PNAS NEXUS

PNAS Nexus, 2025, 4, pgaf110
https://doi.org/10.1093/pnasnexus/pgaf110
Advance access publication 20 May 2025
Perspective

# Marine ecosystem services and natural capital in China: Opportunities for improved understanding, valuing, and policy

Laurence J. McCook [a,b,c,*], Lyutong Cai [d], Chung Wing Yeung [e], Shang Chen [f], Zhiyun Ouyang [g], Put Ang [h], Michael Bordt [d,†], Ling Cao [i], Zhu Chen [j], Baolong Han [g], Hui Huang [b], Xinming Lei [b], Jiansheng Lian [b], Feixue Li [k], Guifang Xue [l] and Peng Zhao [m]

[a]College of Science and Engineering, James Cook University, Townsville, Queensland 4811, Australia
[b]South China Sea Institute of Oceanology, Chinese Academy of Sciences, 164 Xingangxi Rd, Guangzhou 510301, China
[c]Seneca Impact Advisors, 64 Connaught Road, Hong Kong SAR 999077, China
[d]Statistics Division, United Nations Economic and Social Commission for Asia and the Pacific, United Nations Building, Rajadamnern Nok Avenue, Bangkok 10200, Thailand
[e]Climate Action, AVPN, 33-35 Hillier Street, Sheung Wan, Hong Kong SAR 999077, China
[f]First Institute of Oceanography, Ministry of Natural Resources, 6 Xianxialing Rd, Laoshan District, Qingdao 266061, China
[g]State Key Laboratory of Urban and Regional Ecology, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, 18 Shuangqing Rd, Haidian District, Beijing 100085, China
[h]Institute of Space and Earth Information Science, The Chinese University of Hong Kong, Fok Ying Tung Remote Sensing Science Building, United Rd, Hong Kong SAR 999077, China
[i]State Key Laboratory of Marine Environmental Science, Xiamen University, 4221 Xiang'an South Road, Xiamen 361102, China
[j]Guangdong Ocean Association, 547 Nanhua E Rd, Haizhu District, Guangzhou 510220, China
[k]School of Geography and Ocean Science, Nanjing University, 163 Xianlin Avenue, Qixia District, Nanjing 210023, China
[l]KoGuan Law School, Shanghai Jiao Tong University, 1954 Huashan Road, Xuhui District, Shanghai 200240, China
[m]School of Marine Science and Engineering, Hainan University, 58s Renmin Avenue, Haikou, Hainan 570228, China
*To whom correspondence should be addressed: Email: laurence.mccook@jcu.edu.au
[†]Michael Bordt sadly passed away on August 5, 2021, before this manuscript was completed.
**Edited By:** Edson Severnini

## Abstract

This paper reviews the context and prospects for markedly improved sustainability of marine ecosystems and resources in China, based on accounting of marine ecosystem services and natural capital along with supporting policy and governance frameworks, in turn based on existing approaches in China's terrestrial social-ecological systems.

Such integrated accounting, policy, and governance would provide a unique, novel, and innovative approach to regional-scale, sustainable ocean management. China is uniquely placed to implement such accountability, given the extensive adoption of accountability in terrestrial landscapes and the strong commitment to "ecological civilization" at the highest levels of national policy.

Specifically, the paper outlines:

1. The current, seriously degraded state of marine ecosystems and resources in China, largely due to economic drivers that ignore the valuable economic services provided by healthy marine ecosystems;
2. The critical context of, and high-level commitment to, China's considerable development of environmental accounting, implementation and governance frameworks in terrestrial landscapes;
3. Existing approaches for assessing marine natural capital in China, and the relationships between them;
4. Currently available assessments;
5. Current governance arrangements for marine ecosystem management in China.

The paper then provides a potential implementation pathway for a system of standardised, nationally integrated, provincially-implemented marine environmental accounts, policy and governance, adapted from existing terrestrial arrangements.

Such accounting, if embedded in rigorous governance and policy structures to drive real-world implementation, could generate a major improvement in sustainability of China's marine ecosystems. Given the extent of China's marine jurisdiction, and severity of ongoing degradation, such improvement could have enormous environmental and economic benefits within China, and at a global scale.

**Keywords:** marine natural capital, ecosystem goods and services, gross ecosystem product, sustainable marine management, environmental economics

**Competing Interest:** The authors declare no competing interests.
**Received:** November 30, 2024. **Accepted:** March 19, 2025

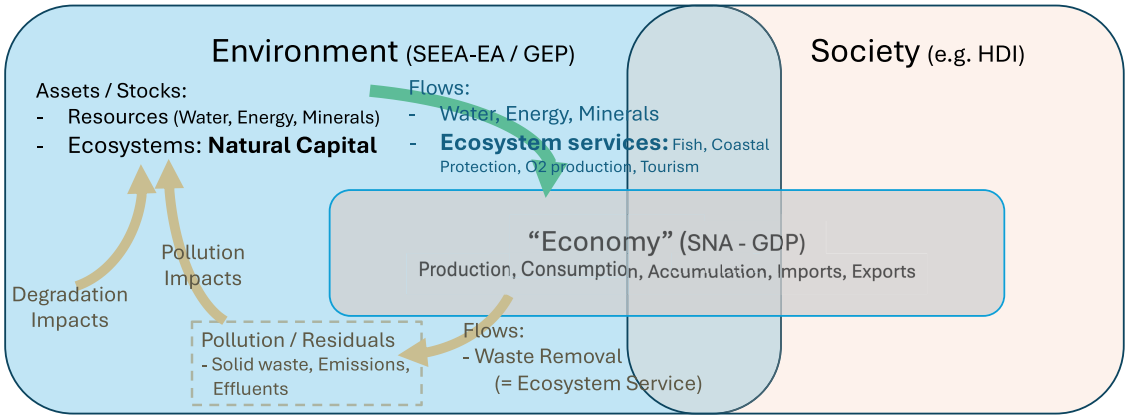


**Fig. 1.** Natural capital and ecosystem services make essential contributions to the human economy. Accounting systems such as the SEEA-EA and GEP aim to assess the stocks of natural capital assets and the flows of ecosystem services to and from the human economy, in order to facilitate more sustainable management from both environmental and economic perspectives. Such accounts provide essential complementarity with the internationally accepted System of National Accounts (SNA), and measures such Gross Domestic Product (GDP) and the Human Development Index (HDI).

## Introduction

The value to human economies of healthy natural ecosystems has been well documented over recent decades, including the identification and categorization of an extensive range of ecosystem goods and services provided to humans. This includes services provided by marine and ocean ecosystems (1, 2). The capacity of ecosystems to continue to provide those services is referred to as natural capital. However, despite this documentation, those values are rarely assessed or accounted for as part of economic analyses (3), and are considered as "externalities" in neoclassical economics. The consequence is that economic analyses, by omitting or ignoring ecosystem services, by default treat their value as zero (4).

Oceans and coastal ecosystems have great value in their own right, but also have very considerable economic value to human society, through marine ecosystem services such as fisheries, coastal protection, tourism value, climate regulation, waste/pollution removal, or oxygen production (Figure 1) (5). But marine resources, and their considerable value to humans, are very poorly understood and widely ignored, placing them at serious risk of degradation due to climate change threats, biodiversity loss, pollution, and unsustainable use (6, 7). Importantly, while ongoing degradation is causing ongoing economic harm, reversal of those impacts and restoration of ecosystems has the potential to markedly increase their value to humans (8).

This is especially true in China, which has a very strong cultural and historical focus on terrestrial rather than marine environments (9), and which is experiencing serious crises due to overexploitation and development in both (10, 11). China's large size, and the consequent scale of environmental impacts, means that loss of ecosystem value is critical on a global scale (China's marine gross domestic product [GDP] in 2020 was estimated at CNY 8 trillion, it has approximately one-fifth of global fisheries catch, it has a continental coastline length of around 18,000 km and approximately one-fifth of the global human population).

Understanding the value of marine eco-resources in China, and the development of policy to support and sustain that value, are grave gaps (6), significant both nationally and internationally. This paper aims to summarize current and developing knowledge and policy to provide direction for ongoing improvements, specifically including development of national accounting for marine natural capital. The scope of the paper is limited to economic aspects that are renewable and dependent on healthy ecosystems (natural capital, including ecological carbon sequestration), whether sustainably managed or not; it does not include other sectors of the ocean economy that are passive (e.g. marine renewable energy, maritime shipping) or harmfully extractive (i.e. non-renewable extractive industries) (as distinct from the *Sustainable Blue Economy*, which includes sustainably managed passive sectors, and does not include ecosystem dependent sectors that are unsustainably managed).

## Innovations in assessing and accounting for natural capital and ecosystem goods and services

The capacity to assess and account for natural capital stocks and flows in a rigorous, objective and standardized manner is fundamental to their incorporation into economic analyses, policy, and management, just as standardized procedures such as the internationally accepted System of National Accounts are used for assessing national economic performance.

There has now been extensive, innovative development of methods for assessing and accounting for both capital and flows of ecosystem goods and services. In particular, the United Nations–supported System of Environmental Economic Accounting (SEEA) (seea.un.org) has been developed as a set of satellite accounts to the System of National Accounts, including the SEEA Ecosystem Accounting (SEEA-EA). However, this development has focused primarily on terrestrial systems, and development of SEEA Ocean Accounts has lagged considerably: although ~90 countries now routinely assess SEEA-EA accounts for terrestrial environments on a regular basis, SEEA Ocean Accounts (www.oceanaccounts.org) are still largely at the pilot stage, although developing rapidly. It is critical to note that, as understanding of ecosystem goods and services, especially in the ocean, is a developing field of knowledge, there are almost certainly goods and services that are still unrecognized. This in turn means that assessments are almost certainly *underestimates*.

Unfortunately, the application of environmental accounting through broader economic policy continues to lag. With the exception of China (see next Section and Supporting Info. I), uptake and application have been only piecemeal: despite the widespread assessments of accounts, few other countries have implemented policy and governance to drive actual accountability for natural capital. Three key steps have been identified for more effective uptake: (i) raising awareness of the interdependence of ecosystems and human well-being, (ii) advancing the fundamental interdisciplinary science of ecosystem services, and (iii) implementing this

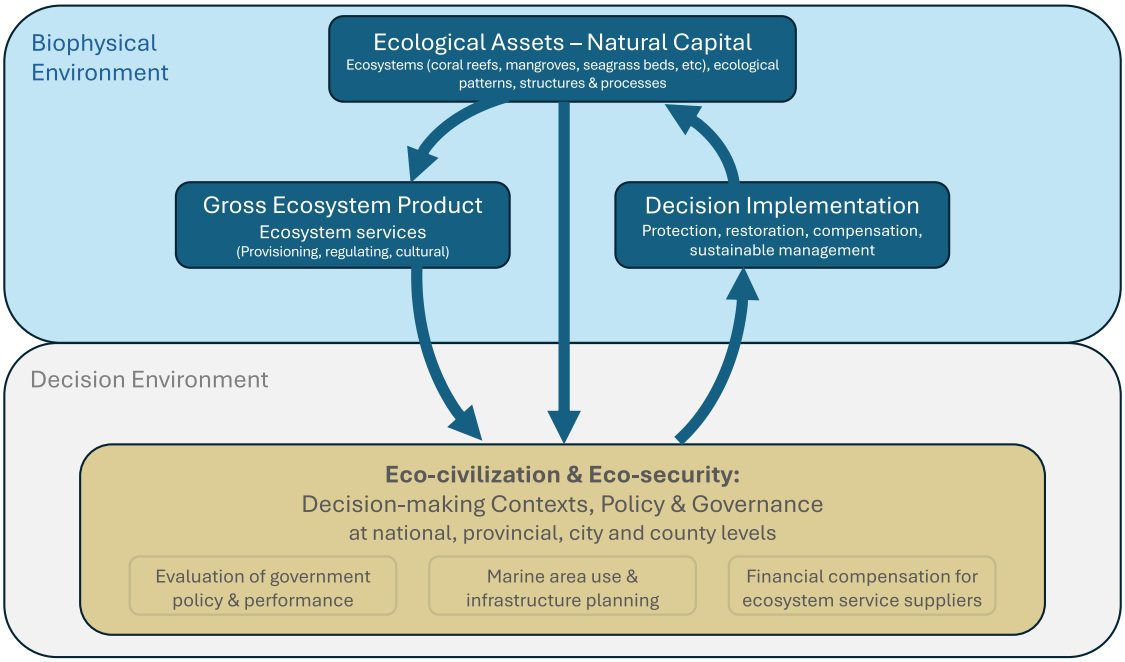


**Fig. 2.** Implementation of eco-civilization (and eco-security): role of GEP in accounting for ecological assets and flows in decision making. Redrawn and adapted for marine ecosystems from Ouyang et al. (17).

science in decisions to restore natural capital and use it sustainably (Supporting Info. II) (12).

Valuation of nature in economic terms does require great caution. First, it carries grave risks of oversimplifying the value of nature to its monetary or financial value, as the goods and services needed by humans are not interchangeable: just as we need food as well as clean water, we need *both* coastal protection and fish for food, whatever their monetary values. A key aspect of SEEA accounts is that although they do allow translation of biophysical measures of *some* services into monetary valuation, they also maintain the biophysical accounts.

A further cautionary note concerns recognition that monetary valuations generally amount to *minimum* values: in addition to the probable omission of unrecognized services (previous), some services are not able to be estimated in monetary terms, although their value is certainly real and positive (e.g. spiritual values, supporting services such as primary production, biodiversity maintenance). Thus, true economic value will almost certainly be considerably greater than estimated financial values.

## Globally significant leadership and opportunity in China: transfer of ecological civilization and ecosystem accounting to marine ecosystems

The concept of *ecological civilization (eco-civilization)* (as expressed by Xi Jinping "綠水青山就是金山银山"[Clear waters and green mountains are as valuable as gold and silver mountains"] in 2005), in which ecological sustainability is a requisite component of social development, has been embedded at the highest levels of policy in China for more than a decade (Figure S1). This is largely due to strong awareness that environmental degradation was having severe impacts on human well-being, both social and economic, and the vicious cycle of environmental degradation and poverty, none of which is reflected in standard economic measures such as GDP (10, 13, 14).

Recent *Five-Year Plans*, China's overarching policy instrument, place high priority on environmental management and accelerated development of legal frameworks to support that management (15). China has also developed an accounting system roughly parallel to SEEA-EA, the *Gross Ecosystem Product* (GEP) (Figures S2 and S3), which also accounts in both biophysical and financial terms, and has recently sought to integrate the two approaches (i.e. SEEA-EA and GEP) (13, 16, 17). An extensive body of research literature (>1,200 publications) (13) provides strong evidence for complementary benefits of environmental sustainability for both ecosystems and people, at impressively large scales. Critically, and exceptionally on the global stage, China has implemented accountability for ecosystem services and assets (through GEP) as part of performance assessment at multiple levels of government [14th Five-Year Plan—Chapter 37, section V (18)]. This accountability serves as a powerful mechanism to drive prioritization of environmental sustainability (Figure 2) [see also (13)].

A more detailed overview of knowledge, implementation. and policy for terrestrial natural capital in China is provided in Supporting Info. I, along with examples of the benefits delivered.

However, understanding and policy for valuing *marine ecosystems* remains a huge gap in China, as elsewhere. For example, research on ecosystem services is overwhelmingly dominated by the enormous body of terrestrial work, with only around 8 to 10 publications on marine ecosystem services or natural capital generally (summarized in next Section). Marine management is generally subsumed within predominantly terrestrial agencies (Supporting Info. III). This gap is significant both nationally and internationally, given China's extensive marine jurisdiction and ocean footprint (9, 19, 20).

Nonetheless, the policy context is changing. In the words of President Xi Jinping, *"To give our future generations clear water and blue sky, we must place high priority on ocean eco-civilization development, strengthen the prevention of ocean environment pollution, protect ocean biodiversity and achieve sustainable exploitation of ocean*

*resources*" [President Xi Jinping, Opening remarks, Ocean Economy Conference, ShenZhen, Guangdong, 15 Oct 2019 (21)].

Under recent Five-Year Plans, including the most recent 14th Five-Year Plan (18; English translation available from 22), China has ambitious goals in the development of the marine economy, including building sustainable marine ecosystems and practices and industries [Chapter 33 (18)], as well as participating in global marine governance (7, 9, 20) and a strong focus on "green development and harmonious coexistence between humanity and nature" [Part XI, Chapters 37–39 (18)]. China is increasingly taking leadership roles, such as hosting COP 15 of the Convention on Biological Diversity, with associated investment in delivery and reporting on national objectives of the Sustainable Development Goals (SDGs; specifically SDG 14, Life Below Water). Together, this context provides an exceptional opportunity for fostering economic policy to drive substantial improvements in sustainable management of marine resources, to the mutual benefit of the country's people and environments (7, 13, 20).

## Marine natural capital in China: State of knowledge and policy

### Knowledge of marine environmental condition and resources

China has an extensive coastline, spanning from the tropical and subtropical South China Sea and East China Sea to the temperate Yellow Sea and Bohai Sea. Influenced by monsoon winds, ocean currents, and the estuaries of large rivers, notably the Huang He (Yellow River), the Changjiang (Yangtze River), and the Zhujiang (Pearl River), the coast has highly diverse habitats, with high dominance by seagrass beds and salt marshes in the north and coral reefs and mangrove forests in the south (23). The condition of China's marine and coastal habitats, including both coastal and remote coral reefs, has been broadly documented and shown to have experienced serious degradation over recent decades (7, 9, 11, 24–30), including:

- Habitat losses, especially from coastal development and construction, as well as overuse;
- Increased pollution, especially from terrestrial runoff leading to eutrophication, toxic algal blooms, sedimentation, and chemical and major plastic pollution;
- Temperature and other climate impacts (especially on coral reefs); and
- Declines in fisheries resources (9, 31).

Although marine protected areas and other management strategies have been widely implemented, there are serious bottlenecks for their effectiveness (20, 32, 33). Around 53% of temperate coastal wetlands, 73% of mangroves, and 80% of coral reefs in China were lost between 1950 and 2000 (34). Naturally, these declines in environmental condition will have had major impacts on the economic value of the goods and services that depend on the ecosystems (8). Similarly, although improved management measures such as seasonal fishing moratoriums and effort controls have been introduced, fisheries resource assessments show that overfishing in China's coastal waters has caused a decline in the mean trophic level of fish stocks, signifying reduced economic value (9, 31).

### Valuations and assessments in China's marine ecosystems

Although there is extensive research documenting the values of extractive resources such as fisheries and minerals, there has been relatively little work on valuations of China's marine ecosystem services generally. Using the protocols outlined in the Technical Directives for Marine Ecological Capital Assessment, Chen and colleagues (35) published a series outlining concepts and attributes of marine ecological capital, along with constituents, indicators, and methods for both flows and standing stocks (36–39). This was followed by specific assessments for Shandong province, on the Bohai/Yellow Sea (40, 41). A national-level assessment of marine ecological capital of territorial seas (to 12 nm from coast) in 2005 to 2011 (36, 37) estimated the standing stock of living coastal resources (including fisheries) at CNY 6.0888 billion (CNY 60.888亿, approximately USD 870 million), an average of CNY 30,039 (CNY 3.00万or USD ~5,000) per $km^2$ (39), and estimated the ecosystem services provided in 2008 at CNY 1,034 billion (CNY 1.03万亿or ~USD 147.7 billion), an approximate average of CNY 5.57 million (CNY 510万, USD ~796,000) per $km^2$ (38).

For marine fishery resources specifically, current assessment methods for stock status and catch value are well established, as evidenced by empirical studies for the entire China seas (9) and for the East China Sea specifically (42). However, dedicated economic valuation of existing resource stocks remains limited.

Importantly, these valuations are significant underestimates because, in addition to being more than 12 yr old, they do not include tourism or several important ecosystem regulation services, such as raw material production, genetic resource supply, cultural usage, biological control, and disturbance regulation (coastal protection) services from marine ecosystems [e.g. (1, 43)]. For example, 88.7% of domestic tourism is ocean related (8)—Sanya, Hainan, attracts an estimated 16 million (1,600 万) tourists per year, around 8 times more than visit the Great Barrier Reef in Australia (7), where tourism in 2015 and 2016 was estimated to attract around USD 4.275 billion (~CNY 27.65 billion or "276.5 亿; 44)." Studies elsewhere have shown that coastal habitats, such as reefs and mangrove forests, can provide protection against storms and floods to built infrastructure, protection worth tens of billions of US dollars, which is highly cost-effective compared with the artificial defenses widespread in China (29, 45–47).

In 2019, a pilot project using SEEA Ocean Accounting protocols (https://www.oceanaccounts.org/), with support from the UN Economic and Social Commission, estimated mangrove assets in Beihai City, Guangxi Province. Total carbon stock of Beihai mangroves was calculated as 0.67 million tC.

In 2022, a World Wide Fund for Nature (WWF) report, Reviving China's Ocean Economy, estimated the approximate (minimum) value of China's Shared Wealth Fund ocean assets at CNY 54 trillion (USD ~8.2 trillion), and the annual sustainable gross marine products at CNY 2.1 trillion (USD ~318 billion), including carbon sequestration (8). Again, however, the actual value is likely to be much higher because many key ecosystem services are difficult to quantify or express in monetary terms. Such services include regulatory services such as atmospheric regulation, carbon storage and water filtration, and cultural, recreational, and aesthetic values. Recreational service value may include recreational fishing, which depends on coastal resources and communities. Small-scale subsistence and commercial fisheries can be difficult to value but are critical to livelihoods, food security, and culture of millions of people. Importantly, these values would grow significantly in response to ecosystem restoration and sustainable

**Table 1.** Marine ecosystem services included in assessment protocols.

| Ecosystem services | WWF shared wealth fund | Technical directives for marine natural capital assessment | Ocean accounts (SEEA-EA) |
|---|---|---|---|
| Provisioning services | | | |
| 1. Food production (incl. fisheries) | ✓ | ✓ | ✓ |
| 2. Oxygen/clean air production | ✓ | ✓ | ✓ |
| 3. Material production (chemicals, medicines, etc.) | ✓ | ✓ | ✓ |
| 4. Provision of genetic resources | ✗ | ✗ | ✓ |
| Regulating services | | | |
| 5. Climate regulation | ✓ | ✓ | ✓ |
| 6. Carbon sequestration | ✓ | ✓ | ✓ |
| 7. Waste treatment/removal | ✓ | ✓ | ✓ |
| 8. Biological/disease control | ✗ | ✗ | ✓ |
| 9. Disturbance regulation (including coastal protection) | ✓ | ✗ | ✓ |
| Cultural services | | | |
| 10. Recreational value (including tourism) | ✓ | ✓ | ✓ |
| 11. Cultural/heritage value | ✓ | ✗ | ✓ |
| 12. Scientific value | ✗ | ✓ | ✓ |
| 13. Educational value | ✗ | ? | ✓ |
| 14. Spiritual/therapeutic value | ✗ | ? | ✓ |
| Supporting services | | | |
| 15. Primary production | ✓ | ✗ | ✓ |
| 16. Nutrient cycling | ✓ | ✗ | ✓ |
| 17. Biological diversity maintenance | ✓ | ✓ | ✓ |
| 18. Habitat provision (including larval supply) | ✓ | ? | ✓ |

"✓" symbols indicate the ecosystem services is included: inclusion; "✗" symbols indicate the ecosystem service is not included; "?" indicates uncertainty.

fisheries management but are at risk of serious decline due to climate change threats, biodiversity loss, pollution, or unsustainable fisheries and aquaculture development (8, 9, 31, 48).

Current work of relevance includes a collaboration between the Chinese Academy of Sciences Research Centre for Eco-Environmental Sciences and WWF China to develop ocean accounts valuing marine ecosystem goods and services for coastal counties in the Greater Bay Area, using the GEP approach. The Greater Bay Area refers to the megalopolis of 11 large cities surrounding the Pearl River Delta, which includes a human population of around 71 million (nearly 1% of the global population) and a GDP of CNY 13 trillion (USD 1.8 trillion; 2022); this study will have considerable impact and relevance to other regions, both nationally and internationally.

There is a critical gap in knowledge of the impact of marine environmental degradation on ecosystem services and the values of those services. This gap highlights the urgent need for stronger links between natural capital and environmental policy in the marine realm. The 14th Five-Year Plan (Chapter 33) places explicit emphasis on the importance of improving regulation and management to protect the health and integrity of marine ecosystems, while developing the marine economy. Ocean accounting offers the tools to understand the costs and benefits of different strategies toward that goal (7, 8, 20).

## Methods and approaches to assessing marine value

The different approaches used to assess marine natural capital and services have important differences in how they are calculated and what they include, which reflect the differences in purpose and hence application. Importantly, the 3 main approaches considered here (i.e. i. Marine Ecological Capital stocks and flows, which are analogous to GEP+Ecological Assets used for Chinese terrestrial ecosystems; ii. The SEEA-EA related Ocean Accounting; and iii. The Shared Wealth Fund applied by WWF) all only include values for sectors that depend on healthy ecosystems (i.e. ecosystem goods and services). Broader approaches and metrics, such as the sustainable blue economy (which includes sustainable nonecological resources such as energy), marine GDP (which includes nonrenewables such as mining), and natural resource balance sheets, are compiled by the Ministry of Natural Resources (49) and the National Bureau of Statistics using standardized protocols (50).

GEP, the analogous Marine Ecological Capital stocks and flows, and the SEEA-EA Ocean Accounting are all intended to function as accounting tools, are all broadly similar in approach of identifying both stocks (natural capital) and flows (services), and all are broadly based on the Millennium Ecosystem Assessment categorization of ecosystem services, although differing in specific inclusions and calculation methods (Table 1) (13, 16, 35, 51, 52). The SEEA-EA is intended as an international statistical standard, which provides guidelines to conduct comparable ecosystem accounting in different countries. Within the GEP protocols, GEP serves as a metric, an aggregate measure of the value added of all final ecosystem services—material, regulating, and nonmaterial—constructed using similar methods as those underpinning GDP, focusing on the flow of ecosystem services (13).

The GEP approach has been formalized in a national standard for evaluation (53) and specifically identifies the concept of "Ecosystem Products," similar in concept to "final ecosystem services" in the SEEA-EA. The Chinese government highlighted the importance of realizing the value of ecosystem products (54), including evaluation, monitoring, and sustainable management mechanisms.

As early as 2006, Chen and Li (21) proposed a framework of *Ocean-based Green GDP* to present the outcomes of ocean-related economic activities, rather than the Gross Marine Product. The cost of ocean resource depletion and environment conservation as well as the cost of ocean waste management should be calculated to reflect the influence on ocean environment caused by economic "development" (21).

Guidance for marine assessments is provided by the Technical Directives for Marine Ecological Capital Assessment (35). The official Directives are in Chinese language only; therefore, an English translation is provided as Supporting Info. IV to facilitate comparison with other assessment frameworks and enhance accessibility in international contexts. Developed and applied by Chen et al. for the National Standardization Administration, the Directives closely parallel the terrestrial GEP (+ Ecological Assets) approach to calculate both Marine Ecological Capital Stock Value (MECSV) and Marine Ecosystem Service Value (MESV), with different units, analogous to the terrestrial ecological assets and GEP, respectively (55). This protocol incorporates a subset of marine ecosystem services (Table 1). In March 2024, the National Technical Committee 207 on Environmental Management of Standardization Administration of China (Marine Ecological Capital Stock Value and Marine Ecosystem Service Value) for marine gross ecosystem product accounting" [std.samr.gov.cn/gb/search/gbDetailed?id=14CAA43B48655CA1E06397BE0A0A2477 (56)], an important opportunity for advancing evaluation of marine natural capital.

Ocean accounting methodology [www.oceanaccounts.org/tag/guidance/ (57)] has been under further coordinated development since 2019 by a global consortium of United Nations and national statistics and environment departments, other multilateral agencies, and academics. It broadly transfers the terrestrially focused guidance of SEEA and SEEA-EA to the ocean context, identifying ocean assets as a combination of produced capital and human capital (58). Again, values are calculated in terms of ecosystem supply and use to understand both stocks and flow from marine ecosystems to the ocean economy.

Both the Technical Directives (Marine Ecological Capital Stock Value and Marine Ecosystem Service Value) and the SEAA Ocean Accounts frameworks incorporate fisheries capital (stock) and services (flow), along with other food production where data are available (Table 1). Fisheries service value within a specified period can be derived from production data for capture fisheries and aquaculture scaled by nearby market prices for seafood; however, capital value of fisheries requires additional stock surveys. Under routine data constraints, rather than quantitatively determining biomass stock, fisheries stock assessments typically evaluate stock exploitation status, which provides proxy indicators for capital accounting.

As noted for terrestrial accounts (13), there is need for more detailed and specific alignment of approaches to marine natural capital accounting.

## State of policy, laws, and governance for marine ecosystem services

A critical aspect of effective natural capital accounting in terrestrial China has been application: accounting is strongly embedded within policy and governance frameworks that ensure outcomes are realized, for both conservation and economic benefits. Unfortunately, for marine natural capital, the policy and governance contexts have lagged well behind those on land, although the 14th Five-year Plan emphasizes actively expanding the space for maritime economic development and building a sustainable marine ecological environment ("blue economy"). There are separate National Plans for Marine Economic Development and for Marine Ecological and Environmental Protection and Marine Functional Zoning; the National Five-Year Plan for Marine Economic Development for 2021 to 2025 cannot be found online. The 2016 to 2020 plan emphasized marine ecological civilization, conservation, and sustainability (15) but did not directly incorporate natural capital accounting. The provincial Five-Year Plans for Marine Economic Development for 2021 to 2025, including those for Guangdong, Hainan, Zhejiang, Shandong, and others, are available online. All of these plans emphasize marine ecological civilization, conservation, and sustainability.

There is a strong policy basis for marine ecological and environmental protection measures, and design of coastal and marine *Redlines* and protected areas are based on environmental attributes, but existing policies do not incorporate assessment of marine ecosystem service value (15, 20, 59, 60). Marine Ecological Redlines regions limit development of marine environments, by establishing a lower limit of 35% of natural coastlines for the mainland and 85% for islands, along with 25% of maritime area and a minimum 30% of China's total ocean area. These restrictions are intended to conserve ecologically sensitive or vulnerable areas, as well as identifying legal rights of use in specific planning areas and requiring environmental impact assessments before construction. All use and coastline construction must be publicly transparent and fully disclosed (60).

More generally, although China has a very extensive body of marine ecosystem research and knowledge (61), that information is not strongly applied in policymaking. Further, to the extent that policy exists, it may not be implemented adequately yet.

Current applications of marine ecosystem accounting are largely limited to post hoc estimation of eco-compensation for developments that damage coastal habitats (15) but, operationally, rarely serve to redirect development to minimize that damage.

Marine environmental governance in China recently underwent a major revision, with the newly formed Ministry of Natural Resources and Ministry of Ecology and Environment absorbing and integrating the marine biodiversity protection responsibilities of the former State Ocean Administration and several disparate government ministries (15, 62). Within these new Ministries, governance devolves to provincial departments; for an overview of marine governance, see Supporting Info. III [see also (7, 20, 33, 61–63)]. After a few years of implementation of the new governance framework and development of their respective 5-year plans, the roles and responsibilities of these Ministries are better clarified with stronger, more coherent governance of issues like water pollution and spatial planning from land to sea under management by a single Ministry (63). This provides an important opportunity for closer policy integration, particularly of economic and environmental plans, and specifically an opportunity for the transfer of terrestrial natural capital policy to marine ecosystems (20). There is an explicit policy position of "conservation first, protection prioritized, and natural restoration oriented." However, coordination of responsibilities between the two new ministries remains a long-term challenge, with particular challenges around land-based marine pollution and the establishment of coordination at provincial and local levels (15, 62). Further, the new Ministry of Natural Resources remains more focused on terrestrial than marine environmental value (20, 62).

Governance of China's marine fisheries has long been administered by the agricultural authorities (currently the Ministry of Agriculture and Rural Affairs). Management of domestic marine fisheries incorporates comprehensive stock assessments as the basis for control targets for total marine catch (64). Additionally, identification of critical nursery habitats for key fisheries species is used to guide allocation of specific reserves (aquatic germplasm resource reserves) to protect fishery sustainability (65). However, given the strong dependency of seafood production on marine ecosystem health, management by quite separate regulatory authorities poses significant challenges for governance coordination.

In terms of informal governance, public participation, engagement, and stewardship are typically limited in China, due to the cultural terrestrially centered focus, and because the lack of awareness of life below water fosters overexploitation as a tragedy of the commons (7, 20). Nonetheless, there are illustrative success stories, such as the "Blue Bay Guardians Project," in which a group of fishers in Langya village, near Qingdao (Shandong Province), organized to discourage bottom trawling and thereby protect seahorses (66).

### Demonstrated potential benefits of valuing marine ecosystem services

In addition to the benefits of valuing natural capital in terrestrial ecosystems (Supporting Info. I), recognition of the value of marine ecosystem services has proven to have significant benefits, by strengthening support for environmental protection or restoration which in turn generates increased service delivery. On Australia's Great Barrier Reef, not just identification of the revenues generated by tourism and fisheries, but also comparison of that revenue with investment in protection showed that protecting the ecosystem provides exceptional return on investment; this, in turn, dramatically enhanced support for protection (67), although the case remains strong for more substantive investment (68).

Analysis of the economic value of marine fishery resources indicates that harvesting fish stocks at maximum economic yield, rather than maximum sustainable yield, not only enhances fishery profitability, but also improves ecosystem resilience (69). This principle has been institutionalized in fisheries governance frameworks (e.g. in Australia; 70).

Coastal protection from storms is a key ecosystem service of particular relevance for much of China's increasingly developed coastline (7, 29). In southern China, protection and restoration of coral reefs, mangrove habitats, and seagrass beds would enhance and restore protection of coastal infrastructure from storms, while protection and restoration of coastal wetlands, seagrass beds, and oyster reefs would provide similar value in northern China, including the Bohai and Yellow Sea. Such coastal protection of infrastructure can often have enormous economic value (29, 45–47, 71).

Oyster reefs, mangrove forests, seagrass beds, and other coastal wetlands are also highly effective at filtering turbid and polluted seawater, sequestering the removed materials and thereby improving habitats for other species, fisheries, etc.

## The way forward: Expanding China's existing leadership to natural capital of coastal, marine, and ocean habitats

### Nationwide, province-based ocean accounting and policy implementation

China's leadership in the effective implementation of environmental accounting in terrestrial ecosystems (Supporting Info. I), together with the clear mandate in national policy for a sustainable blue economy, provides a critical opportunity for development of ocean accounting as a way forward. There is extensive research documenting China's marine ecosystems and the problems and issues facing them but insufficient transfer of that knowledge into policymaking.

The key proposal of this paper is the rapid, national-scale use of environmental accounting and evaluation as a policy driver to improve management and conservation of marine ecosystems, closely parallel to the procedures in place in terrestrial systems (Figure 2). This section outlines key challenges and recommendations toward that goal, drawing on the previous review (Marine natural capital in China: State of knowledge and policy), as well as lessons learned in development of accounting and implementation in China's terrestrial ecosystems and international experience (Supporting Info. I and II; 8, 10, 12).

Development of nationwide ocean accounting is a natural next step for natural capital accounting and for marine governance in China. This accounting, undertaken and implemented at provincial levels, must be *firmly embedded in policy and governance frameworks to ensure that accounting is applied and used to provide direction and long-term economic and environmental stability*. A robust set of ocean accounts, embedded within a governance framework parallel to that on land (Figure 2), with robust transparency, would have great benefit for a wide range of applications, such as:

- Improved spatial use and planning, and design of protected areas including major functional areas and Redline areas;
- Better development planning, including more comprehensive economic evaluation of proposals, decisions, and scenario options;
- Performance assessment and incentivization for local and provincial governments and leadership;
- Transfer funding from national to local governments, ensuring that ecosystem service protection is perceived as an investment, rather than as a cost;
- More rigorous biophysical and monetary compensation from private developers for use of public/common ecological assets;
- Better public engagement and commitment/stewardship, as the costs of overexploitation and pollution are identified and communicated to the community.

Provincial-level implementation is appropriate to ensure that implementation is appropriate to local contexts. However, nationally coordinated and standardized governance frameworks are vital to ensure comparability and to provide direction.

Development should be similarly ambitious to the terrestrial precedents. Rapid scaling up from previous and further pilot studies should target comprehensive national coverage for the 11 coastal provinces. Ideally, the Hong Kong and Macau Special Administrative Regions would be coordinated with Guangdong province in an integrated framework for the Greater Bay Area; similar regional coordination for provinces adjacent to the Bohai Sea would be beneficial.

Pilot studies of accounting, governance, and policy applications would provide valuable tools for learning and development and for community engagement, as demonstrated in terrestrial applications. The use of scenario analyses of different policy and governance instruments is also recommended (e.g. "dashboard" presentation of a range of indicators under different scenarios; 3). Explicit calculation/estimation and presentation of benefits and avoided costs are vital aspects of changing the perception that conservation causes economic losses, and demonstrate the complementarity of environmental and economic sustainability (72, 73).

### Development of accounts for marine ecosystems

Key challenges, requirements, and recommendations include:

- Development of a consolidated, standardized accounting framework, based on integration of the existing Technical Directives and the SEEA Ocean Accounts, and cross-referenced with both. This process would potentially involve initial, more detailed cross-referencing of the two systems, to identify commonalities and differences, followed by

collaborative workshops to resolve an integrated approach appropriate to Chinese circumstances but readily transferable for international contexts.
- Determination of appropriate spatial resolution for accounting, acknowledging that different resolutions are probably required for different ecosystem services.
- Determination of data requirements and channels for ongoing acquisition, along with tools or platforms for data storage, handling, and analysis.
- Acquisition of historical data, where possible, to provide historic baselines and scope for ongoing adaptive improvement.
- Values of ecosystem services and capital documented, applied, and presented in both biophysical and monetary terms, as currently occurs on land. It is important that presentation to lay and public audiences includes biophysical measures, to avoid oversimplification by monetary valuations.
- Development of pricing estimations for full range of services, although policy application should be largely based on biophysical measures and should not be delayed by uncertainties around pricing estimates or methods.
- Adequate resourcing, with transparent linkages to the economic benefits of the accounting. This includes funding, human capacity and infrastructure resources.
- Robust transparency and accountability for ongoing improvement to governance and policy.

## Development of governance and policy

Governance frameworks and policies for marine ocean accounting can be modeled on, and integrated with, existing terrestrial frameworks, facilitated by the recent integration of terrestrial and marine ecosystem management within the Ministry of Natural Resources. As on land (Supporting Info. I), initial policy development could focus on:

- Implementation of systematic, coordinated, and regular accounting for marine natural capital and ecosystem services;
- Explicit inclusion of marine ecosystem services as part of the national goal of sustainability for ecosystem services;
- Functional zoning for (marine) ecosystem services, along with:
  - Ecological protection Redlines;
  - Systematic planning and enhancement of marine protected areas systems to explicitly incorporate ecosystem services;
- Ecological protection and restoration, with incentives provided by:
  - Ecological compensation, including transfer payments to county (local) and municipal governments;
  - Promotion of opportunities for sustainability in marine sectors, including facilitating and providing finance for development of sustainable activities and reducing impacts on natural capital (8, 74);
  - Accountability by government agencies (and businesses) and leadership for sustainability of marine natural capital and services, as assessed by accounting (i.e. sustainability of natural capital integrated into performance assessment, including incentives).

Each of the previous aspects seems entirely consistent with, and indeed would give substance to, the direction and intent of relevant national plans and policies (summarised in previous section). The explicit integration of marine natural capital into the national goal of sustainable supply of ecosystem services would provide powerful impetus for effective implementation, and is a key recommendation to emerge from China's current programs (10).

Although accounting is proposed to be implemented at the provincial level, other aspects of governance would also need to devolve to lower levels of government (city and county) as for terrestrial arrangements (Supporting Info. I).

Although development of the required governance framework will be more complex than that on land, due to the more complex jurisdiction in marine habitats and the unfamiliarity of underwater ecosystems and processes to lay participants, it is nonetheless both timely and feasible, given the evolving coordination between the Ministries of Natural Resources and Ecology and Environment. An adaptive collaboration between academic experts, government agencies, and multilateral bodies should be able to provide robust guidance with high prospect of ocean accounts facilitating better coordination. The potential effectiveness of such an approach is well demonstrated by the terrestrial precedent. It is also critical that governance implementation is fully transparent, and embeds ongoing adaptive development and refinement, in order to optimize governance structures.

Adequate resourcing, with transparent linkages to the economic benefits of the accounting, and of ecosystem protection, would be critical for development of effective governance and implementation capacity.

A key recommendation emerging from international efforts involves the better alignment of private short-term goals (e.g. business goals) with societal long-term goals, by means of reforming institutions, policies, and practices (Supporting Info. II) (12). This improved alignment is particularly relevant in China's marine sectors, and links closely to the need for policies to support and finance sustainable use of marine natural capital (Supporting Info. II) (8). A high-impact, and relatively simple, example of this realignment would be diversion of the subsidies that lead to overcapacity in fishing fleets toward the promotion of sustainable fishing activities (8).

Ideally, accountability for marine natural capital would extend to business reporting cycles, as well as to government bodies. Policies that promote sustainability, including the direction of financing toward sustainable use of ecosystem services and away from sectors or activities that harm ecosystem health, will drive widespread business transitions to sustainability. A range of existing and potential actions have been discussed previously (8, 74); concrete examples include the commitment of several Chinese banks and asset managers to the United Nations Environment Program Finance Initiative's *Sustainable Blue Economy Finance Principles* and the active fostering of investment and financing capacity for small and medium businesses by the Ministry of Natural Resources and Shenzhen Stock Exchange.

A key requirement of this realignment of private and societal goals is the reversal of the burden of proof around who identifies, values, and pays the costs of lost ecosystem services (which are generally common or public assets). The investment of time and funds required to document impacts on ecosystem services should rest with the bodies who stand to profit or gain from the use of those resources, and not with government agencies (or nongovernmental organizations) responsible for protection. Currently, those investments are treated as a cost of environmental protection, whereas they are in fact a cost of exploitation. Implementing this reversal would remove a significant cost of environmental management, largely to the benefit of government agencies/taxpayers.

## Broader context

Development and implementation of marine natural capital accounting requires careful consideration of several additional related issues. First, linkages between ecological compensation (facilitated by environmental accounting) and the restoration/protection of ecosystem services should be carefully integrated with management of cumulative environmental impacts, and the principle of *no net environmental loss*. Specifically, this principle advocates not only that any environmental losses must be offset by gains elsewhere, but also for the application of a hierarchical "*avoid / mitigate / offset*" framework (75–77). That is, parties are required to demonstrate that they have progressively avoided all impacts to the fullest extent possible, then mitigated remaining impacts as far as feasible, and only then offset any remaining impacts to achieve a net gain. In this context, ecological compensation must not sidestep obligations to first avoid and then mitigate damage, and financial payments for compensation must not obviate the need to maintain the biophysical services being compensated.

Further, there is need for rigorous criteria to assess additionality of restoration/protection activities in the context of payment for ecosystem services (i.e. the extent to which the payment facilitates additional service delivery to a baseline or business as usual scenario; see Supporting Info. I for how this is currently addressed within terrestrial accounting).

Second, in addition to protecting ecosystem services, there is still a critical need to ensure environmental sustainability of non-ecosystem services (i.e. services that do not depend on healthy ecosystems, such as energy, shipping and transport sectors; 8).

Third, ocean accounts would have direct benefits for improving sustainability of national food security, given China's dependence on, and preference for, fish and other seafoods. Chinese authorities are also giving increasing attention to the concept of "eco-security" as an aspect of eco-civilization; again, accountability for marine ecosystem services will be directly supportive of securing those services.

Ocean accounts would also contribute to accounting under international commitments, including the Convention on Biological Diversity (15) and the Sustainable Development Goals, not limited to the ocean goal (SDG 14), but also including poverty (SDG 1) and hunger alleviation (SDG2), sustainability (SDG 11), climate action (SDG 13), and many others (8).

Although international and global ocean governance for marine natural capital is largely out of scope for this review, two points are worth noting. First, by implementing both ocean accounting within its Exclusive Economic Zone (EEZ), and the policy/governance to give effect to that accounting, China would be providing crucial global leadership to drive sustainability in the ocean economy. Second, however, there is serious risk that accountability for natural capital within the EEZ could incentivize unsustainable use of high-seas marine capital, in effect exacerbating the current global tragedy of the commons. At present, international ocean governance, such as the United Nations Convention on the Law of the Sea regime, does not systematically address ecosystem services outside fisheries, and lacks the mechanisms to address this challenge. The domestic implementation of marine natural capital accounting should be accompanied by global leadership by China to ensure that disputed areas and the high seas are appropriately protected [e.g. (78)], as well as by restraint on the part of governments and businesses in relation to conducting exploitation outside China's ocean territory.

Finally, it is worth emphasizing the emerging lessons of China's situation for the international community. Ecosystem accounting, and ocean accounting specifically, provides broadly applicable, standardized, and internationally recognized mechanisms, suitable for integrating into national accounts and statistics, to support eco-security and food security, and for reporting for international/multilateral agreements (3). In particular, many countries currently routinely assess (terrestrial) natural capital but fail to actually incorporate the (often declining) results into action. The development of policy and governance frameworks to drive sustainability, as being implemented in China on land, is an urgent need at a global scale. Ocean and environmental accounting has the potential to reverse the burden of proof for private exploitation and degradation of public or common ecosystem capital.

## Conclusions

Environmental degradation, particularly of coastal and marine ecosystems, is not only a direct loss, but also results in serious degradation of natural capital, the capacity of ecosystems to provide services that benefit humans. This degradation has been particularly severe in China, where the extensive research and information available on marine ecosystems is not driving sufficient changes in policy and management to protect and restore ecosystems and their services.

This paper shows that establishing standardized, marine ecosystem accounting, embedded in rigorous governance and policy structures to drive real-world accountability, could drive a step change in reducing degradation. The accounting and related policy frameworks could readily be adapted from, and integrated with, the existing highly effective frameworks in China's terrestrial environments, aided by international developments in ocean accounting. A wide range of Chinese and international case studies of environmental accounting on land and in the sea, and the policy application of that accounting, provide crucial demonstrations of the probable benefits such accounting could drive. Given the global scale of China's ocean footprint—whether measured by economic activity, length of coastline, human population, or seafood consumption—reducing the degradation of marine ecosystems would have globally significant benefits. In the words of Chen Shang (36) "Marine environmental protection is profitable, not expensive."

## Acknowledgments

The authors greatly appreciate the contributions of T. Praphotjanaporn, M. Ruckelshaus, A. Guerry, G. Daily, and M. Beck to the workshop and A. McCook and two anonymous reviewers for valuable comments on the draft manuscript. The authors acknowledge the passing of our dear friend and colleague, Dr. Michael Bordt, who contributed greatly to development of the workshop, drafting of this manuscript, and to international collaborations to develop ocean accounting.

## Supplementary Material

Supplementary material is available at *PNAS Nexus* online.

## Funding

This paper stems from a workshop hosted by the South China Sea Institute of Oceanology, Chinese Academy of Sciences in 2019, with support from Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, and from the United

Nations Economic and Social Commission for Asia and the Pacific. L.M. was supported in part by a President's International Visiting Professor Fellowship (2016VEA025) from the Chinese Academy of Sciences, and by James Cook University.

## Author Contributions

Laurence McCook (Conceptualization, Funding acquisition, Investigation, Methodology, Visualization, Writing—original draft, Writing—review & editing), Lyutong Cai (Investigation, Methodology, Visualization, Writing—original draft, Writing—review & editing), Chung Wing Yeung (Investigation, Methodology, Visualization, Writing—original draft, Writing—review & editing), Shang Chen (Conceptualization, Investigation, Methodology, Visualization, Writing—original draft, Writing—review & editing), Zhiyun Ouyang (Conceptualization, Funding acquisition, Investigation, Methodology, Visualization, Writing—original draft, Writing—review & editing), Put Ang (Visualization, Writing—original draft, Writing—review & editing), Michael Bordt (Conceptualization, Funding acquisition, Investigation, Methodology, Visualization, Writing—original draft, Writing—review & editing), Ling Cao (Visualization, Writing—original draft, Writing—review & editing), Zhu Chen (Visualization, Writing—original draft, Writing—review & editing), Baolong Han (Visualization, Writing—original draft, Writing—review & editing), Hui Huang (Funding acquisition, Visualization, Writing—original draft, Writing—review & editing), Xinming Lei (Visualization, Writing—original draft, Writing—review & editing), Jiansheng Lian (Visualization, Writing—original draft, Writing—review & editing), Feixue Li (Visualization, Writing—original draft, Writing—review & editing), Guifang Xue (Visualization, Writing—original draft, Writing—review & editing), and Peng Zhao (Visualization, Writing—original draft, Writing—review & editing).

## Data Availability

All data used for this work are previously published, with data sources referenced where cited.

## References

1 Millennium Ecosystem Assessment. *Ecosystems and human well-being: a framework for assessment*. Island Press, Washington, DC, 2003. p. 71–84.
2 Kumar P. *The economics of ecosystems and biodiversity: ecological and economic foundations*. Routledge, New York, NY, 2010.
3 Fenichel EP, *et al.* 2020. Modifying national accounts for sustainable ocean development. *Nat Sustain*. 3(11):889–895.
4 McCook LJ. 2022. What do we need to achieve conservation impact at the rate and scale required to avert further catastrophe? *Limnol Oceanogr Bull*. 31(3):72–74.
5 Peterson CH, Lubchenco J. On the value of marine ecosystems to society. In: Daily G, editor. *Nature's services: societal dependence on natural ecosystems*. Island Press, New York, NY, 1997. p. 177–194.
6 Zhan Q, *et al.* 2020. Review on the evaluation of the marine natural resources assets. *J Ludong Univ Nat Sci Ed*. 36:155–160.
7 McCook LJ, *et al.* Towards best practice management of coral reefs and marine protected areas in the South China Sea: challenges and opportunities…. In: Xue G, Zheng J, editors. *The law of the sea and emerging issues*. China Democracy and Legal System Publishing House, Beijing, China, 2017. p. 83–110.
8 Reviving China's Ocean Economy 2022. *Empower sustainable development*. World Wide Fund for Nature Beijing Representative Office, Beijing, China, 2022.
9 Cao L, *et al.* 2017. Opportunity for marine fisheries reform in China. *Proc Natl Acad Sci U S A*. 114(3):435–442.
10 Ouyang Z, *et al.* China: designing policies to enhance ecosystem services. In: Mandle L, *et al.*, editor. *Green growth that works: natural capital policy and finance mechanisms around the world*. Island Press/Center for Resource Economics, Washington, DC, 2019. p. 177–194.
11 Zhang K, Dearing JA, Tong SL, Hughes TP. 2016. China's degraded environment enters a new normal. *Trends Ecol Evol*. 31(3):175–177.
12 Guerry AD, *et al.* 2015. Natural capital and ecosystem services informing decisions: from promise to practice. *Proc Natl Acad Sci U S A*. 112(24):7348–7355.
13 *Ecosystem accounts for China. Results of the NCAVES project*. National Bureau of Statistics of China, Beijing, China, 2021.
14 Ouyang Z, *et al.* 2016. Improvements in ecosystem services from investments in natural capital. *Science*. 352(6292):1455–1459.
15 Wang J, Zou K. 2020. China's efforts in marine biodiversity conservation: recent developments in policy and institutional reform. *Int J Mar Coast Law*. 35:409–423.
16 *The SEEA ecosystem accounts for China. Policy brief*. United Nations SEEA, Beijing, China, 2021.
17 Ouyang Z, *et al.* 2020. Using gross ecosystem product (GEP) to value nature in decision making. *Proc Natl Acad Sci U S A*. 117(25): 14593–14601.
18 The Chinese Government. The outline of the 14th five-year plan (2021-2025) for national economic and social development and vision 2035 of the People's Republic of China. https://www.gov.cn/xinwen/2021-03/13/content_5592681.htm.
19 McCook LJ, *et al.* 2019. MPAs in southern China: upgrading conservation effectiveness in the "eco-civilisation" era. *Aquat Conserv*. 29(S2):33–43.
20 Chen D, Li P. 2006. Basic framework of ocean-based green GDP accounting (Chinese only). *Ocean Dev Manage*. 23:42–45.
21 The Chinese Government. Xi Jinping's congratulatory letter to China Ocean Economy Expo 2019. https://www.gov.cn/xinwen/2019-10/15/content_5440000.htm.
22 FAO. *Outline of the 14th Five-Year Plan (2021-2025) for National Economic and Social Development and Vision 2035 of the People's Republic of China (FAO translation)*. 2021 [cited 2024 30/4/2024]; Available from: https://faolex.fao.org/docs/pdf/chn205796.pdf.
23 Olds AD, *et al.* 2016. Quantifying the conservation value of seascape connectivity: a global synthesis. *Glob Ecol Biogeogr*. 25(1): 3–15.
24 Cao W, Wong MH. 2007. Current status of coastal zone issues and management in China: a review. *Environ Int*. 33(7):985–992.
25 Han Q, Huang X, Shi P, Zhang Q. 2006. Coastal wetland in South China: degradation trends, causes and protection countermeasures. *Chin Sci Bull*. 51(2):121–128.
26 Huang X, *et al.* 2006. Main seagrass beds and threats to their habitats in the coastal sea of south China. *Chin Sci Bull*. 51:136–142.
27 Hughes TP, Huang H, Young MAL. 2013. The wicked problem of China's disappearing coral reefs. *Conserv Biol*. 27(2):261–269.
28 Lian J, Huang H. Mainland China. In: Kimura T, Tun K, Chou LM, editors. *Status of coral reefs in east Asian seas region: 2014*. Ministry of the Environment, Government of Japan, Tokyo, Japan, 2014. p. 49–68.
29 Ma Z, *et al.* 2014. Rethinking China's new great wall. *Science*. 346: 912–914.

30 Zhang XL, Li PY, Li P, Xu XY. 2005. Present conditions and prospects of study on coastal wetlands in China. *Adv Mar Sci*. 23: 87–95.

31 Szuwalski C, Jin X, Shan X, Clavelle T. 2020. Marine seafood production via intense exploitation and cultivation in China: costs, benefits, and risks. *PLoS One*. 15(1):e0227106.

32 Chen M, *et al.* 2023. Assessment of marine protected areas in the East China Sea using a management effectiveness tracking tool. *Front Mar Sci*. 10:1081036.

33 Zhao Y, *et al.* 2022. An evaluation of management effectiveness of China's marine protected areas and implications of the 2018 Reform. *Mar Policy*. 139:105040.

34 Lei G, *et al. Blueprint of coastal wetland conservation and management in China*. Higher Education Press/Paulson Institute, Beijing, China, 2016. p. 30.

35 Chen S. *Technical directives for marine ecological capital assessment*. Standards Press of China, Beijing, 2011.

36 Chen S, *et al.* 2010. Marine ecological capital: concept and attributes. *Acta Ecol Sin*. 30(23):6323–6330.

37 Chen S, *et al.* 2010. Marine ecological capital: its value's constituents and assessment indicators. *Acta Ecol Sin*. 30(23):6331–6337.

38 Chen S, *et al.* 2013. Marine ecological capital: valuation methods of marine ecosystem services. *Acta Ecol Sin*. 33(19):6254–6263.

39 Ren D, *et al.* 2011. Marine ecological capital: valuation of standing stock of marine living resources. *Acta Ecol Sin*. 31(17):4805–4810.

40 Du G, *et al.* 2011. Valuation of ecological capital in Shandong coastal waters: standing stock value of biological resources. *Acta Ecol Sin*. 31(19):5553–5560.

41 Wang M, *et al.* 2011. Valuation of ecological capital in Shandong coastal waters: provisioning service value. *Acta Ecol Sin*. 31(19): 5561–5570.

42 Teh LS, Cashion T, Cheung WWL, Sumaila UR. 2020. Taking stock: a Large Marine Ecosystem perspective of socio-economic and ecological trends in East China Sea fisheries. *Rev Fish Biol Fish*. 30(2):269–292.

43 Moberg F, Folke C. 1999. Ecological goods and services of coral reef ecosystems. *Ecol Econ*. 29(2):215–233.

44 Deloitte Access Economics. *At what price? The economic, social and icon value of the Great Barrier Reef*. Deloitte Access Economics, Brisbane, Australia, 2017.

45 Beck MW, *et al.* Breaking waves. In: Spalding M, Brumbaugh RD, Landis E, editors. *Atlas of ocean wealth*. The Nature Conservancy, Arlington, VA, 2016. p. 34–45.

46 Ferrario F, *et al.* 2014. The effectiveness of coral reefs for coastal hazard risk reduction and adaptation. *Nat Commun*. 5:3794.

47 World Bank. Managing coasts with natural solutions: guidelines for measuring and valuing the coastal protection services of mangroves and coral reefs. In: Beck MW, Lange G-M, editors. *Wealth accounting and the valuation of ecosystem services partnership (WAVES)*. World Bank, Washington, DC, 2016. p. 167.

48 Costello C, *et al.* 2016. Global fishery prospects under contrasting management regimes. *Proc Natl Acad Sci U S A*. 113(18):5125–5129.

49 *China's ocean economy statistics (Chinese language)*. Ministry of Natural Resources, Beijing, China, 2021.

50 National Statistical Office. National statistical quality assurance framework. 2021. https://www.stats.gov.cn/sj/zxfb/202302/t20230203_1901137.html.

51 Ouyang Z, *et al.* 2013. Gross ecosystem product: concept, accounting framework and case study. *Acta Ecol Sin*. 33: 6747–6761.

52 Millennium Ecosystem Assessment. *Ecosystems and human well-being: synthesis*. World Resources Institute, Washington, DC, 2005.

53 National Development and Reform Commission. *Norms for accounting for gross ecological products (Chinese only)*. National Development and Reform Commission, and National Bureau of Statistics, Beijing, China, 2022.

54 *Opinions on establishing and improving the mechanism for realizing the value of ecological products*. Central Committee of the Chinese Communist Party, Beijing, China, 2021.

55 General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China, Standardization Administration of the People's Republic of China. GB/T28058—2011. Technical directives for marine ecological capital assessment. 2011.

56 Environmental Management. 20240276-T-469. Technical guidelines for marine gross ecosystem product accounting. 2024.

57 Global Ocean Accounts Partnership. Technical guidance on ocean accounting for sustainable development (v.1.0 March 2021). https://www.oceanaccounts.org/tag/guidance/.

58 GOAP Secretariat. *Technical guidance on ocean accounting for sustainable development*. Global Ocean Accounts Partnership, Sydney, Australia, 2021.

59 Ministry of Natural Resources. Regulation of sea use for regional development. 2016 [accessed 2016 Jun 15]. https://f.mnr.gov.cn/201807/t20180702_1967395.html.

60 Ministry of Natural Resources. Establishing marine ecological redline regime [accessed 2016 Jun 15]. https://www.mnr.gov.cn/dt/hy/201603/t20160308_2332871.html.

61 Sun J, Song Y, Shi Y, Zhai J, Yan W. 2022. Progress of marine biodiversity studies in China seas in the past decade. *Biodivers Sci*. 30(10):22526.

62 Deng Y, Shi Y. 2023. Recent developments of China's institutional reform for ocean management: an appraisal. *Coast Manag*. 51(2):91–114.

63 Zhang C. China's marine governance reshuffle, three years on. 2021 [accessed 2024 Jul 17]. https://dialogue.earth/en/ocean/18692-china-marine-governance-reshuffle-three-years-on/.

64 Ministry of Agriculture. Notice on strengthening the management of domestic fishing vessels and implementing total allowable catch control of marine fishery resources. 2017 [accessed 2025 Mar 6]. https://www.moa.gov.cn/govpublic/YYJ/201701/t20170120_5460583.htm.

65 Ministry of Agriculture. Measures for the administration of aquatic germplasm resource reserves. 2016 [accessed 2025 Mar 6]. https://www.gov.cn/zhengce/2016-05/30/content_5721419.htm.

66 Zhou C. How can informal protected areas help China achieve biodiversity goals? 2022 [accessed 2024 Nov 1]. https://dialogue.earth/en/ocean/how-can-informal-protected-areas-help-china-achieve-biodiversity-goals/.

67 McCook LJ, *et al.* 2010. Adaptive management of the Great Barrier Reef: a globally significant demonstration of the benefits of networks of marine reserves. *Proc Natl Acad Sci U S A*. 107(43): 18278–18285.

68 *Investing in the Great Barrier Reef as economic infrastructure: final report*. Jacobs Australia, Brisbane, Australia, 2016.

69 Grafton RQ, Kompas T, Hilborn RW. 2007. Economics of overexploitation revisited. *Science*. 318(5856):1601–1601.

70 Dichmont CM, Pascoe S, Kompas T, Punt AE, Deng R. 2010. On implementing maximum economic yield in commercial fisheries. *Proc Natl Acad Sci U S A*. 107(1):16–21.

71 Narayan S, *et al.* 2016. The effectiveness, costs and coastal protection benefits of natural and nature-based defences. *PLoS One*. 11(5):e0154735.

72 Arkema KK, *et al.* 2015. Embedding ecosystem services in coastal planning leads to better outcomes for people and nature. *Proc Natl Acad Sci U S A*. 112(24):7390–7395.
73 Arkema KK, *et al.* 2023. Evidence-based target setting informs blue carbon strategies for nationally determined contributions. *Nat Ecol Evol*. 7(7):1045–1059.
74 de Vos K, Hart B. *The ocean finance handbook: increasing finance for a healthy ocean*. Friends of Ocean Action, Geneva, Switzerland, 2020.
75 *IUCN Policy on biodiversity offsets*. International Union for the Conservation of Nature, Gland, Switzerland, 2016.
76 Gardner TA, *et al.* 2013. Biodiversity offsets and the challenge of achieving no net loss. *Conserv Biol*. 27(6):1254–1264.
77 Bull JW, *et al.* 2013. Biodiversity offsets in theory and practice. *Oryx*. 47(3):369–380.
78 Sun Y, Huang L, McCook LJ, Huang H. 2022. Joint protection of a crucial reef ecosystem. *Science*. 377(6611):1163–1163.