DOI: 10.51756/marlife.1113070

Marine and Life Sciences

E-ISSN: 2687-5802

Journal Homepage: https://dergipark.org.tr/en/pub/marlife

Review Article

The Smart Sea concept and its application for ocean management in a changing climate

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Received: 07.06.2022

Accepted: 19.09.2022

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Keywords

Digital technologies

Food security

Knowledge systems

Ocean health

Solution options

Sustainable management

ABSTRACT

Global environmental change is a defining issue of our time. The ocean is a key component of the Earth system, and yet, in-depth understanding of its roles in sustaining life has not received the attention which it deserves. Humanity must develop a new relationship with the ocean characterized by protection, sustainable production, and prosperity. Society has too much to gain by implementing sustainability solutions and too much to lose by ignoring them. Our actions or inaction now will have far-reaching implications for future of all life on Earth. Ocean blueprint that calls for enforcing 30% Marine Protected Areas by 2030 requires real transformative action. This paper contains new ideas for combining the efforts of natural and social scientists, and traditional users of sea, and explores the potential of modern technologies to assist in this campaign. ‘Smart Sea’ concept introduced in this paper envisages synergies among the problem-solving approaches including digital tools, and eco-engineering and eco-mimicry solution options. Knowledge gaps have been highlighted and relevance of new knowledge systems emphasized together with enabling conditions to address the uncertainties associated with the ocean ecosystem. The ocean has a central position in actions towards preventing global warming of 1.5°C but measures to achieve it should consider that the ocean carbon sink is dynamic and is adversely affected when excessive carbon dioxide produces acidification. The selected measures are likely to have trade-offs, requiring analysis of multiple dimensions, for ensuring sustainable outcomes. The prevailing ocean health and urgency to mitigate it calls for combining global and local solutions, technologies and actions driven by safe and innovative solutions, and wherever possible, based on proof-of-concept. Deviating from the on-going incremental data collection systems to new forms of data-sharing using modern technological tools will contribute to addressing the glaring vacuum in knowledge of the ocean and facilitating a concerted global action for maintaining its ecosystem services. An attempt has been made in this paper to consolidate different opinions and experiences in moving from generalities to specifics for sustainable solutions that support economies, food security and the society.

Introduction

The Ocean, covering almost 71% of the Earth’s surface, creates the primary life-support system of the planet. It is home to a rich biodiversity and plays a significant role in food security, global economy, and climate regulation. This vital ecosystem faces unprecedented challenges due to human and environmental pressures. Much of the life on Earth depends on the invaluable marine ecosystem functions and services. Ocean health is central to the delivery of these roles, especially oxygen generation, climate regulation, biodiversity conservation, food security, income, and livelihood. Any significant progress in the ‘Building Back Better’ (BBB) paradigm which is currently being advocated by The Organization for Economic Co-operation and Development to protect the natural capital and accelerate progress in sustainable

Cite this article as

Mustafa, S., Shapawi, R., Hill, J., Azul, A. M., Shaleh, S. R. M., Estim , A., Waheed, Z., Chen, C. A., Saleh, E., Hoque, M. A. & Galaz, G. P. B. (2022). The Smart Sea concept and its application for ocean management in a changing climate. *Marine and Life Sciences,* 4(2): 100-113.

development is inconceivable without shifting our attention to the ocean. In this context, an integrated outlook of ocean health and human health should be at forefront of global attention. It emerges from the intricate nature of the two that our actions toward the ocean will have a strong bearing on the future condition of the whole planet and health of the societies around the world (Borja et al., 2020). The increasing anthropogenic pressures driving the degradation of marine ecosystems and their services are being increasingly highlighted by scientists in the recent years (Pecl et al., 2017). Concern is growing about the sustained and cumulative pressures such as pollution, habitat loss and overfishing, and their consequences for the communities (Depledge et al., 2019). Undoubtedly, the restoration and preservation of coastal and marine ecosystems, and mitigating the effects of climate change at this critical time for the global environment (de Groot et al., 2013; Pueyo-Ros et al., 2018; Pouso et al., 2019) will support the BBB goals.

Scientific and technical assessments assert the need for an interdisciplinary and multi-actor framework to protect and restore ocean health. Despite the urgency, achieving marine conservation and protection remain challenging on account of ever-increasing environmental threats, technical planning, shortage of environmental management personnel, limited financial resources and inadequate decision-support. Expenditure in employing large numbers of marine park rangers and mobilizing costly navigational assets is high and this constrains the enforcement efforts. The Strategic Plan for Biodiversity, including the Aichi Biodiversity Targets (2011-2020) under the Convention on Biological Diversity, required at least 10% of coastal and marine areas to be conserved for protecting marine biodiversity. The UN Sustainable Development Goals (SDGs), 2016-2030, identified ‘Target 14.5’ that reiterated support for this call for action. However, at present, only 2.7% of the ocean is effectively protected (Sala et al., 2021). The Decade of Ocean Science for Sustainable Development (Ocean Decade), as proclaimed by the United Nations with a timeframe of 2021-2030, requires taking actions to reverse the cycle of decline in ocean health using scientific knowledge and integrated research. It calls for going far beyond the Aichi Target and bringing 30% of the total area of the world’s exclusive economic zones under conservation as a Marine Protected Area (MPA) by 2030. The message being widely used is “30x30 Blueprint” for the ocean. This initiative is in the interest of the social-ecological pathways since decline in the ocean will eventually reduce its capacity to perform functions and provide ecosystem services to sustain humanity. The sequence of events is straightforward: direct and indirect impacts on the ocean pose a threat to its ecosystem stability which undermines the ecosystem services, leading to a decline in the well-being of people relying on these services. In addition to protection and restoration of marine biodiversity, the conservation measures are anticipated to harness the benefits of blue economy. The limited success in MPA enforcement is due to lack of adequate actors and stakeholders’ participation (Mascia et al., 2010; McCay and Jones, 2011; Levine et al., 2015). This problem can be addressed by integrating the socio-spatial dimension of management with the geospatial tools.

Conservation of designated marine areas supports resilience of vulnerable coastal and marine organisms and critical habitats and protects biodiversity that tend to maintain ecosystem services (Cooney et al., 2019; IUEP, 2018). Several studies have provided evidence of conservation interventions contributing to the health of the ecosystem resulting in benefits to the communities. Lester et al. (2009) have suggested measuring biomass and numerical density referring to the mass of living organisms and the number or density of individuals of a targeted species, respectively in a given area at a given time. A practical approach to measuring density is determination of catch per unit effort (CPUE). Even a record of the size of a marine animal is used in quantifying the beneficial effects of different levels of conservation efforts in MPAs (FAO, 2018).

Curtailing biodiversity loss and restoring ecosystem functions and services are among the key dimensions of the BBB approach. These are fundamental to the economy and human welfare (Mustafa et al., 2020; OECD, 2020). There are many challenges in understanding the true nature of marine biodiversity. The ocean is home to millions of species (Mustafa & Saad, 2021). The World Register of Marine Species contains a record of 240,000 living species that have been identified and described until 2021. If the trend of marine biodiversity loss in several parts of the world is any indication, the number of species appears to be declining (EASAC, 2005). Over 70% of the Earth’s surface is ocean, yet more than 80% of it remains unmapped, unobserved, and unexplored (NOAA, 2020). This condition can be characterized as the ‘Triple U’ ocean paradox! Even with the knowledge so far gained, it is evident that as much as 87-90% of the global ocean is impacted by human activities (Halpern et al., 2015; Jones et al., 2018). The abundance of marine fish has declined by 38% since the 1970 levels (Hutchings et al., 2010), global coverage of marine critical habitats (seagrasses, mangroves, and coral reefs) has decreased by 30–35 % (IOC, 2017), the percentage of overfished resources has increased to 34.2 (SOFIA, 2020), and as many as 500 oceanic dead zones now cover 245,000 square kilometres (IOC, 2017). Furthermore, the ocean acidification is mounting an increasingly serious challenge to marine life (Worm & Lotze, 2016). Having absorbed about one-third of all the carbon dioxide emissions in the past 200 years, the average pH of ocean surface has decreased by 0.1

unit-from 8.2 to 8.1, and this trend will lead to further decrease of 0.2-0.3 units by the end of the century (Orr et al., 2005; OF, 2020). Mechanisms governing the ocean's dynamic equilibrium appear to be unique in the face of the changing nature of impacts, interdependencies, and non-linearities between the causes and effects but there are limits beyond which natural oceanic processes are vulnerable. All these ocean attributes and conditions demand a different type of human-ocean relationship, new theoretical constructs, novel methodologies, participatory approaches, and translational studies to mitigate the current and anticipated ecological and social challenges.

A precautionary approach in conservation planning is necessary even though 80% of the ocean remains unexplored. Action cannot be delayed for this reason. In the vastly unknown ocean where there is a scientific uncertainty of the effects of direct and indirect human actions, common-sense perspectives and compelling reasons can be used for managerial actions. The current level of verifiable evidence, historical trends, and synthesis of knowledge about the problem-solving measures provide a basis for marine conservation planning in response to the prevailing and anticipated challenges. In this context, this article introduces a new perspective, the 'Smart Sea Concept' (SSC)- that can significantly contribute to implementing the global agenda for marine conservation, especially for enforcement of MPAs. SSC should obviously support marine biodiversity and blue carbon stocks of mangroves, sea grasses and other habitats to strengthen the ability of marine life to capture the biological carbon and remain the biggest carbon sink. While the ocean is emerging as an important element of climate policy, more efforts need to be invested in enforcing measures to reduce greenhouse gas (GHG) emissions. Reasons for urgency to act in this matter are obvious from the climate model simulations, new data analyses and more accurate methods of integrating scientific evidence that show that oxygen levels have dropped in many ocean regions and acidification has increased faster than at any time before and global mean sea level increase amounted to 3.7 mm year-1 between 2006-2018 (IPCC, 2021). It will be difficult for many ocean ecosystems, especially coral reefs, and vulnerable marine animals to adapt to such a rapid change. Mitigation measures can be prioritized keeping in view that ocean carbon sinks have more capacity to take up progressively larger amounts of carbon emissions in absolute terms, but the proportion of emissions absorbed reduces under high emissions scenarios, leaving the carbon dioxide in the atmosphere which in turn accelerates climate change. Under such a situation, enhancing ocean's blue carbon stocks should be accepted as a matter of priority.

The Smart Sea concept

There is much discussion on potential actions that can be undertaken to protect and restore marine ecosystems. Among the multiple options, nature-based solutions are considered as practically feasible and low-cost, and without any apparent risks. Thus, measures such as conservation and rehabilitation of seagrass beds, mangroves and coral reefs deliver many biodiversity and ecosystem functions and services while producing no adverse consequences. Nature Based Solutions (NBS) envisage making use of natural capital in reducing human impacts, but the problems confronting the ocean are so enormous that these require exploring synergies among many different solutions, including those intended for mitigating the effects of global warming and climate change.

In this context, the SSC is being introduced. It is designed to be inclusive and adaptable to deliver conservation goals as well as societal impacts. Key components of SSC include generation of scientific knowledge (incremental, transformative and what emerges from retrospective data for prospective use), technology (existing, disruptive comprising eco-engineering tools as well as next generation biotechnology), traditional practices under a co-management system, and lastly, policy support. The entire approach is based on the following three main strategies:

1. Deploying the digital technologies of the Fourth Industrial Revolution (IR.4) to harness the power of scientific knowledge and discoveries.
2. Synergizing eco-engineering and other complementary approaches that can improve the operationalization of marine conservation measures and produce payoff.
3. Valuing sustainability of traditional practices in a society-centric approach and refining them via biomimicry ideas.

SSC provides pathways to fast-tracking progress in achieving the goals of marine conservation and sustainable development. Akin to the 'smart city' campaign, the SSC envisages using modern technologies but is more inclusive of activities that optimize coastal zone management, seek habitat restoration, promote biodiversity, control illegal activities at the sea, and facilitate knowledge-sharing for sustainable blue economic growth and a better quality of life for the society.

With technological innovations monitoring of the ocean from remote locations is entirely possible. A variety of platforms may be used from which equipment and sensors can be deployed to measure ocean conditions. Satellite data can help in tracking "Illegal, Unreported and Unregulated” (IUU) fishing, movement of illegal fishing vessels, facial recognition to identify culprits, and drones to warn off poachers and intruders. Ending IUU that currently amounts to 20% of the global fish catch worth US$ 23.5 billion (FAO, 2017; WEF, 2017) is the target 14.4 of the UN SDG. Artificial Intelligence particularly holds the promise of helping in electronic surveillance and enforcement regulations and creating enabling conditions to achieve more with less resources. Fernandes-Salvador et al. (2022) have highlighted the practical importance of applying artificial intelligence techniques to capture fisheries, especially for improving traceability of fishery products, fishing gears and good practices. These authors have outlined the potential of such technology applications for employment opportunities for skilled professional such as fresh graduates.

However, unlike the smart city, the SSC is based on green recovery and continued investment in blue-green development shaped by the sustainability paradigm. This necessitates a fundamental system-wide transformative change in management across biological, ecological technological, economic, and social factors from local to global level to have an actionable impact (IPBES, 2019). However, without supporting policies and commitments it will be difficult to achieve the milestones, goals and trajectories by 2030 and beyond.

Ocean-based developments happen to coincide with the ground-breaking innovations that offer emerging technologies in areas of fifth-generation wireless communications and connectivity, 3D printing, sophisticated sensors, Internet of Things (IoT), Big Data analytics, robotics, nanotechnology, and biotechnology in addition to artificial intelligence. Relevance of some of these tools in specific applications in marine monitoring have been recently demonstrated by earlier studies (Watnabe et al., 2019; Xu et al., 2019). Adoption of these advanced technologies will pave the way for increased digitalization and machine-to-machine communication for automation and improvement of efficiency and productivity. However, in view of the slow pace of progress in meeting the target set for conserving 10% of the marine environment, it is unlikely that the world will be able to effectively protect 30% of the sea without a path-breaking approach provided by these emerging technologies. This is a vast sea area to effectively monitor in real-time. Thus, the technological interventions should supplement the conservation efforts through nature-based solutions and not replace them, by offering more efficient means of monitoring and enforcement through significantly enhanced capabilities. BBB strategy can guide the deployment of technologies to a faster recovery and strengthen the resilience in the MPAs covering 30% of the global ocean. Ways in which this can be achieved are summarized in Table 1.

Table 1. Application of IR4.0 technologies to address challenges associated with the ocean. Green represents ongoing implementation of the technologies. Grey refers to early stages of trial involving the technologies. Adapted with permission (WEF, 2017).

IR4.0 technologies	Application areas				
	Sustainable fishing	Pollution control	Habitat protection	Species protection	Ecosystem resilience
Advanced sensors	🟩	🟩	🟩	🟩	🟩
Drones & autonomous vehicles	🟩	🟩	🟩	▨	🟩
Artificial intelligence	🟩	🟩	🟩	🟩	🟩
Internet of Things	🟩	🟩	▨	▨	▨
Robotics	🟩	🟩	🟩	🟩	▨
Computing & data analytics	🟩	🟩	🟩	🟩	🟩
Advanced materials		▨			
3D printing			▨		
Biotechnologies	▨	🟩	▨	▨	▨
Blockchain	▨	▨	▨	▨	

Application of some of these technologies will take time as many countries need to invest financial resources and develop human capital. Use of sensors for measurement of physical and chemical variables and conditions is becoming more popular since marine management systems require real-time monitoring for environmental quality. The oceanographic buoy using sensors record salinity, temperature, dissolved oxygen, among other variables. Sendra et al. (2015) have reviewed the use of low-cost sensors in collection and processing of actionable marine environmental data by wireless connection of the buoys to base stations. Optical sensors are a new addition to the growing list of sensor types. These are particularly useful in monitoring fishing operations and state of the ocean habitats. Because of their zoom capabilities, resolving images even when visibility is low, for detecting activities at the sea, especially IUU, discharge of waste, capture of endangered species can be controlled. MPAs, especially the marine biodiversity spots that are considered eco-regions such as tropical seagrass meadows and coral reefs require rigorous monitoring to maintain their ecological communities and functional links. Cusack et al. (2021) have reviewed the range of applications of modern technologies in managing the ocean resources. Monitoring of enforcement measures is critical in evaluating their effectiveness and deciding further improvement strategies.

Blending of BBB-IR4.0 can also assist restructuring of economic recovery packages focussing on conservation of marine natural capital, especially biodiversity, and sustainable benefits to the society. Investment in NBS for marine ecosystems as outlined in an earlier communication (Mustafa et al., 2019) have provided a roadmap for implementing practical means of improving resilience in marine ecosystem services. The world is lagging in valuing the marine natural capital which is important for integrating the cost-benefit analysis in decision-making. Progress in NBS through BBB-IR4.0 synergy can contribute a great deal to building resilient coastal communities and strengthening the blue economy while at the same time advancing the goals of the Paris Climate Agreement for a low-carbon future.

Climate change and environmental variability are important factors in the BBB approach. Actions should, therefore, be taken holistically across several dimensions, particularly including long-term policies for reducing GHG emissions, protecting marine biodiversity and restoring marine ecosystems.

Ocean health is a fundamental attribute for resilience of marine critical habitats and species. Products or benefits derived from the sea should not be viewed only as a commodity but a vital ecosystem service for the long-term benefit of human society. A fish harvested from the sea and processed into a dish has been a part of the ecosystem and has used the ecosystem services before it was caught. Currently, there are no structured mechanisms for mainstreaming marine natural capital in sustainable development of ocean resources. There is an urgent need to pay attention to this matter as highlighted by Mustafa et al. (2021), rather than delaying and risking future tipping points in resources such as small pelagic fisheries that provide sustenance to many coastal communities around the world.

Addressing climate change requires strategies for mitigation as well as adaptation. Mitigation measures envisage interventions to reduce the GHG emissions and to enhance carbon sinks. Adaptation involves adjustment in natural or human systems to the effects of climate change to reduce risks and to make use of the opportunities available (IPCC, 2021). There is no denying the fact that measures taken for climate change mitigation benefit the marine ecosystem and the society. This has been documented in specific cases (EF, 2018) in terms of: a) Increased biodiversity and productivity, b) Increased resilience of marine ecosystem services, c) Fisheries spill-over that enhanced catch per unit effort, d) Benchmarking of environmental health by providing controls against which the effects of human activity and regulatory measures could be evaluated, e) Protection of geological features or processes, f) Maintenance of cultural values associated with the ecosystem services, g) Improved opportunities for recreation and eco-tourism, and h) Greater avenues for environmental educational and scientific observations. The significance of adaptation strategies for the communities benefitting from the natural capital has been highlighted by Metcalf et al. (2015). It is evident from their work that success in reducing the vulnerability of coastal communities to marine climate change requires some intrinsic capacity of the people to adapt. The process of adaptation can be assisted by removing barriers and developing enablers to adaptation. However, knowledge of communities, especially their socio-economic status, resource dependence, familiarity with prevailing issues and willingness to accept change are among the important factors. It is easier to bring the communities on board if measures do not restrict the opportunities for livelihood and income generation (Adger et al., 2009). Managing trade-offs in such matters is crucial for a long-term implementation of strategic plans. Limiting pressure on a marine ecosystem service or resource should, therefore, be accompanied by supporting aquaculture that is more resilient to climate change, earns premium price to the producers, finds lucrative market and improves the earning capacity of the community. Metcalf et al. (2015) have presented synergies and trade-offs in adaptation strategies and showed how increased employment and income through aquaculture reduced the dependence on the natural capital of the ocean. It also lessened the potential vulnerability of the coastal communities to the impacts of climate change on livelihoods and social-ecological systems. While aquaculture can be practiced as a sustainable source of income, its significance increases when regulations require closure of fishing operations during brief periods such as the breeding season that will result in long-term increase in the catch per unit effort.

Exclusive Economic Zones and MPAs provide sovereign rights to countries to redouble their efforts to direct the resources needed for conservation of marine natural stocks through regulations and their enforcement to mitigate the effects of climate change. This must go together with adaptation strategies for natural systems as well as specific social-ecological systems. These strategies can focus on climate change impacts such as ocean acidification and warming, sea-level rise, geographical shifts in species distribution, oxygen deficit, decreased productivity, and increase in the frequency and intensity of extreme weather events confronting communities at the seafront. The adaptation benefits will become more evident when human welfare resulting from managed marine ecosystems is compared from the unmanaged ones.

Often, the policymaking and enforcement institutions develop measures for implementation that are not backed by any structured system of monitoring and reporting. In particular, the marine enforcement is a victim of this anomaly. Monitoring methods should be integrated in the whole regulatory framework to assess whether additional measures or adaptations of action plans are required, and to evaluate which measures are effective under the prevailing situations. Monitoring systems are improving, and if implemented properly, they can deal with the complex and dynamic nature of the marine ecosystems. For example, the 'Global Fishing Watch' is a platform that uses cutting-edge technology to visualise and track fishing activity in real-time and offers free data sharing. 'Marine Ecological Research Management Aid' (MERMAID) is the online-offline platform that enables scientists worldwide to collect, analyse and share data from coral reef surveys. The 'Spatial Monitoring and Reporting Tool' (SMART) has been developed for marine enforcement and IUU control. On a local area basis, marine buoys are a practical device for real-time monitoring of marine water condition. Marine observations and data integration are now much easier with Light Detection and Ranging (LiDAR), Infrared Acoustic (IRA) and Automatic Identification System (AIS) technological tools.

A leading example of deployment of disruptive green technologies is Canada's Ocean Supercluster initiative (COS, 2021). It is a national development-oriented cluster focussing on growing the ocean economy digitally and in sustainable ways. These programs include transformation of fisheries, aquaculture, and marine bioactive compounds among other sectors. Based on intensive uses of sensor technology and real-time analytics, this ocean initiative is intended to harness the benefits of blue economy in multiple areas. Of particular interest is sustainable protein production and aquaculture feeds on a commercial scale without any significant impact on the environment. The inclusiveness of the program facilitates a broader participation of stakeholders to support start-ups, scale-ups and all enterprises that can link up in the value chain. It is already driving cross-sectoral cooperation and fostering an innovation ecosystem that will propel the ocean economy of Canada on an unprecedented scale.

Since the time for transformative actions is limited, breakthrough ideas that can generate in an innovation ecosystem are urgently needed. The sixth assessment report of IPCC (2021) recommends action to be taken this decade to steadily reduce GHG emissions from now onward until 2030 and accelerate progress towards net-zero emissions by 2050. Without actions on this matter, the ongoing average warming of 1.1°C over the pre-industrial levels will reach the 1.5°C threshold, leading to catastrophic situations (IPCC, 2021). The innovation ecosystems should remain focused on new ways of building resilience in coastal blue carbon stocks with multiple co-benefits, engineering solutions consistent with ecosystem-based adaptations, conservation and rehabilitation of marine critical habitats and leveraging marine biodiversity to provide healing touch to the condition of the ocean. An important area that deserves attention is institutional linkages with society through new and effective arrangements that can lead to the blending of experience and scientific knowledge in a participatory process. Meaningful cooperation that will so ensue will make a real difference to the ocean ecosystem.

Knowledge gaps and uncertainties

Since most of the ocean remains unexplored, it is the least understood ecosystem of the Earth. There are vast knowledge gaps across marine biophysical systems and many uncertainties related to the impacts of climate change such as ocean acidification, warming and deoxygenation, redistribution of biodiversity, adaptive capacities of different forms of life in the sea and the trophic web of life.

Only research can address these knowledge gaps and address the uncertainties. There are technological constraints and enormous costs in exploring the complex ocean environment, especially the deeper part. However, research is progressing with the help of more sophisticated underwater vehicles, sonar, robots equipped with artificial intelligence and sensors and other tools of disruptive technologies. Such research poses questions, aims at answers and evaluates their degree of certainty to make sure that they are well-grounded (NASEM, 2019). In the case of the ocean, a major challenge is to accurately predict its future conditions in order to be able to devise interventions. This process can be accelerated through innovation and by changing the fundamental rules or procedures, or evolution of new enabling technologies to achieve reliable results so fast that was not possible by previously established research protocols. Technologies are needed for rapid progress in ocean exploration and the search for solutions. A recent example is the remarkable work done by a group of researchers on marine environmental DNA (eDNA) (Ames et al., 2021). Their assumption that organisms living in the ocean leave behind traces containing their eDNA which is detectable in water samples collected from the sea was experimentally verified. It is a great leap forward in detecting the unseen and unknown millions of ocean species from the small bits of DNA filtered out of water and identified from the next generation sequencing. Such innovative research is not only relevant to marine biodiversity cataloguing but a solution to many problems such as identifying endangered and invasive species, marine conservation, fisheries, and developing jellyfish warning systems in areas where jelly stings frequently occur.

The power of innovation in the realm of ocean science cannot be overstated in search of discoveries needed to mitigate the enormity of impacts that this ecosystem has been subjected to. The most formidable of these is climate change. The ocean has absorbed more than 90% of the heat accumulated in the Earth's atmosphere and 25% of the carbon dioxide released from the fossil fuel consumption, resulting in seawater becoming warmer and 30% more acidic since the industrial revolution, and the formation of 500 'dead zones' where oxygen deficit has reached a level that most marine species cannot survive (Jones, 2019). Reversing the major shifts in ocean temperature, acidification, deoxygenation, and current pattern demands serious management actions and harvesting the potential of innovations. The global community has forged agreements on reducing the emissions and decarbonization that will help the health of the ocean. The scope of this article is limited to discussion about the enforcement of 30% of the global ocean in 10 years from now in smart ways so that the oceanic habitats such as seagrasses, mangroves and coral reefs, and their associated communities and food webs can contribute more effectively to carbon sequestration and biodiversity, and the reckless exploitation of fisheries resources is brought under control. Most of the oceanic data currently available supports a knowledge-based approach to management even as the scientific community explores new ways of generating additional information of significance in predicting ecosystem changes. The important next step is data mining and extracting evidence needed to model the dynamics of ocean ecosystem and predicting consequences of management interventions to chart a pathway to a sustainable future ocean. This entails a fundamental change in the methods of knowledge creation and testing its validity to be able to influence decision-making. Retrospective examination of scientific data and projections to verify existing conditions can test the accuracy of prospective scenarios and bolster the confidence and certainty in current methods for projecting models of future conditions and extrapolations. Using models based on the past 10-30 years of data to compare with the prevailing ocean condition will provide a comparative basis for testing the predictive validity of the models. Convergence of the outcomes generated by the models should change the rules of the game in favour of decisions and actions in real time. Although in a somewhat different context, the views expressed by Bean et al. (2017) are supportive of this suggestion. These authors proposed that studies on the ocean over the last century have resulted in a critical scientific understanding of this ecosystem and the changes that human impacts have brought about. By leveraging the advancements in technologies and methodologies in recent years this vast volume of data can be categorised and organized to generate integrative models, regional and global portals, and decision-support systems. These models built on marine monitoring data are useful for assessment of the state of the ecosystem (de Jonge et al., 2006), vulnerability to climate change and predicting potential adaptation and mitigation strategies. This has been amply demonstrated in the monitoring of marine biodiversity and ecosystem function in the European Union, leading to adoption of the modelling approach as an instrument of policy performance and review (Hyder et al., 2015; Lynam et al., 2016).

We believe that integrated assessment models of the ocean condition resulting from various pressures, particularly climate change, will continue to improve over time with more focused research. There are, obviously inherent complexities in balancing the trade-offs among the sustainable development requirements, but the solution will continue to examine the nature of driving forces and inclusion of stakeholder interests into the modelling process. Exclusion of any of the dimensions of sustainability or underestimation of the participatory processes in managing the coastal zone and inshore areas will adversely impact the model outcomes and their relevance (Doukas and Nikas, 2020).

Due to sustained impacts ocean biodiversity and ecosystem have degraded to a level that requires not just the intensification of incremental fundamental and applied research but also path-breaking 'disruptive' and all-inclusive approaches to conservation and restoration. Modelling of marine biodiversity scenarios and effects of environmental variability through the tools of predictive analytics can yield information of practical importance (Coll et al., 2020). It is better to continue investing in research to strengthen the knowledge-data matrix in the interest of more effective conservation measures and outcomes. With more than 99% of the habitable area of the ocean remaining without even basic data on biodiversity, the use of new technologies will help in bridging the glaring knowledge gaps (UNESCO-IOC, 2021). The BBB goal is worth pursuing through carefully planned strategies for sustainably managing the ocean in the face of 21st century challenges. Blending disruptive technologies with multiple sources of knowledge in supporting the BBB is the way forward in conserving and restoring the ocean and its natural capital as an adaptive process and not as a destination bound by timelines. This could be a game changer in creating enabling conditions for enforcement of marine conservation targets by 2030 as a milestone and continuing beyond it with additional targets. The Paris Agreement aimed to limit the increase of global average temperature to 1.5°C and attain net-zero carbon dioxide emissions by 2050 to be able to protect not just the oceans but the entire planet from devastating consequences. There is a need to exercise caution in implementing marine conservation based on the theories especially those pertaining to species and marine ecosystems that are not supported by data metrics, and to inculcate an unwavering quest for knowing the unknown of the ocean.

Eco-engineering solutions and the living coastline

In order to open avenues to a broader section of society to take part in ocean solutions, the SSC encourages the application of biological and ecological principles and indigenous practices to engineering designs. This is beginning to yield products that are proving helpful in marine ecosystem protection and restoration. Since the problems are examined holistically through interdisciplinary perspectives, alternatives are considered so as to be able to select the best practical option. The scope for innovation in this area is unlimited. Eco-engineering is unlike geoengineering that envisages large-scale interventions in the Earth systems, including oceans, with the aim of reducing the effects of climate change but without supporting scientific evidence and proof-of-concept.

Many artificial structures can be seen along the coastlines. The most common are the sea walls (vertical or sloping), breakwaters, groynes and jetties, rock revetments and rocky outcrops or artificial headlands. Such structures are developed for specific purposes of society, but most are detrimental to marine critical habitats. Turning these so-called ‘grey’ structures into ‘green’ structures will contribute to a gradual process of partial transformation into ‘living coastlines.’ This can happen by eco-designed tiles along the seawalls or other structures or by appropriately designed objects for placing at the sea floor. Many marine species can establish substrate connectivity with the hard grey structures and reduce the erosional influence of seawater movement caused mainly by currents. The habitat mosaic that so develops supports marine biodiversity and abundance while prolonging the lifespan of the physical structures. The significance of three-dimensional artificial microhabitats for fish through experimental trials has been observed by Arsin et al. (2018) and the need for living coastlines is discussed in a recent article (Mustafa et al., 2020). Quantitative data on how topographic complexity drives species diversity published recently (Bradford et al., 2020; Strain et al., 2020) provide support for the use of 3D-printed structures mounted on hard surfaces. These eco-designed tiles enhanced biodiversity as well as abundance, and the performance was further increased when these structures were seeded with oysters. The role of living shoreline in improving water quality, providing habitat, and increasing biodiversity has been outlined in an earlier communication (NOS, 2021). Living shorelines also provide many other benefits, including naturally adaptive coastal protection, building of defence systems as sea level rises, and increasing marine habitat and spawning areas. The 3D printed coral reefs have opened a new dimension to restoration of marine ecosystem (Klinges, 2018; Mustafa, 2021). These structures can be moulded into complex shapes resembling coral reefs to support new growth of corals and associated marine communities.

Eco-engineering can contribute to solutions against the effects of sea-level rise which is a problem with wider implications that include coastal erosion and inundation of coastal habitats, flooding of wetlands, saltwater intrusion in aquifers, soil salinization, and loss of critical habitats for some species of plants and terrestrial animals. Impoverished coastal communities are adapting by using traditional methods of stabilization of coastline or shifting to higher grounds.

While the solutions inspired by the roles of mangrove and reefs are well-known due to conspicuous features of these marine critical habitats, other designing options that are recently emerging are based on the structural attributes and functions of species like oysters. Structures built from hard materials with design features resembling oysters (BI, 2021) are not only helping in the proliferation of oyster populations but also protection of shoreline from erosion and inundation. Erosion can reduce land elevation and increase inundation, and the stabilization of coastlines by the above-mentioned means can help adapt to local or relative sea level rise. Biomitigation measures or living coastlines reduce land subsidence and counter mechanical forces on the shore to protect the adjoining land even as the world continues to implement long-term measures to control GHG emissions and warming that cause thermal expansion of water and melting of glaciers. A commonly seen adaptation measure is a concrete or stone-stabilized seawall. However, nature-based solutions in the form of mangroves and seagrasses are more cost-effective and long-term solutions that can be supplemented by 3D structures that facilitate growth of shelled organisms capable of resisting the hydrodynamic forces.

Eco-designing is a dynamic area and as research intensifies in this field, a wide range of options will continue to emerge. However, repeated field trials and a long-term monitoring program are necessary to provide quantitative data on the specific benefits of these structures. Selection of materials and design should consider hydrodynamic conditions of the area, chemical properties of water (salinity and pH) and biological features in and around the area for possible settlement and colonization of marine species. In view of a general paucity of information on the exact nature of influence of these structures, deploying them as a substitute to natural habitats or to providing a ‘healing touch’ to the ecosystem will depend on results of the trials.

Nature-based solutions, sustainable cultural practices, and eco-mimicry

NBS and certain traditional practices that use marine resources for food and sustenance without negatively impacting the environment and depleting the natural capital of the ocean should be promoted. Indigenous communities must be assisted to enjoy better dividends as an incentive for them to remain committed to sustainable marine practices. In this context, it should be emphasized that seaweed farming produces 32.4 million tons per year, contributing 51.3% of the total production of marine and coastal aquaculture (Chopin and Tacon, 2021). A method used some by Indigenous communities in Borneo uses a unique buoy comprising wasted plastic bottles and kayaks (canoe) to harvest this seafood. Since 99.5% of the global supply of seaweed comes from Asia (Chopin and Tacon, 2021), this is a significant activity that benefits food security and tends to offset the effects of climate change on the ocean ecosystem.

Indigenous communities have been fishing for thousands of years. They have relied more on traditional ecological knowledge gained through a direct contact with the marine environment rather than on technology. Some of the primitive tools and methods that are still in use have limited capacity for capturing fish, thereby sparing enough fish in the sea to recruit and replenish the fished stock. Indigenous communities are less selective of the species fished and they have hunted different species at different times of the year which gives the stocks a recovery time. This is due to the seasonal cycles of aggregation, spawning migration to inshore areas, flow of juveniles from estuaries to deeper waters, schooling behaviour of small pelagic species such as sardines and mackerels, and the behaviour of predatory species like tuna and ribbon fish chasing the prey (Hickey, 2006; Friedlander et al., 2013), Generally, Indigenous communities have customary rules embedded in their inherited traditions. The fisheries conservation elements in their practices can be incorporated into a co-governance system as a reconciliation process (Atlas et al., 2021) allowing them to continue harvesting in return for their cooperation in management. There are successful case studies worldwide where conservation and habitat restoration efforts in a co-management arrangement have resulted in stock rebuilding, improved harvests, and socio-economic benefits. The findings reported by Chen et al. (2020) based on their work in China, Samoa and Vietnam suggest that what is good for the marine ecosystems is also good for society.

Achieving 30% effectively enforced MPAs will be a significant contribution to restoring and conserving marine critical habitats and biodiversity, and ocean functioning and hence sustainability. The potential benefits are estimated to be six times more sustainable seafood harvest by 2050, 15 million new jobs by 2030, forty times more renewable energy by 2050 and US$ 15.5 trillion from sustainable ocean investments by 2050 (Stuchtey et al., 2020).

Working with traditional communities wherever possible and blending new designs inspired by nature (biomimicry) offer locally effective simple solutions, albeit on a small scale, to the complex problem of trade-off analysis in marine ecosystem services that requires the application of scientific, economic, and social approaches and devices. Considering the heterogeneity of marine ecosystems and geographical disparities in socioeconomic conditions, this analysis will be time-consuming and challenging but our actions must be guided by logic and reason. There is a growing interest in emulating systems, processes, models, or other elements of nature for the sake of solving complex problems. While presenting insights into the importance of putting nature's lessons into practice we must visualize nature in three ways suggested by Benyus (2009): a) as a model for inspiration for designs and processes aimed at problem-solving outcomes, b) as a measure based on biological and ecological events, parameters and metrics to evaluate the relevance of the innovation, and c) as a mentor for observing and valuing nature. Practically, there are cases where biomimicry based on ocean ecosystem is proving successful. Some case studies reported earlier (BI, 2021) can be mentioned here to support the argument. 'ECOncrete' is a three-dimensional design that facilitates biogenic activity and imparts strength to the structure. There can be many adaptations according to beach or rocky shores. Interestingly, the biomimicry concept can be adapted using simple methods or advanced technology tools according to the local capacities. Thus, the production of 'Biotextile fibers' as an alternative to petroleum-based synthetic fibers uses DNA technology to reflect the pathways in Discosoma, a coral relative. This can potentially reduce more than a billion tons of CO_2 equivalent yearly in the manufacture of dyes and the large volume of waste that it generates. Likewise, observations on mantis shrimp that uses its chitin-enforced appendages to crack open the hard-shelled prey without damaging its own structures are used in developing light-weight underwater structures and saving fuel economy for developing turbines. Other examples are pollution-sensing robotic fish and 'robolobster' for designing underwater robots and models of a self-sustained jellyfish-like ocean city. In this context, we need to create pathways for systematically organizing and applying fundamental and applied knowledge based on exploratory principles and verifiable means.

Enabling conditions

It is easy to appreciate the benefits of effective marine conservation, but many countries lack the means of offering alternative livelihoods, mechanisms and trained human resources for deployment of modern devices and tools of management. International cooperation in capacity-building programs is a key to reshaping ocean management consistent with the 21st century challenges. The significance of information exchange and cooperation cannot be overemphasized, especially in identifying knowledge gaps, addressing pertinent questions, advancing the action research agenda based on available scientific evidence, experiences, perspectives and reflections on issues and conservation priorities. There are appropriate bodies within the ambit of the United Nations that can support international cooperation and technology transfer as well as promoting a shared vision of knowledge capacity-building across the regions and worldwide at cheaper and faster rates through digital technologies and real-time connectivity. When countries see benefits accruing from collaboration, they will be more inclined to review and reprioritise their national policies and invest in bridging the digital divide, improving transparency, and creating opportunities for new careers and employment in multiple fields. In this context, it is necessary to emphasize that the knowledge generated thus far provides a strong basis for linking marine biodiversity and geodiversity with different types of impacts and establishing trends. The power of predictive analytics that is growing in recent years from data science tools, computer simulations, statistical modelling and machine learning can be leveraged to generate future scenarios pertaining to marine biodiversity and ecosystems. With the inclusion of multiple parameters and 'Big Data' technology, the analysis of new or recurring trends or outcomes is now much easier compared to that in the past and the processed data can be utilized in conservation and restoration policies and practices. However, there is a certain amount of unpredictability caused by the effects of climate change that may require making strategic modifications, but marine management systems are inherently adaptable to incorporate changes as and when needed in advancing the scope and effectiveness of actions.

Data analytics and simulation modelling can generate enhanced understanding and help in evaluating complex systems to project scenarios with a greater degree of accuracy and confidence. To illustrate the effectiveness of these models, even one or two- decade-old data on marine ecosystem condition or a geospatial biodiversity case scenario can be processed to generate models which can be compared to the existing condition. This will provide a direct and concrete proof of accuracy of the simulation approach. It is a new form of generating scientific information and is not tantamount to acting without evidence. In fact, it will facilitate translation of precautionary approaches into managerial actions by capturing the common-sense notions backed by scientific reasoning in support of a precautionary approach. Precautionary measures have yielded positive outcomes for localized fisheries, biodiversity, and rehabilitation of marine critical habitats (Vander Zwaag, 2018). It does not reverse the burden of scientific proof but places the onus on contradictory approach (Vander Zwaag, 2018). With the review mechanisms that are generally integrated into environmental management structures, adaptive management can be accepted as a part of the whole strategy for sustainable ocean solutions.

Institutions of higher education can take advantage of the world's focus on the ocean sustainability in the current decade by cultivating links with the agencies that offer training and capacity-building. This will be a major step in harnessing the power of knowledge through partnerships to produce impacts. The key steps in this endeavour will be to create mechanisms for examining self-capabilities and reviewing existing research programs focused on topics that value ocean health, support the blue economy, and influence policies consistent with the aims and objectives of SDGs and the Ocean Decade. Important research and development areas requiring invigoration include digital ocean mapping, ocean observation systems, ocean dynamic equilibrium, data-sharing mechanisms, early ocean hazard warning, ocean in earth observing systems, technology transfer and capacity-building, science and policy interface, and research and development aligned with the blue economy. Some of these have been mentioned previously (Ryabinin et al., 2019).

New forms of international agreements are needed for meaningful results and tangible outcomes since there are vast knowledge gaps in our understanding of the ocean, and the disparities among countries in their scientific priorities and capacities to acquire oceanic knowledge are also glaring. This issue must be addressed if the world is to act collectively to move towards global change. SDG17 (Partnerships for the Goals) makes it abundantly clear that global partnerships and cooperation are vital for realizing the objectives and targets of all the SDGs. The key steps are access to science and technology, knowledge-sharing, and innovation. There is a need to establish facilitation mechanisms for this purpose involving realistic and productive international cooperation. Many tropical countries do not possess the necessary technological capacity but have a treasure trove of marine biodiversity and ecosystem services that deserve attention. An outstanding example is the 'Coral Triangle', a marine area of enormous size (5.7 million km2) at the equatorial confluence of the Pacific Ocean and Indian Ocean (Green et al., 2011). It is shared by 6 countries- Indonesia, Malaysia, Philippines, Timor-Leste, Papua New Guinea, and the Solomon Islands, and is a marine biodiversity hotspot, with many endemic species unique to the region. There is an increasing interest in marine bioprospecting and studying the effects of climate change in the Coral Triangle, but these require advanced technologies through international cooperation with countries that have made progress in applying IR4.0 technologies. There could be a 'win-win' situation if agreements are reached on benefit-sharing, intellectual property rights and mutually developing this sector of blue economy through open access (Worm et al., 2006; Mustafa et al., 2019). The Ocean Decade envisions intensifying scientific knowledge, building infrastructure and nurturing international cooperation for a sustainable and healthy ocean. In fact, progress in all the actions outlined below is required under the Ocean Decade depends on this fundamental requirement:

1. Mobilizing scientific research on critically important topics related to the ocean for the Agenda 2030 and Vision 2050.
2. Collecting and synthesizing existing research data and documentation, defining trajectories and trends, and identifying knowledge gaps deserving priority for future research.
3. Generating evidence and developing user-centric solutions.
4. Undertaking new research and nurturing cooperation within and across the world oceans.
5. Bridging science, policy and societal dialogues through data-sharing, and information and communication tools.
6. Developing new co-designed research approaches, methods, and strategies.
7. Enhancing coastal resilience for marine ecosystems and people relying on the resources of the sea for livelihoods.

Since the Ocean Decade is designed to be a participative and transformative process, the framework of agreements should be structured with clear goals and targets agreed upon among the agencies involved in development cooperation. With supporting national policies, international cooperation will proceed without constraints. There should be mechanisms for real-time data sharing and monitoring of progress in the implementation of agreed frameworks. There are, of course, integrated online platforms to advance the flow of information and to prevent unnecessary obstacles to cooperation. Accountability mechanisms should also include clauses for physical verification of progress in beneficiary countries by the supporting agencies, and for the consequences arising from default. Without such mechanisms, knowledge gaps among nations will expand further since disruptive technologies are rapidly advancing in industrialized countries while resource-rich nations remain reluctant in granting access to marine biodiversity in their exclusive economic zones.

Conclusion

Conserving and restoring ocean health is a global responsibility that cannot be ignored. Protection of 30% of the global ocean through MPAs by 2030 is needed to safeguard marine biodiversity, prevent collapse of fisheries, and build resilience in marine life to help it adapt to changing climate and assimilate other impacts. It is an enormous task that can only be delivered using a plurality approach, especially advanced technologies. The potential of new strategies should be explored for actions that can make a real difference by capitalizing on the growing familiarity and significance of digital technologies. Human impacts on the ocean are enormous and without major interventions there is a real concern about the tipping points for many ecosystem components, leading to a situation where the world risks seriously suffering from loss of vital marine ecosystem functions and services. The potential of oceans as a source of solutions should be explored by applying new ideas and perspectives. In this context, the SSC becomes increasingly relevant since it seeks to mobilize multiple approaches, namely the traditional sustainable practices, eco-engineering inspired by biomimicry designs and disruptive technology with a policy support to deliver enduring solutions. New ways of generating knowledge for managing a largely unexplored ocean are suggested as a way forward. Preserving the biodiversity and ecosystem functions of MPAs benefits marine areas globally through the so-called ‘spill-over’ of larvae and other biological gains accruing from enforcement. While the resilience of ocean ecosystems is remarkable and their ability to adapt to environmental change is significant, these attributes have limits. We must move consistently and congruently towards transformative action in ways that integrate natural and human (social-ecological) systems so that marine ecosystem processes continue to function, and socio-economic services continue to flow in a co-management framework and dynamics. Most of the ocean remains unexplored but whatever knowledge is available provides a basis for rational actions. This can be supplemented by action research, participatory efforts, and new methods of generating knowledge.

Everyone has a role to play in achieving ocean sustainability. Scientists can assist by providing deeper insights into the dynamics of ocean ecosystems and prioritizing actions to protect the more vulnerable critical components and collectively designing implementable short-term, medium-term, and long-term recovery plans. Scientific data of the past decades can be used to verify the accuracy of the generated models in projecting the present scenario and to convincingly model the anticipated future conditions of the marine ecosystems for remedial action proactively. Making a retrospective analysis for prospective action can serve the cause of the BBB when there are vast knowledge gaps in ocean science.

The significance of ocean-based solutions to climate change will continue to increase with the expansion of knowledge about this massive ecosystem. The issues of ocean health and climate change are interconnected. While the ocean is key to addressing climate change, mitigating climate change is also critical for the ocean's own stability. For this reason, it makes sense to focus on the problems facing the ocean, but also exploring potential solutions that the ocean offers to combat the climate change. These solutions will enable the ocean to continue to serve as a cradle for the most varied biodiversity on Earth, provide half of the world's primary production, retain its capacity as the thermostat of this planet and regulate the vital hydrological cycle.

All the stakeholders, including scientists, academics, students, policymakers, managers, thinkers, writers, journalists, and the corporate sector can create an alliance for ideas and actions to build momentum for creating a real change in the ocean's outlook as an integral component for sustainable development. This can lead to development of more organized forms of 'ocean citizen science' programs that can present scientific knowledge in a form that will be more acceptable to policy and decision-making institutions and tailored for wider audiences. It is the need of the hour to motivate all sections of the community to engage with the ocean environment and play their part in its sustainability. Awareness of how anthropogenic activities impact the ocean, and the societal consequences of the ocean's response are becoming more broadly known, but challenges remain in supporting communities take appropriate actions. In view of the non-linearity of many factors in the social-ecological systems, there is a need to develop integrated models defining geospatial and specific scenarios for strategic interventions.

COMPLIANCE WITH ETHICAL STANDARDS

Authors' Contributions

The authors contributed equally to this paper.

Conflict of Interest

The authors declare that there is no conflict of interest.

Ethical Approval

For this type of study, formal consent is not required.

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