coupled with a robust monitoring framework[56,107] would help countries ensure their plans are effective, feasible and relevant[56], and allow them to put into practice the precautionary principle—a cornerstone of MSP—in order to adapt to changing conditions[58,108].

Third, the implementation of global ocean sustainability goals requires the effective coordination of different policy arenas[34,101]. So far there is a lack of mutual recognition between MSP policies and climate policies. The need to combat climate impacts is far from being sufficiently imprinted in national and regional MSP policies (for example, see the EU Directive on MSP[58] in Table 1). Conversely, marine planning (and broader ocean governance) is largely absent from climate adaptation strategies, plans or programmes of action[109,110]. These tend to just mention fisheries, biodiversity conservation or coastal areas[109,110]. This misalignment between policies makes it more difficult to ensure that climate change is integrated as a relevant factor in MSP processes. Mutual recognition between climate and MSP frameworks must be pursued by policymakers.

MSP has a real chance to contribute to sustainable ocean use, but to do so effectively it must be prepared for the challenges ahead—a changing ocean being a vital one[14]. There is a growing recognition that ocean resilience is in peril, and that international and national action is needed to address climate change before it is too late[24,26] for our ocean, our planet and humankind. We need to reframe our approach along the above-mentioned lines, and take action accordingly, to effectively develop climate-ready MSP—that way contributing to support sustainable ocean-based solutions[57].

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Author contributions

C.F.S. and R.R. designed the study. C.F.S. developed the first draft of the manuscript. T.A., F.A., H.C., L.B.C., C.N.E., S.G.-M., E.G., B.S.H., M.K.O., H.-O.P. and R.R. commented on initial drafts, and all authors contributed to the final version of the Review article.

Competing interests

The authors declare no competing interests.

Additional information

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