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The mechanics of blue growth: Management of oceanic natural resource use with multiple, interacting sectors

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ABSTRACT

Integrated management of multiple economic sectors is a central tenet of blue growth and socially optimal use of ocean-based natural resources, but the mechanisms of implementation remain poorly understood. In this review, we explore the challenges and opportunities of multi-sector management. We describe the roles of key existing sectors (fisheries, transportation, and offshore hydrocarbon) and emerging sectors (aquaculture, tourism, and seabed mining) and the likely synergistic and antagonistic inter-sector interactions. We then review methods to help characterize and quantify interactions and decision-support tools to help managers balance and optimize around interactions.

1. Introduction

The ocean is a rich source of both renewable and nonrenewable natural resources, which have provided numerous economic, social, and cultural benefits throughout history and afford great opportunities for future provision of benefits [1,2]. These benefits are often realized through economic sectors, of which the overall number and total activity has increased over the last 50 years [3]. Growth in ocean-based economic sectors has come from improved access to, utilization of, and production efficiency from oceanic natural resources [4,5]. At the same time, use of oceanic resources has led to conflicts between sectors (e.g. tourism vs. offshore hydrocarbon extraction), at different levels of organization (e.g. between individuals, groups, and nations), at multiple spatial scales (e.g. in local waterways, regional seas, or global oceans), and across time (e.g. between current and future uses). Continued economic growth from the oceans is likely to lead to more cross-sector conflicts and the potential for environmental destruction, sub-optimal natural resource use, and other socially undesirable outcomes [6].

The history of modern ocean governance and management has been one of increasing complexity, with managers traditionally focusing on individual economic sectors and moving towards integrated systems with multi-sector coordination [7]. Recently, there has been a push for ecosystem-based management (EBM) of coasts and oceans [8]. EBM is a framework through which management efforts are structured around a single place or ecosystem, with the health and productivity of that ecosystem or group of ecosystems as the nucleus of management. The activity of economic sectors and other human uses are regulated to balance their impacts on the health of ecosystems [9–11]. While current management is largely fragmented, with most sectors managed by individual laws, agencies, or regulatory regimes [12,13], there are calls for integrated, cross-sectoral management approaches to achieve EBM [e.g. 14,15].

Cross-sector management is complicated by the dynamic nature of the ocean, which is constantly changing over a range of spatial and temporal scales [e.g. 16]. Climate change and natural variability are directly modifying the ocean through increased sea surface temperatures, higher acidity, and changes to other attributes of physical and chemical oceanography. These changes can lead to melting sea ice, sea level rise, and altered ecosystems (e.g. changes in species abundance and biodiversity) that ultimately affect the ability of humans to derive benefits from the ocean, with both positive and negative impacts on human access to resources and benefits [17]. In addition to acknowledging linkages between sectors, management must be dynamic and adaptive, allowing single sector and multi-sector management

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frameworks to respond in near real time to changing environmental, economic, and social conditions [18].

Reflecting these challenges, the concept of blue growth as a "long term strategy to support sustainable growth in the marine and maritime sectors as a whole" was recently adopted by the European Commission [19]. The concept has been increasingly used as a strategy for achieving both sustainable marine resource use and economic expansion around the globe [20]. But the initial visioning reports addressing the concept do not detail how to operationalize blue growth [21,22]. A critical, but little studied, component of attaining the goals of blue growth is a multi-sector approach to management, including identifying and optimizing cross-sector interactions [21]. A key obstacle to multi-sector management is a lack of information on how sectors interact with each other and how changes in one sector affect the incentives and actions of others. Here, we review cross-sector interactions within the ocean economy and the decision support tools that are available to help manage these interactions.

2. Economic sectors

There is a diversity of economic sectors involved in the ocean economy, and classification of sectors varies by country and region [23–25]. An economic enterprise is considered to be an ocean-based economic sector if it exhibits one or more of three characteristics–being physically located in the ocean, using ocean resources as an input to production, or directly outputting goods or services to the ocean [23]. This review does not include the multitude of possible sectors and subsectors due to space limitations. Instead, to highlight the challenges and opportunities presented by inter-sector interactions, we review several key sectors that are recognized as focal areas for blue growth: aquaculture, wind and wave power, seabed mining, and tourism, as well as several traditional ocean sectors: fisheries, transport, and offshore hydrocarbons (Table 1). The inputs to each sector, including the required ocean resources, are compared (Table 2), as these are often sources of interactions between sectors. Costs that are frequently external to the market price of the sector's products (i.e. not reflected in the market price) are also listed, as these can often be used to determine the nature of non-neutral interactions between sectors.

2.1. Blue growth sectors

Aquaculture, wind and wave power, seabed mining, and tourism are recognized as emerging economic sectors and blue growth focal areas by the European Union [22]. Coastal and offshore aquaculture involves the farming of aquatic organisms (including plants, shellfish, and finfish) in coastal waters and the open ocean. The majority of farmed seafood is currently produced on land [26], but coastal and offshore aquaculture production are likely to increase as technology improves and the cost of farming on land increases [27]. Costs that are often external to aquaculture include: pollution of water by feces, uneaten feed, and chemicals; destruction of local habitats to build aquaculture infrastructure or by pollution; transmission of diseases and parasites to wild flora and fauna; and escaped farmed organisms that can compete or interbreed with wild organisms [27,28].

Wind and wave power are ocean-based renewable energy production sectors. Offshore wind farms use turbines to generate electricity from wind [29] and wave energy operations use a range of techniques to convert wave energy into electricity [30]. Offshore wind accounted for a quarter of the EU's wind power in 2015, and the sector is expected to expand rapidly, especially in Chinese waters [31], as technology improves to move wind farms farther offshore [32]. Wave energy converters can be located at the surface, in the water column, or on the seafloor and can surge, heave, pitch, or oscillate to convert wave energy [30,33]. Wave energy production is expected to increase dramatically by 2050, but it will likely remain a smaller player relative to offshore wind [34].

The environmental impacts of offshore wind and wave power are often external to the market price of energy. The environmental impacts of offshore windfarms occur mostly during construction of the platform and at highly local scales thereafter. Further, platforms can act as a fish aggregating device, while noise and electromagnetic fields can deter marine mammals [35]. Turbines can cause disturbances for or mortality to local and migratory birds [35]. The negative environmental impacts of wave energy that are often not included in the price include disturbance or harm to nearby ecosystems through noise, vibrations, electromagnetism, biofouling, sedimentation, disruption of animal migrations, and functioning as an artificial habitat or fish aggregating device [36].

Seabed mining involves extraction of minerals from the ocean floor [37]. Increased demand for metals and rare-earth elements and technological developments have improved the economic viability of mining the deep seabed [38]. Mining has been proposed on abyssal plains, on seamounts, and near hydrothermal vents [39]. Most seabed mining is currently focused on near-shore, shallow water areas, but technology is improving to allow experimental deep seabed mining operations in the near future [38]. The environmental costs that are

Table 1
Classification of primary ocean economic sectors as either extractive or non-extractive and reliant on living or non-living resources [based on 23,24]. Shaded sectors are included in this review and sectors recognized as blue growth focal areas by the European Union are starred (*).

Extractive	Living marine resources	Fisheries
		Aquaculture*
	Non-living marine resources	Offshore hydrocarbons
		Wind and wave power*
		Seabed mining*
		Salt
		Water
Non-extractive	Living marine resources	Tourism and recreation*
	Non-living marine resources	Transportation
		Construction
		Ship and boat building
	Both	Public administration
		Education and R&D*
		Others

Table 2
Production inputs and outputs to specific ocean-based economic sectors. Inputs shared by individual sectors can increase the likelihood of inter-sector interactions.

Inputs	Fisheries	Aquaculture	Offshore hydrocarbons	Wind and wave power	Seabed mining	Tourism	Transportation
Ocean space - surface	x	x	x	x	x	x	x
Ocean space - midwater	x						
Ocean space - benthic	x	x	x	x	x		
Biological resources	x	x				x	
Aesthetic resources						x	
Physical resource			x	x	x	x	
Labor	x	x	x	x	x	x	x
Fuel	x	x	x	x	x	x	x
Port infrastructure	x	x	x		x	x	x
Other infrastructure		x	x	x			
Vessels	x	x	x	x	x	x	x
Chemicals		x	x				
Output	Seafood	Seafood	Hydrocarbons	Energy	Minerals	Recreation	Transportation

likely external to the price of mined materials are expected to occur predominately on the seafloor and around drill sites due to removal of substrate and sedimentation from both drilling and returned sea water. But environmental impacts can occur at any step in the production process due to accidental events and natural hazards [40], and potential impacts include physio-chemical changes, biological changes, and potentially compounding effects of cumulative changes to surrounding ecosystems [40,41].

Marine and coastal tourism involves recreational activities focused on the marine or coastal zone [see 42 for a discussion of the typologies of marine tourism]. Both the number of types of and the overall demand for coastal and marine based tourism have grown over the last several decades and are expected to continue to increase [43,44]. Tourism can be both consumptive of ocean resources (e.g. sport fishing) and non-consumptive (e.g. whale watching). Environmental impacts caused by tourism can include habitat loss, habitat damage, wildlife depletion, and wildlife disturbance [45]. Evaluation of the non-point source pollution impacts of tourism (e.g. ecological harm from sunscreen use [46]) is increasingly important as tourism becomes more diffuse and widespread.

2.2. *Sectors not included in the blue growth agenda*

Fisheries, offshore hydrocarbon production, and transportation are robust ocean economic sectors that have not been included in the European Union blue growth agenda. Fisheries describe the capture of aquatic biological resources, including plants, shellfish, and finfish. Globally, fish catches peaked in the 1990's and have plateaued or decreased since [26,47]. Many fisheries are depleted or experiencing overfishing [48], and there is substantial potential to increase both yields and profits through rebuilding of depleted stocks [49,50]. At the same time, revenues from global fisheries are expected to decrease by approximately 10% between 2000 and 2050 due to climate change [51]. Fishing externalities can include depletion of the population being fished, depletion of other species that are ecologically linked to the target species, and damage to habitats or ecosystems through direct contact with fishing gear, discharge from vessels, or discharge from at-sea processing plants [52].

Offshore hydrocarbon production describes the extraction of crude oil and natural gas from below the seafloor. Offshore oil and gas production began in the 1960s and 70s [53] and now encompasses about 1/3 of global oil production [54]. Offshore expansion is expected to continue, especially with technological developments that allow for production in increasingly deeper waters (below 200 m) [53,55]. Costs that are often external to the price of hydrocarbons are primarily the result of contamination of surrounding waters with extracted oil or gas. Contamination can occur during routine operation of offshore facilities during multiple phases, including exploration, development, production, transport, or well-abandonment [56]. Effluent from oil production can have long-term negative impacts on oceanic ecosystems and future provision of ocean resources [57].

The marine transportation sector uses vessels (e.g. container ships, bulk carriers, tankers, and ferries) to move people and goods from one location to another across oceanic and coastal waterbodies [58]. Between 1992 and 2012 there was a fourfold increase in global ship traffic [59], and over 80% of current global trade volume is shipped via sea [60]. Further, marine transportation volumes are expected to increase with future economic growth [60]. Costs that are external to the price of shipping typically include environmental impacts and subsidies. Shipping can harm the environment through discharges at sea (e.g. oil, wastewater, paints, ballast water, and marine liter), airborne emissions (e.g. engine exhaust, refrigerants, and other volatile chemicals), noise, and shipwrecks or scrapping [as reviewed in 58]. Of particular concern for ocean ecosystems is discharge of ballast water, which can contain pathogens and non-native and potentially invasive species [61,62].

3. Interactions

Ocean economic sectors increasingly utilize adjacent or overlapping ocean spaces and share inputs to production. As such, interactions between sectors will become increasingly common and potentially alter the private and social profitability of enterprises and sectors. Below we review the types of interactions between sectors and their context dependencies.

3.1. *Types of interactions between sectors*

To categorize cross-sector interactions, we use concepts from ecological theory (Fig. 1). Synergistic interactions include mutualism, where all sectors benefit from an interaction, and commensalism, where one sector benefits but the other is unchanged. Antagonistic interactions include amensalism, where one sector is harmed and the other is neither improved nor harmed, antagonism, where one sector is harmed while the other benefits, and competition, where all sectors are harmed [63–66]. Below are examples of each type of interaction and how they can affect the profitability of an enterprise or sector by altering the dynamics of the input costs or output price associated with production.

Interactions between sectors that affect inputs to production are most common. For example, mutualistic inter-sector interactions can be found in the co-development of offshore structures to accommodate the activities of multiple sectors [67,68]. If a wind installation and aquaculture operation share mooring equipment, they both benefit from

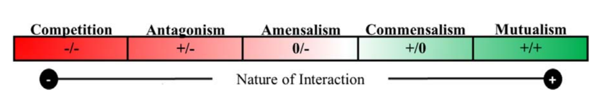

Fig. 1. Typology of interactions between economic sectors. Red interactions are antagonistic and green are synergistic.

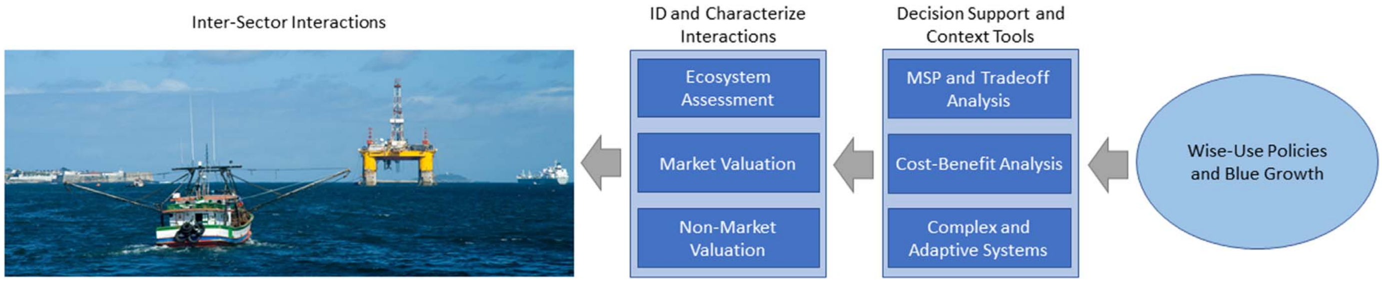

Fig. 2. Schematic of inter-sector interactions (a tourist coastline, fishing trawler, oil platform, and coastal freighter in Brazil), methods available to identify and characterize potential interactions, and decision support tools that can help stakeholders and policy makers realize wise use of ocean-based natural resources and blue growth. (Photo: Colourbox.com).

reduced infrastructure costs. Further, there may also be reduced fuel and labor costs due to opportunities for sharing crew and equipment transportation [69–71]. Similarly, industries that rely on ports as an input to production (e.g. tourism and transportation, Table 2) can share facilities and reduce overall input costs. Commensality can be seen in the development of surfing and fishing based tourism around wave power structures. Tourism benefits through provision or enhancement of a biological or physical resource (fish or waves), while wave energy enterprises are unaffected by the presence of surfers and fishermen [72]. An example of amensalism can be found when offshore hydrocarbon operations are sited near tourism locations. Tourism operations may see their access to aesthetic resources diminished, as customer enjoyment may be reduced by the sight of hydrocarbon structures, but the hydrocarbon operation may be unimpacted [73]. Antagonism can be found when seabed mining is located on seamounts or other prime fishing zones, excluding fishermen from access to the area [39,74]. An example of competition can be found when other economic sectors are located in shipping lanes. Both the transportation sector and the other sector are prone to additional risks of collision with shipping vessels and added safety costs [75].

Interactions between sectors that affect outputs of production are less common but can also influence the overall profitability of an enterprise. Output interactions are largely the result of changes in perception by different market actors that result in increased or diminished demand for a good and, as a result, a change in price. A mutualistic interaction can be found when two industries (e.g. tourism and aquaculture) are sited in close proximity and enhance each other's reputation, leading to product differentiation and increases in the price of both. For example, if an eco-tourism enterprise operates near an aquaculture operation that markets itself as a sustainable farm, both enterprises may see an increase in their demand and price due to added publicity. The interaction is commensalism if only one of the prices increases (e.g. the eco-tourism operation successfully differentiates its product and the price increases, but the price of the seafood produced by the aquaculture operation remains the same).

Similarly, antagonistic interactions can affect production outputs. An example of amensalism can be seen in the aftermath of a marine oil spill, when fisheries and aquaculture products from the region are negatively impacted by contaminants in oil. Negative public perception of seafood from the region can reduce demand and lower prices, even after the seafood has been cleared as safe for human consumption by regulatory bodies [76]. An example of an antagonistic interaction can be found in the marketplace between fishery and aquaculture products. Fishery trade organizations often try to market their products as being different than and superior to farmed products, potentially altering demand to increase the price of wild products and diminish the price of aquaculture products [77].

3.2. *Context-dependency of interactions between sectors*

Characterizing and anticipating interactions between sectors is complicated because the nature, intensity, and probability of an interaction may be context dependent in how it affects inputs and outputs of production. For example, when fishing is allowed in close proximity to an aquaculture operation, the interaction can lead to mutualistic effects on inputs, where the aquaculture operation acts as a fish aggregating device, increasing the catchability of fish and subsequent profits for fishermen [28]. And at the same time, fishermen can act as sentinels for the farm and monitor and report operational problems such as theft, vandalism, or equipment malfunctions [78]. But the co-location of fisheries and aquaculture can also lead to commensalism if the fishermen do not have a close or working relationship with the farm and do not provide helpful monitoring [79]. Further, if the relationship between the fishermen and the farm is unfriendly, the interaction can be antagonistic if fishermen actively impede farm production through vandalism or other types of interference [80].

Context can also produce opposite interactions. For example, the development of marine wind farms near tourist areas can result in commensalism when tourists view wind farms positively and see them as providing an aesthetic resource or recreational benefit at no expense to the wind farm [81–83]. If the public perception of wind farms is negative, the interaction can result in amensalism, where the aesthetic resource is diminished. A similarly dynamic relationship can be found between wave farms and surfing tourism and fisheries [72,84,85].

4. Quantification and decision-support tools for managing interactions between sectors

Managing the interactions between ocean economic sectors is a critical component of blue growth. The first challenge is for interactions to be identified and quantified. Second, decision-support tools and frameworks can help society and policy makers manage interactions given broader economic and social goals. In this section, we review several tools that are currently available to evaluate and balance interactions between sectors (Fig. 2).

4.1. *Tools to characterize and quantify interactions*

A diversity of tools is available to help stakeholders and policy makers characterize and quantify the nature of interactions between sectors. To achieve management goals around interactions, it is important to understand the type of interaction (as described in Section 3.1), the context-dependency of the interaction (as described in Section 3.2), and the possible options to mitigate or enhance interactions. Ecosystem Services (ESs) are one important method for evaluating the nature and value of interactions between sectors. ESs describe the range of benefits humans derive from ecosystems and natural capital stocks [86] and are broadly defined as being either supporting, provisioning, regulating, or cultural services [87]. Assessment and valuation of the change in ESs associated with interactions between sectors can help characterize and anticipate interactions between sectors, both at present and in the future. Ecological assessments, market valuation, and non-market valuation can all be used to evaluate tradeoffs and changes in ESs associated with inter-sector interactions.

4.1.1. Ecological assessment

Ecological assessments can help determine the characteristics and value of interactions between sectors by establishing a baseline of ESs, natural resources, or ecosystems, and then comparing stocks before and after interactions [88,89]. Indicators of marine ecosystem health, ESs, and natural resource stocks can be measured by increasingly sophisticated sensors placed on living animals, vessels, stationary or mobile platforms, and satellites [18,90]. Sensors can also be networked to transmit and share data in real time, employing an underwater "internet of things" to expand monitoring capacity [91]. Data from interconnected sensors can then be synthesized and made accessible to decision and policy makers in real time to increase the speed and efficiency of ecosystem health evaluation and management [92]. While assessments of the stocks and flows surrounding ESs, natural resources, and ecosystems are useful for determining the characteristics and value of interactions, they do not provide context as to the larger social and economic value of the interaction [88].

4.1.2. Market valuation

Markets are mechanisms through which consumers and producers express willingness to pay (demand) for and willingness to produce (supply) a particular good or service. In a competitive market, the equilibrium point between demand and supply reveals a market equilibrium price for the good being traded, resulting in the optimal allocation of scarce resources. If an interaction between sectors impacts a good or a service that is traded, the value of the interaction can be quantified with the market price method, based on the demand and supply curves in question, as well as the equilibrium market price. If, for example, a fish harvest that is traded in markets is affected by offshore wind power generation, the market price method will demonstrate the net economic benefit and thus the net welfare impact of simultaneously harvesting stock and generating electricity. The market price method is only applicable in cases where the goods or services in question are traded in markets. As many ecosystem goods and services are not traded, the market price method is unable to reveal total value derived from a particular ecosystem or affected by interactions. As a result, non-market evaluation is routinely applied.

4.1.3. Non-market valuation

When a good is not traded and therefore does not have a clear market price or if the market price does not encapsulate the full social value, non-market valuation techniques can be utilized to help quantify the likely changes in private and social value associated with an interaction between sectors. Non-market valuation techniques are considered to be either revealed preference or stated preference approaches [for reviews of non-market valuation techniques, see 93–95]. Revealed preference approaches (e.g. hedonic price, travel cost methods, as well as avoided and replacement costs) are helpful in determining the potential change in economic welfare based on the use-value of non-market goods. Stated preference approaches (e.g. contingent evaluation and choice modeling) are helpful in determining economic welfare associated with both use and non-use values of non-market goods. Complementing market valuation methods with non-market valuation methods can help attain the "total economic value" or the full economic welfare impacts of interactions between sectors. For example, if offshore wind generation is expected to impact coastal tourism in a particular area, non-market evaluation can be used to reveal the welfare changes associated with changes in willingness to pay for recreation in the affected area and the economic value of the potential environmental impacts of both wind generation and the expected changes in tourism.

4.2. Decision support tools to help societies manage cross-sector interactions

Once interactions have been characterized and quantified, they can be compared and managed with tools such as marine spatial planning, tradeoff analysis, and cost-benefit analysis. Additionally, complex and adaptive systems and heuristic approaches can ensure that management is adaptable and dynamic in the face of changing environments, economies, and societies. Balancing the costs and benefits of interactions can help policy makers and society optimize around interactions to harness the desired benefits of ocean-based natural resources.

4.2.1. Marine spatial planning and cross-sector tradeoffs

Marine spatial planning (MSP) is broadly defined as a set of tools used to delineate human use of coasts and oceans. These tools span numerous forms, from Geographic Information Systems used to map out the distribution of important quantities (e.g. fish habitat, oil reservoirs, or shipping lanes) to the design of governance institutions that greatly impact the behavior of humans located in or near marine systems. For example, marine protected areas (MPAs) are areas of the ocean that are off-limits to fishing, and their design revolves around questions of the size, shape, and location of protected areas. MSP, through improved management and MPA design, has been instrumental in preserving marine biodiversity and has been adopted in many places around the globe [96]. To date, 14.9 million km^2 of the world's oceans have some form of protection, guarding marine organisms against numerous perturbations [97]. But MPA design is just one example of marine spatial planning.

Many MSP endeavors focus on a single economic sector. In contrast, the cutting edge of MSP is now spatial optimization over multiple sectors. For example, White et al. identified locations where offshore wind-turbines could be placed to maximize both energy production and marine conservation [98]. A key step in this methodology was to develop a bioeconomic model with which to describe the inherent tradeoffs between wind energy production and the biological effects of offshore turbines. These kinds of tradeoffs can be quantified empirically (see Section 4.1), and several optimization tools can then be used to map out where different industrial sectors might be located in order to maximize aggregate measures of success (e.g. cross-sector profit). Cross-sector management is a logical extension of the two-sector optimization seen in White et al. [98]. There has been some criticism that MSP can result in an overvaluation of integrated use relative to environmental protection and that conducting a full tradeoff analysis can be prohibitively expensive [99], but quantifying the inherent tradeoffs between sectors is central to being able to optimize spatially across sectors and achieve blue growth.

4.2.2. Cost-benefit analysis

Cost-benefit analysis (CBA), where the economic costs and benefits of the production of goods and services are compared to determine the expected net economic value of different choices, can be a valuable tool for evaluating the tradeoffs associated with interactions between sectors. In CBA, all the economic costs and benefits associated with the activities of a particular sector are assessed. For a sector to contribute to blue growth, the benefits must outweigh the costs. The costs and benefits accounted for in a full CBA include both costs and benefits that are derived from use and non-use values, revealing the Net Present Value of the activities in question. For example, offshore power generation produces economic benefits in the form of electricity that is sold in markets and economic costs that are based on both market and non-market values. Costs assessed using market valuation include, for example, the direct costs of building and operating the power generation units. Costs assessed using non-market valuation include the potential negative environmental costs of the activity, the negative impact on other economic sectors that generate non-market value, as well as implications for the existence value of the ecosystems in question.

There are several disadvantages to using CBA in the context of blue growth. First, the assessment of the value of non-market goods is only an approximation, as practitioners are often valuing the "priceless". Second, if an action provides "net" economic benefits, CBA assumes that an activity should go forward even if it may cause significant environmental harm, evoking weak sustainability. This means that CBA rests on the assumption that any market or non-market good can be traded for another one. Third, in CBA the choice of the appropriate discount rate when assessing the present value of future benefits and costs has been a source of debate for years. In the context of economic benefits or costs associated with changes in environmental quality, the choice of a high discount rate has been criticized as it can create an unreasonable imbalance between the present and the future [100–102].

4.2.3. Complex and adaptive systems and heuristic approaches to governance

Marine economic systems often contain numerous competing sectors, each comprised of heterogeneous actors. In such cases, it may be impossible to characterize and quantify all the different interactions and subsequent tradeoffs between sectors. As a result, marine systems as a whole might respond in unexpected and potentially negative ways to management actions targeting any one sector. However, there is an opportunity to learn from other complex adaptive systems in the use of "heuristic" approaches to cross-sector management. For example, the vertebrate immune system provides the human body–a complex and adaptive system–resilience to a number of known and unknown perturbations [103]. It has three major properties. First, the vertebrate immune system has early warning signals of any problem. Second, there is a generalized response to all perturbations, which buys the body time to develop an adaptive response and a specialized solution to the problem. Finally, immune systems are polycentric in nature: there is no central controller directing how the body responds to perturbation. Responses are dispersed and decentralized, giving the body faster response times to perturbation. Ocean governance institutions that mimic these properties will help create resilient coastal communities, steering marine systems away from catastrophic states and towards ones that more closely align with the concept of blue growth.

5. Summary

As the global exploitation of ocean-based natural resources expands through an increasing number and diversity of economic actors, interactions between sectors are increasingly likely. Integrated, multi-sector management is required if the benefits of interactions are to be harnessed and potential pitfalls avoided. We present a typology of interactions and review the state-of-the-art methods for characterizing and quantifying cross-sector interactions. Further, we highlight tools and frameworks for balancing costs and benefits of interactions with other facets of natural resource use. Many of the methods and tools discussed here have yet to be widely adopted by national and international policy makers and managers. The cost of not acting to optimize cross-sector interactions includes the lost opportunities of optimal natural resource use and the potential for costly litigation as conflicts between sectors increase [e.g. 78]. We believe it is imperative that cross-sector interactions are identified and incorporated into governance frameworks. Doing so will greatly improve the chances of realizing blue growth.

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