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Assessing the Complexity of Social-Ecological Systems: Taking Stock of the Cross-Scale Dependence

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Received: 1 July 2020; Accepted: 30 July 2020; Published: 3 August 2020

Abstract: Human demands and activities introduce cross-scale pressures in different systems and scales, affecting the provision of ecosystem services and causing an unbalanced effect on human well-being within the territory. The existing institutions are frequently considered panaceas since they do not take into account the different spatial and jurisdictional scales of the social-ecological systems (SES). This paper aims to broaden the existing DPSIR (Drivers–Pressures–State–Impact–Response) assessment frameworks to strengthen the ecosystem approach and promote an integrated cross-scale perspective. The concept of the Cross-scale Ecosystem-Based Assessment (DIET) was developed and applied to a case study on the demand of seafood provisions. The assessment has indicated that the activities related to the specified demand occur at different scales and generate cumulative impacts and pressures on other scales, especially in the coastal zone. The existing responses to address this issue are highly fragmented, both spatially and among sectors. DIET was applied here to the land–sea interface to illustrate how coastal zone governance and management can be improved and how the impact of certain drivers or activities in the SES can be reduced. DIET may help to reduce the governance morbidity and prevent panaceas by fostering the integration of institutions in pursuing flexible, adaptive and fit-for-purpose policies to address complex issues so as to secure social-ecological justice and well-being for all humans.

Keywords: conceptual framework; environmental assessment; institutional fit

1. Introduction

The sustainability of social-ecological systems (SESs) depends, in part, on the fit of institutions to the problems, their contexts and scales [1–3]. Therefore, it is necessary to consider the systemic complexity and the wicked effects of environmental problems on the governance and management of a common-pool resource, or ecosystem service, as well as the territory. Thus, assessment approaches that consider the dialectical and causal relationship between environment and society, and include the different scales and process of a social-ecological system [4,5], are fundamental to facing the challenges of sustainable development in its three interdependent dimensions: ecological, economic and socio-cultural [2].

The discussion of the sustainability of different systems has been the subject of a range of studies, and many methodologies and tools that introduce integrated and holistic assessment approaches have been proposed and evaluated [6]. The assessment approaches to assist in the understanding of social-ecological systems are varied, and include applied tools such as the Drivers–Pressures–State–Impact–Response (DPSIR) framework and its adaptations [7–9], scientific information [10–12], and institutional arrangements [3,13,14]. To properly assess the cross-scale nature of SES problems and their causal chain, it is essential to recognize that they feature complex and dynamic interactions within the territory.

This can be exemplified by the land–sea interface, with drivers operating at some scales (centered in the continental and coastal zones) that are decoupled from the scales of the negative impacts they cause (normally in the coastal and marine zones). Such a cross-scale integration is still not captured by the existing assessment frameworks and, consequently, is not being taken into account in the governance of SESs.

The coastal and marine zones harbor vigorous social-economic activities, such as tourism, energy, fisheries and shipping, that support the demands from the continental zone. It allows a cultural and social appropriation that identifies them as a leisure space, and safeguards preserved spaces, which today are even more valued as ecosystem services [15] and for well-being [16]. The ecosystem services provided by the coastal zone are varied. With the biophysical processes that promote the functioning of the marine and coastal zone (e.g., maintenance of life and biodiversity, atmospheric circulation, remineralization of nutrients, etc.), these environments guarantee the survival of hundreds of millions of people, and contribute to more than 60% of the total economic value of the biosphere. It is estimated that, although coastal zones cover only 8% of the world's continental surface, the benefits from these ecosystems are responsible for approximately 39.8% of the total estimated value of global ecosystem services, reaching up to USD 27.7 trillion [17]. However, in practice, the oceans continue to suffer from the cumulative and synergistic negative impacts of human activities that occur both on land and in the sea [18]. There was an estimated loss of USD 10.9 trillion annually in ecosystem services in the coastal zone, for the period from 1997 to 2011 [17].

The trend of great population expansion and urbanization in the coastal zone adds even more complexity to this system. Coastal areas attract a large concentration of people linked to various human activities, such as fishing, industry, tourism and transport. All of these activities and uses engender conflict over territorial use in a dynamic and integrated transitional environment between land and sea domains [19].

Thus, the coastal zone's sustainability is directly related to anthropic activities located in the continental, coastal and marine zones [20]. The impacts and pressures coming from this land–sea interface alter the state of the environment in all domains or compartments (continental, coastal and marine zones); therefore, it is imperative to consider cross-scale dependence in the management of the territory [21]. However, the existing institutions are sectorized and fragmented, and, generally, do not take the different spatial and jurisdictional scales of the social-ecological processes into account [22]. As sectoral management regulates only one activity or compartment, they lose the dimension of their cumulative and synergistic impacts, since different activities exert pressure, simultaneously, on marine ecosystems, destroying habitats (e.g., suppression of mangroves) or altering the environmental quality (e.g., litter, eutrophication) [22]. These pressures have cumulative impacts on the structure and functioning of ecosystems and, therefore, the sectoral management is considered inadequate [18,23] since it does not consider the different interdependencies and scales of planning and acting.

The issues of scale and the dynamics associated with it have become more relevant with a comprehensive understanding of global processes and sustainability issues. By scale, we mean the parts of a system that can be classified as spatial, temporal, jurisdictional, analytical or network [4,24–26]. There is a growing recognition that many problems have causes and solutions that span multiple levels within a given scale, such as the modes of production that can affect the marine and coastal space during the stages of production, distribution and consumption, especially when their productive phases use the sea's support function [27]. Often, however, there is an admission of ignorance or unwillingness to address specific levels and cross-scale interactions [4]. Therefore, these interactions must be explored—especially from the point of view of public policies—to gain a better understanding of the scenario and the level of policy fragmentation.

It is also relevant to understand and analyze the urban expansion of large metropolises, megacities, metropolitan regions, mega-regions, or other conceptualizations of large-scale urban processes. When close to the coast, these urban phenomena are responsible for a large part of the socio-economic flows to and from the coast, causing unbalanced positive and negative impacts in different scales

and influencing the territory's dynamic [28,29]. On the other hand, the impact of the expansion of oil and gas developments, renewable energy facilities (off-shore wind farms) and fishing activities has intensified [30], and, consequently, has been causing a series of impacts in the coastal and marine areas [31]. The analysis of these large-scale phenomena and their impacts, which are influenced by regional, macro-regional or cross-cutting processes, must be developed within a context of sectoral and political-institutional integration that goes beyond traditional territorial and institutional jurisdictions. Thus, the problems that plague the coastal and marine zones need to be addressed in different dimensions and scales, with a clear demand for institutional fit [32,33], so that the institutions created are not merely interpreted as panaceas or magical solutions to complex problems [3,14]. Institutions here refer to any formal and informal rule, norm, code or convention that societies use to organize and regulate their actions [1,33,34]. Hence, we are considering that institutions are designed to address environmental problems by affecting driving forces, activities, pressures and the state of the environment [35]. We also assume that the institutions are supposed to seek congruence between the social and ecological dimensions to pursue a pathway to sustainability [33].

In response to this cross-scale interdependence and the misfit of institutions to complex problems they seek to address, this paper aims to broaden the analytical foundation of the Drivers–Activities–Pressures–State–Impacts–(Welfare)–Responses (DAPSI(W)R), so as to strengthen the ecosystem approach and promote an integrated, functional and cross-scale perspective for land–sea governance and management. The concept of the Cross-scale Ecosystem-Based Assessment (DIET, from Portuguese "Diagnóstico Integrado Ecossistêmico e Transescalar) framework was designed by allocating the DAPSI(W)R components in different compartments (continental, coastal and marine zones), and its steps were then applied to an illustrative case study on the human demand for the service of seafood provision. The novelty here is to develop a framework that is useful and applicable to any SES within a cross-scale perspective, not only along the land–sea interface, allowing a qualitative assessment of the impacts derived from the demand of a given ecosystem service, as well as of the cumulative impacts of multiple human drivers and activities on different environmental compartments. DIET also has the capacity to evidence the gaps, overlaps and complementariness of responses so as to address the different processes involved in each social-ecological issue, from drivers to impacts, thus fostering the ecosystem-based management.

2. Theory and Methods

2.1. Ecosystem-Based Management along the Land–Sea Transition

Ecosystem-based management (EBM) is a form of natural resource management that has emerged and matured over the past few decades [36,37]. However, the application of this concept in decision-making still faces significant obstacles, and few guidelines are available to inform decision-makers on how to select or develop specific management measures to achieve EBM goals [38].

EBM was born from the perception that traditional ways of managing natural resources were not enough to solve complex environmental problems, and that it was necessary to innovate through a more comprehensive view, which considered social-ecological systems, and brought a more integrated approach, not only considering human beings and the environment, but also the integration between the different levels of management (vertical and horizontal) [36].

According to [39], EBM is "an integrated management approach that requires consideration of the entire ecosystem, including humans, to maintain an ecosystem in a healthy, productive, and resilient condition so that it can provide the services humans want and need" [39]. As an example, this approach offers new opportunities for the sustainable use of the coastal and marine zones. However, to be implemented, it requires a better understanding of the functioning of marine social-ecological systems, how they generate goods and services, how well these benefits are used, how systems degradation affects human well-being and, especially, how to consider cross-scale dynamics in decision-making. This relies on the understanding of the social-ecological processes and the scales (temporal and spatial)

on which they operate, which will demand adjustments in institutions and governance in relation to the existing responses.

EBM is well aligned with what has been going on for almost 30 years, being discussed in the context of the eight design principles postulated by Ostrom and the researchers from the Ostrom Workshop at Indiana University [40,41] as essential elements for explaining the success of institutions in maintaining common-pool resources (e.g., clearly defined boundaries, congruence between appropriation/provision rules and local conditions, collective-choice arrangements, monitoring, graduated sanctions, conflict-resolution mechanisms, minimal recognition of rights to organize, and nested enterprises).

In practice, EBM and the design principles seek to use lessons learned from the past in order to build mechanisms/institutions for the management of common-pool resources (especially in the Ostrom approach) [41], but also in the management of ecosystems and territories [36,42]. Both approaches are guided by principles of the maintenance of natural resources and ecosystems, social participation and decisions guided by these choices, monitoring, recognizing the scales and connections between ecosystems, and input of knowledge for the construction of management strategies.

The land–sea interactions occur at different scales of socio-ecological processes [20,43], including the natural processes (physical, biological and chemical), which are responsible for the supply of ecosystem services [44]. Social processes (anthropic activities and their threats, management strategies, political decisions) that are characterized as key agents of transformation also affect flows at the land–sea interface [21], retroactively influencing the population's way of life and well-being. Therefore, if a management strategy does not consider the land–sea interface, it can reduce the ability to detect and manage the negative impacts arising from human actions [45].

In summary, EBM recognizes that (1) the biophysical and human components of an ecosystem interact in complex ways; (2) society depends on and benefits from the environment through ecosystem services; (3) ecosystem services are directly and indirectly affected by different human activities [7]; and (4) management actions reflect social choices [36]. Additionally, given the complexity of the systems, the solutions must also consider several scales and levels [4,5].

2.2. Assessing Cross-Scale Dependence in the Land–Sea Interface

Coastal zone management, like several other complex issues such as climate change and biodiversity loss, is often described as a "wicked" problem, which is a kind of problem with "no definitive formulation, no stopping rule, and no test for a solution" [46].

Wicked problems have been approached by different disciplines, from ecology to political science, to discuss varied subjects [47–51], and in addition to the different approaches to the matter in question, all of them agree that there is no straightforward approach to confront them. However, there are systemic approaches that encourage understanding and simplifying the problematic causal chain to support decision-making [9,52].

The (DAPSI(W)R) [53], which is an adaptation of the DPSIR method [54], is one of these systemic approaches relevant to identifying social-ecological problems/issues and the causal mechanisms underlying them. The DPSIR tool seeks an integrated systems analysis in which the driving forces (D, drivers) of social and economic development exert pressures (P, pressures) that change the state (S, state) of the environment. Changing the state of the environment leads to impacts (I, impacts), for example, on human well-being and the health of the ecosystem, which demand responses (R, responses) to mitigate the causes or to adapt to these impacts, such as social control and the redirection of investments and policies to influence human activity. In short, the DPSIR family of frameworks provides a list of institutional responses with no emphasis on their cross-scale impacts, and without taking into account the importance of evaluating it under the ecosystem-based approach. It is also well known that, on one hand, DPSIR is focused on the problem's structural side [8] and mostly focused on the biophysical and ecological pressures [54], yet there is little focus on the relevant features to understand problem structure (e.g., collective-action problem, social participation, bottom-up and

top-down approach, economic impacts) or the governance systems that are needed to solve problems that are addressed in political science literature [3,14,51].

Therefore, it is understood here that, preceding a discussion about an institutional assessment, or in other words, how institutions should perform or should be designed so as to address management problems [13], it is imperative to have a comprehensive understanding of the social-ecological problems, the associated driving forces, and their effects at various scales. It is also relevant to map the institutional responses that exist, aiming to address a given problem and to identify gaps, overlaps and/or complementariness. Using a simple analogy, it would be like holistically diagnosing a patient's problem and its causes and then discussing the forms of treatment, which may be a completely new treatment or an adjustment of existing ones.

In this context, the DPSIR-based tools are used to identify and visualize environmental problems in a simplified and objective way, through a logical cause-and-effect structure involving society's actions and the environment [55]. It is applied as part of an assessment process to analyze the parts of the whole in detail, and generate deeper insights into environmental problems [56].

Thus, this approach contributes to the understanding of social-ecological processes simply and objectively [35], and can be used by decision-makers to understand a given environmental problem or the impacts of public policies and political choices [55,57,58]. The analytical framework DPSIR allows the construction of the nexus, or conceptual model, which supports decision-making guided by a logical chain of results and theories of scientifically-based changes [59,60].

Still, the DPSIR method seeks to integrate knowledge from different areas, taking into account economic, social and environmental information in order to obtain more detailed analysis for decision-making, bridging the gap between science and management [9,35,54,61]. In addition, some authors have also used this tool to identify political solutions related to socio-economic and environmental problems, which can be used to improve management policies and strategies [62,63]. Since the proposal of DPSIR, it has undergone some adaptations. One of them, DPSWR (Drivers–Pressures–State Changes–Impacts on Human Welfare–Response), sought to incorporate the benefits (W, welfare) associated with ecosystem services into the DPSIR matrix, and highlight the differences between impacts on the environment and impacts on human well-being [64]. This method [64] improved the understanding of the definition of categories, and established a conceptual link between them.

In 2013, Kelble and collaborators adapted the DPSIR to Driver, Pressure, State, Ecosystem service and Response (EBM-DPSER), replacing impacts with ecosystem services (E), aiming to capture the complexity and diversity of human–nature interactions. The intention was to include not only anthropic impacts on the environment, but also the benefits that nature provides to society [7]. Later, Elliott (2014) [65] and Smith et al. (2016) [66] proposed the DAPSI(W)R method, recognizing that pressures are mechanisms of change, and that it is not the Driving Forces that cause the pressures, but human actions (Activities). These authors also replaced Impact with impact on Welfare. This last adaptation is used here for the DIET conceptualization as it dialogues with the EBM approach. In this approach, the ecosystem process, services and societal benefits are taken into account through the interface with the social-ecological system components and processes, and the effects of changes to the natural system on the human uses and benefits of the marine system [53].

2.3. DIET—An Assessment of Complexity at Cross-Scale SES

It seems useful to develop an interdisciplinary approach that benefits from a problem structuring method, such as DAPSI(W)R, in gaining a sophisticated grasp of the nature of the problem by coupling it to the institutionalist approach, which, by contrast, is much richer in considering the cross-scale dependence, and in assessing different sorts of governance systems and how they may be brought together to assist in addressing the problem.

The Elinor Ostrom's IAD (Institutional Analysis and Development) and SES (Social-Ecological Systems) frameworks, for instance, have been developed and employed mostly by social scientists and policy analysts, and, besides the current criticisms and advances [41,67], work well to evaluate the

governance system and the design of the institutions. DIET, on the other hand, focuses on developing a deep and qualitative assessment that embraces the principles of Ecosystem-Based Management (EBM; Figure 1) [36], and proposes a way to assess the causes (drivers, activities and pressures) and effects (state, impacts and welfare) of SES processes that occur across different scales of the territory. It is a qualitative assessment of the socio-economic/cultural, cause–effect and cross-scale processes that highlights gaps, overlaps and/or complementariness in the institutional responses. Further, we indicate the use of an ecosystemic and integrated approach to adapt and adjust institutions and management arrangements (Responses) to different dimensions (ecological, economic and socio-cultural) and scales (spatial and political-institutional).

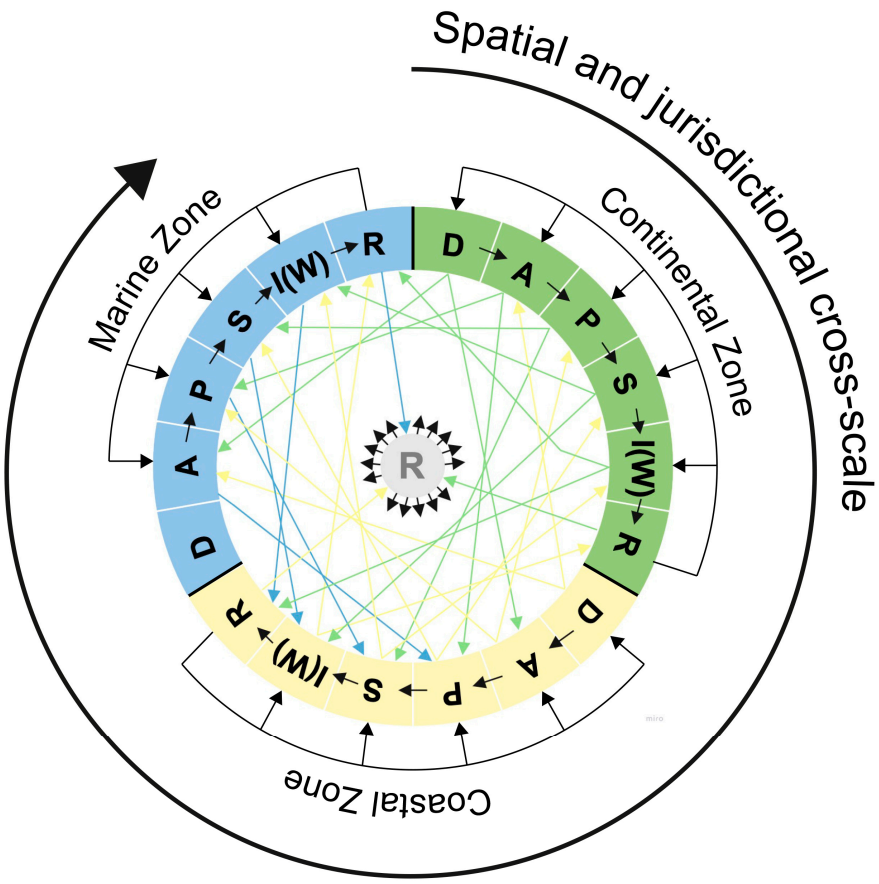

Figure 1. DIET schematic illustration. It highlights the importance of territorial and jurisdictional cross-scale dependence between (**D**)rivers—environmentally relevant sectoral trends, such as societal need for food; (**A**)ctivities—actions needed to provide the societal needs; (**P**)ressures—resource exploitation trends; (**S**)tate Changes—changes in the ecosystem that will affect the services provision; (**I**)mpacts **(W)**elfare—on human welfare and on the environment; and (**R**)esponses—the societal mechanisms effecting ecosystem management. The interdependences illustrated here are not exhaustive, but show their relevance to advancing the social-ecological systems' governance and management. Source: Image prepared by the authors. Yellow arrows indicate flow from the continental zone to the other zones. Green arrows indicate flows from the coastal zone to the other zones, and blue arrows indicate flows from the marine zone to the other zones.

DIET seeks to contribute to the systematization of information related to the causes and effects of a given environmental problem, highlighting the cumulative impacts and the cross-scales connections, in order to better inform decisions on multiple scales and sectors and to find gaps and weaknesses to be filled and repaired, respectively.

DIET helps to highlight the main three processes that operate in the SES's territorial dynamics:

1. Socio-economic/cultural process: the drivers (D; e.g., leisure, energy and food) will demand a certain activity (A; tourism, oil and gas production and fishing) and, therefore, will initiate multidirectional flows among the continental, coastal and marine zones (e.g., transportation of people, mineral resources (oil pipelines) and transportation of food products);
2. Cause–effect process: These multidirectional flows will lead to pressures (P; suppression of vegetation), which, in turn, will produce changes in the environmental state (S; marine pollution or loss of biodiversity) and generate impacts (I) on human well-being (W; provision of seafood, water quality). All these environmental changes and the benefits of nature for people can demand responses (R; coastal management plans, fisheries policies) in the form of public policies that can stimulate, organize and reduce a particular driver and activity, and their effects on the SES, including the flow among compartments;
3. Cross-scale process: Interactions can occur within or between scales, leading to substantial complexity in understanding the causes, processes (dynamics) and impacts of certain flows, which directly affect the responses (public policies) demanded. The cross-scale process brings an integrated and systemic interpretation of socio-economic/cultural and cause–effect processes.

DIET facilitates and supports the application of EBM, incorporating a range of EBM principles along different stages. First, the nature of the DAPSI(W)R tool allows us to consider the connection between ecosystems and to define and address different temporal and spatial scales. Second, it can incorporate different sectors and representatives of society and consider all forms of knowledge, whether technical, scientific, traditional or local, involving different sectors, relevant aspects of society and scientific disciplines, in order to carry out an integrated, interdisciplinary and participatory assessment that considers cumulative impacts on ecosystems and adjacent ecosystems. Third, through the gaps identified, policy options, such as integrated and adaptive management and appropriate monitoring, can emerge as solutions to address the problem.

The assessment approach we outline here is consistent with what has been applied in the World Ocean Assessment [10], in the Global Environmental Outlook 6 [11], as well as in the Intergovernmental Panel on Biodiversity and Ecosystem Services [12], which includes systematizing secondary information and discussing it with peers and stakeholders to get a better understanding of the problem. It is also coupled with broad discussions on institutional fit [33] and assessment approaches [3,13,14] that aim to contribute to more effective and adequate management and governance systems, in order to face the complexity of social-ecological systems.

DIET will not offer, at this stage, any insight into how the governance mechanism should be. Rather, it can assess the problem and offer elements that will allow a better dialogue with the policy options that are currently available, and that can be assessed through the IAD [3], institutional diagnosis [13], or the panaceas toolkit [14].

DIET is a flexible lightweight method that fits different scales and compartments, and allows researchers to see and evaluate system dynamics moving from the drivers to the responses, as well as going backwards from the impacts to locate the main driver. It can be applied as a diagnostic tool in an area where an activity is already in place; for instance, to understand the dynamic in a food provision chain between the coast/sea and a metropolis, as was done here (see below). However, it can also be applied to discuss future enterprises, as in the construction of a great dam or port. It offers the possibility of qualitatively assessing the possible impacts and the changes in the environment, in order to mitigate or to adapt, or even to deny a certain development plan, concerning its impacts on society and the environment across different scales. Once it is done, it can be read in a bidirectional flow (from driver to response and from response to driver), depending on the main question to be answered.

To be applied, DIET involves four steps (Figure 2):

1. Define the object of the assessment. DIET is very flexible. The object of your own assessment may be an entire ecosystem, a territory, a specific impact, an activity or a driving force. You choose where to start and from there you develop a comprehensive understanding of the system;

2. Depict social-ecological systems and the problems of structuring. Apply the DAPSI(W)R matrix, moving back and/or forward from the starting point to map the socio-economic/cultural and cause–effect processes. This step also helps to identify the actors, the different sectors, and their respective roles and responsibilities. It is also essential to identify the potential polluting and extractive activities, and the respective political responses given to this problem, as well as to define indicators for monitoring. See Section 3 for more details;
3. Identify the cross-scale dynamics: indicate the scale and levels (e.g., continental, coastal, or marine zones) of the DAPSI(W)R components operating in the cross-scale processes;
4. Identify the institutional gaps to address the problems. Gaps here include policies and process failures (e.g., lack of stakeholder involvement, decisions not reflecting societal aims, and others). At this stage, the EBM principles should be consulted to highlight the existing gaps, overlaps and complementariness, and guide the debate of policy options to address the problem (see Section 2.1 for more details).

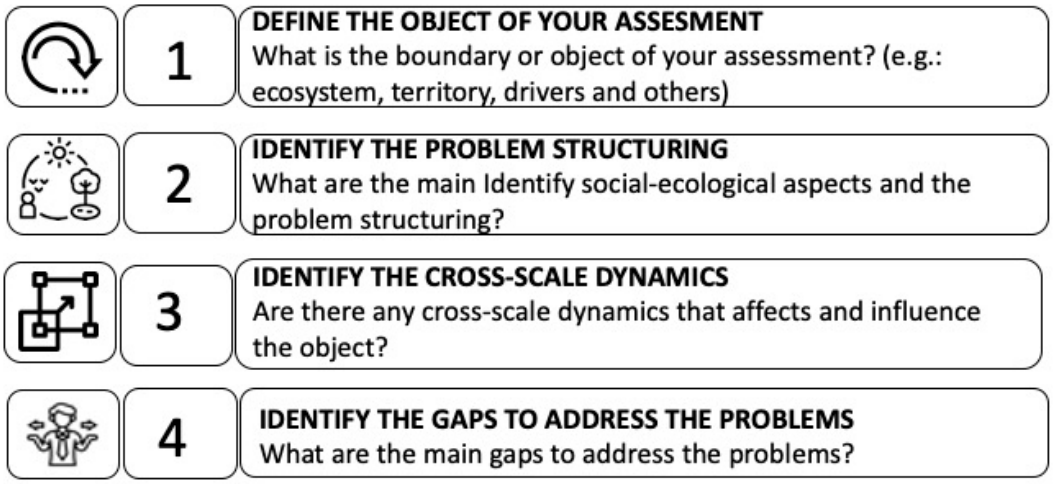

Figure 2. DIET application framework in four steps. Source: elaborated by the authors. Flaticon Icons (https://www.flaticon.com).

2.4. The São Paulo Macro Metropolis Setting

The São Paulo macro metropolis (SPMM) represents an interesting case for exploring the DIET approach, since the main metropolis is not located on the coast. However, the high land–sea connection provides the flows and dynamics between its main metropolises—São Paulo and Campinas (Figure 3)—which concentrate more than 12 and 1 million inhabitants, respectively. The dynamics between the São Paulo megacity and the coastal zone are intense, going far enough to be considered a coastal megacity, and yet they are also so close, considering the socio-economic flow between the metropolis and the coast.

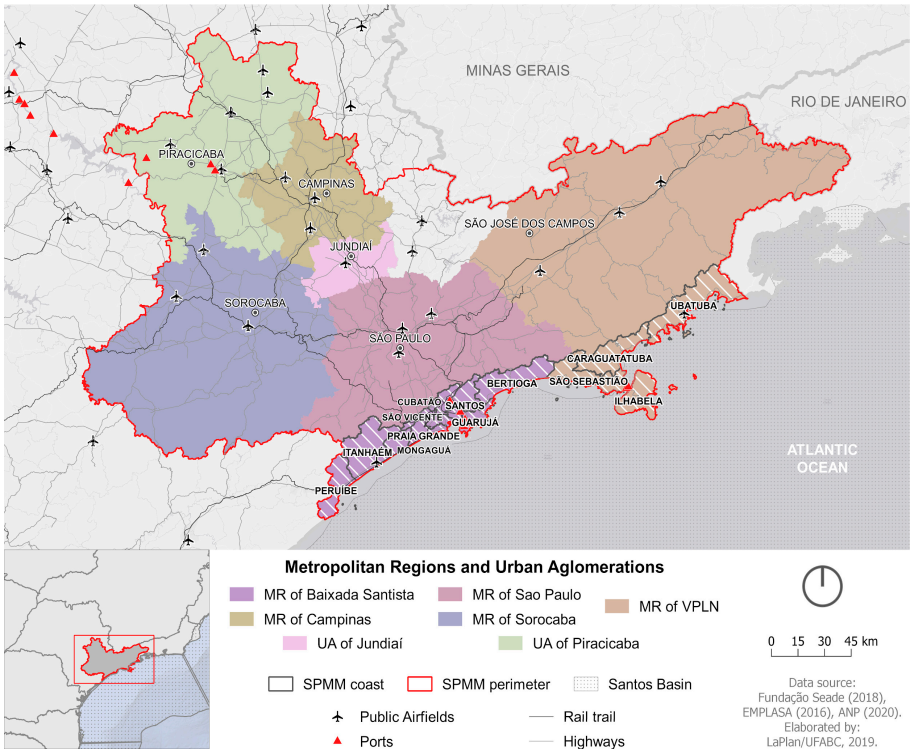

Figure 3. Location of the Macrometrópole Paulista (SPMM) with emphasis on the coast, highlighting the location of the metropolitan regions (MRs), urban agglomerations (UA), Santos basin, and main infrastructure (ports, airports, railways and highways). Source: LaPlan (UFABC)/FAPESP, 2019.

The SPMM is one of the largest urban settlements in the southern hemisphere. It houses the metropolitan region of São Paulo—among the sixth largest in the world [10]—in addition to the metropolitan regions of Baixada Santista, Campinas, Sorocaba and Vale do Paraíba, and the North Coast, as well as the urban agglomerations of Jundiaí and Piracicaba. They occupy an area of 53,400 km^2, equivalent to 21.5% of the State of São Paulo, including 174 municipalities and 50% of the urbanized area throughout the State [68]. This region concentrates the main Brazilian ports and airports, a road complex, and major hubs of knowledge, technology and innovation [69]. The region's socio-economic relevance is reflected in its numbers. It highlights the value of this new territory in the context of the State of São Paulo, with almost 75% of the population, and being responsible for more than 80% of the State's GDP. Additionally, the dynamics of SPMM are marked by inter-metropolitan and macro metropolitan pendularity, and high contrast between positive economic indices and low social development indices [70].

The SPMM (Figure 3) comprises two coastal metropolitan regions: the Baixada Santista (MRBS) and the Vale do Paraíba and Litoral Norte (MR of VPLN) [29]. Of the 39 municipalities of the Vale do Paraíba and Litoral Norte metropolitan region, four are on the coast (Caraguatatuba, Ilhabela, São Sebastião and Ubatuba). The Baixada Santista metropolitan region is composed of nine municipalities, all of which are located in the coastal zone: Bertioga, Guarujá, Itanhaém, Mongaguá, Peruíbe, Praia Grande, Cubatão, Santos and São Vicente.

The coastal zone of the SPMM comprises 4225 km^2, presenting a population of about 2.2 million inhabitants in 2019 [71], with some areas experiencing high urban development and demographic density. The coastal zone is considered a critical area for biodiversity and brings together a set of marine and terrestrial protected areas, which cover 37% of the territory in the MRBS [72] and 80% of the Northern Coast [73].

For the definition of the SPMM coast, it is necessary to consider the interdependence of the land–sea interaction, including the flows and dynamics between its main metropolises that are not

located in the coastal zone. Nonetheless, the individual relevances of port complexes, industries, oil and gas exploration, fisheries, and high tourism potential all compete and use the same territory, intensifying the conflict and the interdependence between regions [74–76].

There are two ports in the region, the Port of São Sebastião and the Port of Santos, the latter being the largest seaport in Latin America [77]. The presence and expansion of these two ports are strategic, and represent a potential distributive rearrangement of consumer goods, allowing the targeting of a large portion of its industrial and agricultural activities in order to supply domestic and international markets [29]. Nonetheless, this development has consequently led to population increase and urban growth, which has altered the natural characteristic of the environment [78,79].

This ongoing development economy will produce significant changes and reinforce the need for better integration of this region into the expanded metropolis [80]. The existing flows and connections between the coastal zone and the metropolitan centers reveal different and unique dynamics that cause different impacts, stimulating reflection on the necessary governance arrangements.

In order to analyze the drivers and the SES's dynamics, we divided the spatial and jurisdictional scale according to the current State of São Paulo legislation [81], whereby the coastal zone is the geographic space delimited within the terrestrial area by the Atlantic drainage watershed in the São Paulo territory, and within the marine area up to the 23.6 m isobath (represented in the larger scale nautical charts of the Hydrography and Navigation Directorate of the Ministry of the Navy). It encompasses all ecosystems and natural resources in its terrestrial, transitional and marine compartments [81]. The marine zone is 200 nautical miles, and extends to the continental shelf (territorial sea not included), defined as the Economic and Exclusive Zone (EEZ). Further, the continental zone includes all the non-coastal municipalities of the SPMM.

3. Results

Study Case—The Demand for Seafood Provision in the São Paulo Macro Metropolis

Seafood supply in the São Paulo State is as complex and diverse as the metropolitan area's structure, and it demands cross-scale activities to be able to provide food from sea to land. This is especially true considering the metropolitan region of São Paulo, which is the largest fish consuming center in the country [82]. The State of São Paulo has industrial fishing fleets that account for approximately 70% of the total volume of fish discharges, and that operate throughout the southeastern and southern regions of Brazil, mainly between Cabo Frio (Rio de Janeiro State) and Cabo de Santa Marta Grande (Santa Catarina State). These fleets are based in the municipalities of Santos/Guarujá, Ubatuba and Cananéia, and account for about 10% of the production units of São Paulo State [83]. In other municipalities, fishing activity is typically artisanal, and even in those with industrial fleets, artisanal fishing is also relevant. The largest volume of fish discharges is registered in Santos/Guarujá (66%), followed by Cananéia (12%) and Ubatuba (9%) [83]. The metropolitan region of São Paulo consumes 302,729 tons/year, which results in an estimate of per capita consumption of 15.1 kg/inhabitants/year. The estimate is higher than the Brazilian consumption (9.5 kg/inhabitants/year), and higher than Latin American consumption (10.5 kg/inhabitants/year), although lower than the world average (20.3 kg/inhabitants/year) [82,84].

The main seafood production on the SPMM coast comes from Santos and Guarujá, and is distributed widely across the state. The biggest producer on the North Coast of São Paulo is Ubatuba, where artisanal fisheries play a significant role [85]. The seafood supply chain in São Paulo operates with a high level of informality, with diverse links and intermediaries. For instance, the main fishery input is through the Company of General Warehouses of São Paulo (CEAGESP) [86], which also receives seafood from other countries (mostly China and Chile), from the São Paulo coast and other states. The main seafood suppliers outside São Paulo State are from the states of Rio de Janeiro, Santa Catarina, Rio Grande do Sul and São Paulo. A general estimate shows that the biggest fish consumer market in São Paulo is represented by restaurants, followed by grocery stores (large and

small scale) [82]. However, not all fishery resources from the São Paulo coast go through CEAGESP. Some operators buy seafood directly from the fishermen for restaurants and even the grocery store [82].

The seafood provision dynamics for this expanded territory include different activities that begin in marine (fisheries and shipping) and coastal zones (highway construction, road transportation, ports activities, shipping, fisheries and aquaculture) and flow to the continental zone (highway construction and road transportation). All those activities are necessary to keep the seafood provision dynamic flowing through the territory, and have the potential to create pressures on the system, which entail cross-scales changes (e.g., deforestation, CO_2 emission, exploitation of fisheries, land use conflict, bycatch and overfishing). As a result, the state of the system is affected, but not only on one scale.

The central pressures directly related to fishing activities are overfishing of target species and capture of non-commercial species (bycatch). Additionally, fishery activities may generate litter at sea, resulting from abandoned, lost, or otherwise discarded fishing gear [87], increasing the disposal of solid waste in the ocean. Due to the current dynamics, the discarded gear may impact coastal and marine ecosystems. Ultimately, this impact is responsible for harming marine fauna and causing economic loss across scales [88], including the fisheries themselves.

Shipping and ports are also included in seafood provision chains and are considered activities that can bring environmental risks of great magnitude [79]. Seafood in SPMM is sustained by both regional extractive fisheries and importation from other countries. Consequently, this increases the number of ships and, demands extensive port structures and dredging activities to support capacious vessels. These activities enhance the disposal of waste, effluent and contaminants in the ocean, and boost illegal human occupation in the port area [63].

It is interesting to observe that the seafood provision chain of the SPMM coast causes cumulative impacts on the provision ecosystem services. However, what is also highlighted here is a great cumulative impact on regulation and cultural services, especially in the coastal zone. This gives a hint as to what pressures and activities a manager must dedicate more attention to in order to alleviate the impact. It seems obvious to have a focus on fishery management, but this alone will not help to improve the seafood provision chain quality. Nor will it even guarantee that coastal management is able to guarantee the provision of the ecosystem service. It is necessary to look at the pressures and activities from other scales that are directly or indirectly impacting the ecosystem services, in order to identify the central nodes of complexities.

To connect the marine and coastal zones to the continental zone, several logistical transportation axes are implemented in the SPMM for complementing port activities and the food provision chain, besides other fluxes (e.g., tourism). The highways are a crucial flow path, connecting the Port of Santos, and other municipalities of the State of São Paulo, and other regions of Brazil. The construction of railways and highways is responsible for the deforestation of extensive areas, including the suppression of mangroves. In addition, highways increase the flux of people coming from the continental zone, which is considered the major driver of displacement flows of people in the SPMM [89].

All these activities occur at different scales, and generate cumulative impacts and pressures at other scales. For instance, deforestation, CO_2 emission, dredging, land use conflict and overfishing are pressures that are particularly harmful to coastal ecosystems, influenced by activities on land (continental and coastal zones) and in the ocean. The complexities of the seafood provision chain have the potential to intensify the impact on human welfare (e.g., degraded habitats, loss of water quality and others) and the different ecosystem services (provision, cultural and regulation) already being caused by other drivers (demands).

The pressures are mostly concentrated in the coastal zone, although activities are carried out at different scales/zones. These given pressures in the coastal zone trigger changes in the state of the environment at different levels, but mainly in the coastal and marine zones. Similarly, the pressures from the continental zone change the state of the coastal and marine zones. However, the pressures in these three zones rarely affect the continental zone negatively.

Through DAPSI(W)R, it was possible to identify the main existing responses in place to address the given drivers, activities, pressures, states and impacts. The SPMM presents a set of institutional responses related to the seafood provision complex system. These policies are responsible for regulating the development of human activities (e.g., transportation, ports and land use), environmental conservation, urban planning policies and coastal zone management (Figure 4).

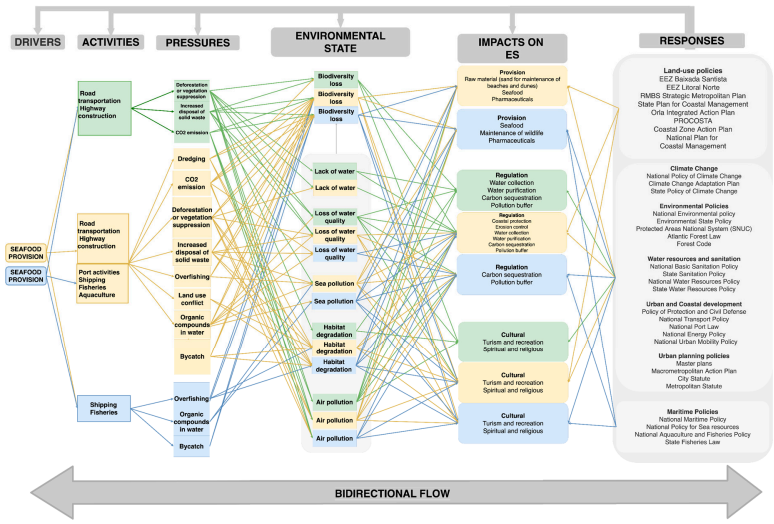

Figure 4. Schematic application of DIET for the seafood provision in the continental, coastal and marine zones of the São Paulo macro metropolis. Green boxes: DAPSI(W)R in the continental zone. Yellow boxes: DAPSI(W)R in the coastal zone. Blue Boxes: DAPSI(W)R in the marine zone. The framework may be read in the bidirectional flow.

The policies interacting at different levels and scales, however, do not necessarily reinforce each other. There are examples where the institutions overlap in geographical scope and are functionally connected. However, they are issue-specific policies, and are not normatively linked [90]. For instance, in the marine zone, the main policies are the National Aquaculture and Fisheries Policy [91], the National Maritime Policy [92] and the National Policy for Sea Resources [93]. The National Aquaculture and Fisheries Policy is responsible for regulating, authorizing and establishing criteria such as sustainable fishing effort, total allowable catch and the monitoring of fishing activities. The National Maritime Policy seeks to guide the development of maritime activities in an integrated and harmonized manner, and the National Policy for Sea Resources aims to articulate the sectoral policies in the coastal and marine environments. Those policies apply to marine and coastal zones, but there is no normative interplay among them.

In the coastal zone, on the other hand, the central institution is the National Coastal Management Plan (PNGC, in Portuguese) [94]. This policy has as its main objective "to regulate the use of coastal natural resources, the occupation of coastal spaces and identify its vulnerabilities, potentialities and existing trends". The PNGC also defines the legal instruments at different levels (municipality, state and federal government), such as the Ecological Economic Coastal Zoning at the regional level, or the State Coastal Management Plan. Despite the importance of this policy, the definition of the coastal zone in PNGC disregards the integration among coastal and continental zones, as well as the marine zone with the coastal zone. Hence, the PNGC is unable to cover the continental area's drivers which affect the social-economics and environmental quality of coastal and marine environments, and does not include any jurisdiction in the marine zone.

The SPMM also includes a set of sectoral policies related to environmental conservation, port activities, transportation, water resources, sanitation and land use (Figures 4 and 5). Although coastal and marine policies in SPMM consider and require the integration of sectors, the institutional

responses are not yet sectorized. Once the assessment and combat of cumulative impacts of different activities are understood as crucial for sustainability, sectoral approaches are considered unsuitable for sustainable management [95]. The sectoral policies responsible for regulating human activities are focused on increasing the country's economic competitiveness and economic development. The Port Law, for example, does not mention sustainability, or the social-economic and environmental impacts resulting from this activity, acknowledging only the need for environmental licensing for the installation of ports and their structures, and the need to monitor dredging activities. Other sectoral policies, such as the National Transport Policy [96], base their objectives on sustainable development, and considers social-environmental responsibilities. However, even when policies mention sustainability and the environment quality, they do not have clear guidelines or methodologies, neglecting possible environmental impacts [97].Even so, a more recent effort that aimed to integrate the SPMM territory and the SPMM Action Plan [69] does not include provisions towards sustainability or territorial integration, failing to address climate change, tourism and fisheries as important aspects of development for the coastal zone [29].

Another important example of a lack of integration between policies is between the PNGC and the Protected Areas National System (SNUC, in Portuguese) [98]. The SNUC is a sectoral policy that plays an important role in environmental management, creating marine protected areas that cover both coastal and marine zones. It plays an important role in the management and regulation of human activities and uses in both regions [99]. These policies are geographically overlapped. However, they differ as regards methods, criteria, objectives and rules, resulting in a single issue being determined by more than one agency and more than one level of government, leading to fragmentation of territory management [99,100]. The same also applies to the Maritime National Policy and Marine Resources National Policy, which present different guidelines and no integration among their objectives [101].

It is noted that all the responses are concentrated in the coastal zone and its interaction with different domains (marine and continental zones) (Figures 4 and 5). However, those policies are fragmented, often referred to as a "blue patchwork" when related to the marine zone [99]. In the case presented here, as it includes continental and coastal zones, it is an even larger patchwork. Nevertheless, it is relevant to highlight that, besides the policies that are all applicable to the coastal zone, they are highly sectorized and fragmented. Hence, interplay management may be crucial to reduce fragmentation, improve compliance and monitoring, and increase cost-effectiveness [90]. For this specific case, the focus would be mainly on the coastal zone's management policies. The policies applicable in the coastal zone are sectorized and do not necessarily converge or present formal links among them, which would create more difficulties for integration. However, getting to know them and understanding where the gaps lie helps us to oversee the linkages, and derive insights where needed to search for more synergy. For instance, policies applicable only to the coastal zone, such as the EEZ Baixada Santista or the Strategic Metropolitan Plan, need to reinforce the State Fisheries Law and be aligned with the National Plan for Coastal Management. Further, for the seafood provision, the policies located in the core of the SES, which are applicable to all zones, need to reinforce each other and find linkages with the other zones.

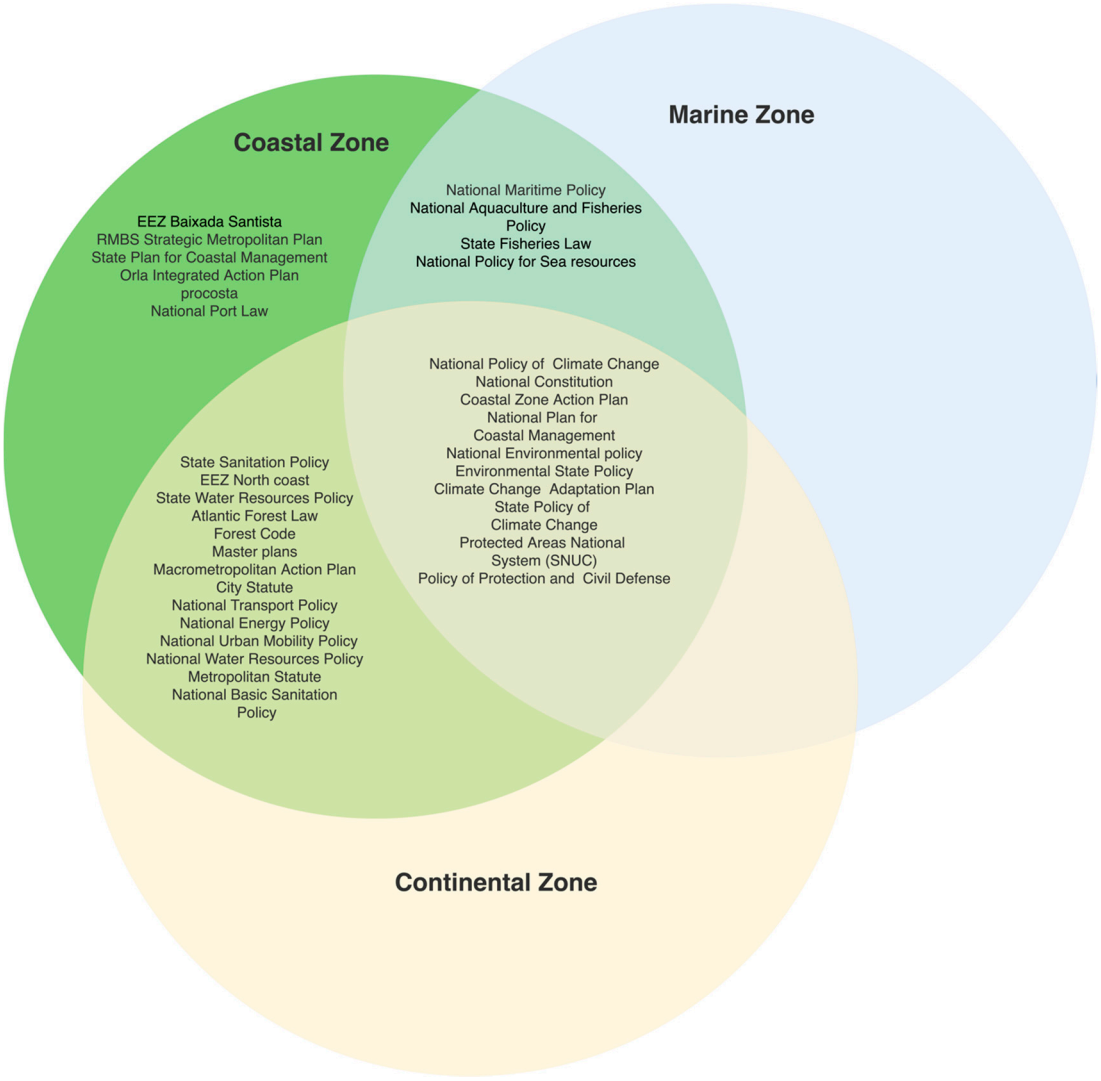

Figure 5. The main responses identified in the comprehensive DIET assessment of the seafood provision demand in SPMM. Source: elaborated by the authors.

To foster sectoral integration, policies need commonplace and integrated goals and guidelines. Different sectoral agencies are inclined to work together when demanded by formal procedures. This by itself will not guarantee integration and effectiveness, but it will, at least, create more synergy among the institutions. EBM includes a holistic view, encompassing the complexity of seafood provision by maintaining both environmental integrity and socio-economic prosperity, offering innovative insights for managing [36]. When coupled with DIET, it helps us to oversee the gaps, overlaps and complementariness in order to overcome sectoral fragmentation.

One way to move forward with integration is to promote interplay management, which may vary from exchanging information between decision-making bodies to coordination and implementation of policies [102]. Even in a fragmented environment, interplay management enables synergies and convergence between and across policies and sectorial institutions. When the possibility to change or review institutions is absent, practitioners and institutional entrepreneurs can exchange experiences and try to improve and adapt through practices in functionally linked policies.

The DIET application here illustrates the potential in capturing opportunities for interplay management in the cross-scale processes without entering into the specificities of a given problem or the management of a specific human activity. To propose a solution, or even to derive insights on how to

move forward to reduce the governance morbidity, it is necessary to follow the EBM principles, mainly to provide the best available interdisciplinary science to fill the knowledge gaps. This should include knowledge of the social-ecological systems that provide the services, the socioeconomic systems that benefit from them, and the institutions that need to fit the purpose to ensure sustainable use.

When management or planning considers the effects of specific activities on habitat or other ecosystem components, it only concerns the overall goals for that sector [22]. For instance, the National Fishery Law [91] and the State Fisheries Law [103] are mostly based on the fish populations, but are not dedicated to, or do not contain a provision for, marine litter or ghost nets. In this sense, the institutions are lacking an EBM approach. Stressors associated with human activities interact in complex ways and across scales to affect marine ecosystems, but there is still a lack of a spatially explicit assessment of cumulative impacts, both ecologically and economically. DIET supports decision-making processes, indicating patterns of cumulative change, that is, which pressures are most responsible for the change, as well as which places are experiencing the greatest increases and changes in the environmental states. Therefore, those changes will end up altering the status of ecosystem services.

4. Discussion

DIET supports a qualitative approach that builds a comprehensive understanding of the cumulative human impact on ecosystems, including cross-scale features, of any SES. Here, we argued that through DIET, it is possible to discuss cause–effect relationships aiming to integrate coastal management within a more expanded territory, considering the flows and dynamics among regions and scales. We also highlighted the cross-scale dependence of metropolitan regions and their respective urban agglomerations on the coastal and marine zones. The impact flows and connections between the coastal zone and the large metropolis, and the other metropolitan centers, reveal different and unique dynamics that represent a challenge for management and planning [104], stimulating a reflection on the necessary governance arrangements, and methodological and management tools that can contribute to decision-making with the application of science.

The seafood provision chain case study in SPMM shows that to promote the development of activities (e.g., aquaculture and fishing), it is imperative to take into account the pressures and impacts that go beyond the coastal and marine zones. It is a discussion of cross-scale dependent governance [26], such as the connection through road transportation and shipping, for instance, which entails pressures at different spatial and temporal scales. This will, in turn, create cumulative impacts on human well-being, mainly on the coast. These activities and the resulting pressing impacts reinforce the importance of reviewing the current governance paradigms in the SPMM territory, not only because of its political-institutional profile, but because, as pointed out by [80], "we live less in a city and more in a region," and it is through these countless flows that this city–region connects with the coastal and marine zones. By the same logic, this territory is also technically connected with the marine zone. The territorial sea and the portion of the exclusive economic zone corresponding to the Santos Basin have interdependent relationships with the SPMM that need to be incorporated into the governance of the region.

This qualitative assessment provided insights that may promote the effective management of this territory and reduce the impacts that ecosystem services depend upon. This involves, among other measures: (1) fish and shellfish populations are healthy and monitored to avoid biodiversity loss; (2) the habitats across different scales are taken into account, and measures are considered to restore degraded environments; (3) water quality is monitored, thus watersheds need to be integrated into the coastal management; and (4) pollution of water and air is controlled.

For the specific case of SPMM, but also in general, these factors are influenced by anthropogenic activities other than the direct effects of fishing. Current fisheries management tends to focus disproportionately on the maximum sustainable yield of particular target species, rather than the many other factors that affect population size. The cumulative and interactive consequences of different human activities are primarily ignored in management plans [22]. The São Paulo State Fisheries Law,

for instance [103], which is not yet regulated, does not include special provisions to consider EBM in the current management. Consequently, the cumulative impact of fisheries across all sectors may be much greater, or in rare cases, more than the sum of individual impacts, because of interactive or multiplicative effects. These different scenarios concerning how activities can interact are illustrated in the DIET case study presented here. DIET highlighted that the provision of ecosystem services from the coastal and marine zones benefits people in different zones; however, food provision, for instance, benefits mainly the continental zone. At the same time, it causes impacts on the coastal and marine zones. In this case, the coastal and marine zones work more as providers of resources than receptors of impacts. This relationship can be quantitatively tested in the future, although there is a large data availability gap.

We note that DIET provides flexibility to support management in a way that can be read and built in any direction to fit the purpose. It is a matter of choice if one wants to understand the seafood provision chain, as was done here, or if one wants to understand what is causing biodiversity loss. So, DIET allows the feeding of the information, and the ability to read the flow in different directions. It is essential to have reliable knowledge and data to input into DIET for a deeper analysis; however, the lack of data in this application does not limit the effort to understand the process, as the qualitative analysis emerges from the linkages found in the secondary literature. A subsequent step would be to provide quantitative data through the literature and stakeholders elicitation.

DIET focuses on the ecosystem functions, processes and services oriented towards management, using the EBM principles as a core goal [36]. In this sense, DIET aims to contribute to, address and assess wicked problems, especially on a cross-scale interplay (as in the land–sea interface), that have no definite solution, but should include some central components, such as addressing linkages across scales, building on current institutions and ongoing processes to create synergy, engaging stakeholders from different sectors and raising awareness about the impact of human activities, and targeting intermediate outcomes that contribute to overall improved economic, social and environmental status. In doing so, managers and decision-makers should avoid the spread of panaceas, which would be a simple solution to complex problems [14], with the complexity being used as an excuse for inaction [49]. DIET aims not to simplify the problem, but at least highlights the central nodes of complexity and places where interplay management should be taken into consideration, taking advantage of the connections [105,106] instead of exacerbating overlaps and fragmentation. It allows managers bridging the science policy gap to explore how to adapt and improve current institutions so as to maintain the capacity of complex and dynamic ecosystems to provide services for human well-being. The disparity between environmental problems and institutions has been going on for a long time, and innovative solutions may emerge when practitioners make sense of the complex problems and call for EBM principles, as well as more equitable and inclusionary decision-making [22,36,107].

5. Conclusions

This article has proposed a qualitative approach that combines an assessment of the direct and indirect impacts derived from the demand of a given ecosystem service, as well as of the cumulative impacts originating from multiple human drivers and activities on the environment that supports such service. This approach not only describes the problem of structuring, but of identifying the fluxes and cross-scale linkages, so as to support a more effective decision-making process in a cross-scale territorial strategy. To exemplify the approach, we have presented an illustrative case of the demand of seafood provision in SPMM.

The DIET approach is a systemic assessment that includes different scales, allowing one to visualize flows and impacts, and to illuminate governance arrangements to deal with a given problem. It allows us to directly address several of the challenges inherent to EBM, integrating several areas of science, and capturing the complexity of the interactions between the biophysical and human components of an ecosystem. By highlighting ecosystem services and guiding responses by EBM, it emphasizes the extent to which society, its ways of life and its economic activities depend on and benefit from nature.

In other words, applying DIET before the discussion of the various policy options may help to make sense of current affairs, and to achieve a more comprehensive solution that fits the problem, rather than spreading more panaceas.

Linking ecosystem services to activities allows, at a minimum, a qualitative assessment of the cumulative impacts originating from different activities, and captures the direct and indirect effect of multiple human uses across the system that cause the impairment of human well-being. As expected, coastal and marine zones support human well-being and economic development, addressing, adjusting and mitigating cumulative impacts. Although DIET was exemplified to discuss the land–sea interaction in the context of the direct or indirect influence of metropolitan regions, the structure of DIET is oriented towards the problem's structuring. It aims to guide governance processes that support an ecosystem approach in any cross-scale context.

For the application of DIET to management, there are still many practical challenges to be overcome. Among them we can consider the following: the integration of different areas of knowledge that use different methodologies and definitions; the quantification of the vulnerabilities of ecosystem services; the development of appropriate metrics that allow monitoring; the incorporation of scientific uncertainties in the adaptive management cycle; and the inclusion of social justice as a relevant component.

The use and dissemination of DIET in different case studies will contribute to its improvement and advancement of the management of natural resources and territorial planning. The application of DIET in the territory of the SPMM was not exhaustive; however, it evidenced that DIET has interesting characteristics to be deeply explored through this new approach, including mainly the capacity for management at different levels and scales, and the flows that entail territorial interdependence.

Author Contributions: Conceptualization, L.R.G. and A.T.; Data curation, L.R.G. and M.O.; Investigation, L.R.G.; Methodology, L.R.G., M.O. and A.T.; Supervision, A.T.; Writing—original draft, L.R.G., M.O. and A.T.; Writing—review and editing, L.R.G., M.O. and A.T. All authors have read and agreed to the published version of the manuscript.

Funding: Please add: The authors would like to acknowledge the support of the São Paulo Research Foundation (FAPESP: LRG: 2018/00462-8 and 2019/04481-0), Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq: AT: 309697/2015-8 and 310553/2019-9) and the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior—Brasil (CAPES)—Finance Code 001 (MO). The work is part of the activities of the ongoing thematic project, "Environmental Governance in the São Paulo Macrometropolis, due to climate variability" (FAPESP: 2015/03804-9), linked to the FAPESP Global Climate Change Research Program.

Acknowledgments: The authors would like to thanks Mariana Andrade for graphic elements design. The comments and suggestions from Luciana Y. Xavier (Oceanographic Institute of University of São Paulo), Thamiris Brandão Campos (IAG-USP) and Pedro Henrique C. Torres (Energy and Environmental Institute of University of São Paulo) were essential to improve the previous version of this manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

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