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Prototype of social-ecological system's resilience analysis using a dynamic index

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ABSTRACT

Resilience is understood as a social-ecological system (SES) property that embodies nature and society and a research perspective with high potential to be applied in reaching sustainability goals. A system's property is composed of ecological and social limits representing boundaries that, if trespassed, result in the system's regime change with increasing uncertainties. These changes can impact the reliability of delivering a set of desired ecosystem services, and consequently, society's wellbeing can be negatively affected. Thus, modeling a complex and adaptive SES, with feedback, nonlinearities, and path–dependence becomes a crucial tool to inform building a responsible governance behavior that tackles SES resilience. This work built a prototype model of SES resilience for a case study in a Brazilian coastal city with the following aims: 1) to formalize the principles underpinning resilience into a dynamic index, 2) to assess the extent to which this understanding highlights system interdependencies and tradeoffs, and 3) to learn about the benefits of making quantitative assessments of such socio–institutional principles. Multiscale Integrated Model of Ecosystem Services – MIMES (Boumans et al., 2015; Oliveira et al., 2022) is a SES modeling framework using System Dynamics that embraces complexities' attributes in an interdisciplinary and integrated model. Constructing a causal loop diagram embracing the social sphere represented by the seven resilience principles proposed by Biggs et al. (2015), revealed the necessity to include social goals in the model. It was considered that the *Homo economicus* represents the most common social perspective and determinant for those goals. Ten different types of ecosystem services were extracted from the ecological part of the simulation (Oliveira et al. 2022) and then combined with those seven resilience principles into the Dynamic Resilience Index (DRI) using a Cobb Douglas–like production function. The numerical simulation produced four insights about resilience that are described and discussed: 1st insight: resilience of what to what? The resilience of the whole system in providing a set of Ecosystem Services against changes in slow variables; 2nd insight: resilience presents seasonal variations; 3rd insight: the system is operating as if it is in the K phase during ecological succession; 4th insight: not all resilience principles have the same weight in resilience. Conclusions point out that resilience can present seasonal variations, and that response diversity and functional redundancy are leverage principles with higher influence in resilience.

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1. Introduction

Integrative human-nature perspectives such as social-ecological or coupled human-nature systems consider economic activity (social) a human feature that occurs inside a larger and finite natural system (ecological). These perspectives are research agendas that have increasingly been taken into account after global diagnoses of the state of ecosystem services (ES) (Leemans & de Groot, 2003) and the value they represent to society (Costanza et al., 1997; MEA - Millennium Ecosystem Assessment, 2005; de Groot et al., 2012; Costanza et al., 2014). These perspectives also understand the benefits people get from nature (ES) and society in intricate networks of relations and dependencies within each other and consider those subsystems are linked once they affect and are affected by each other in complex dynamic relations (feedbacks). Effective management of the ecosystem can be made by those who recognize these links as well as the limits of the combined social–ecological system (Burroughs, 2011).

The ecological subsystem of the SES must be managed sustainably to obtain a continued yield of the desired set of ES in the short and long term (Daily et al., 2000; Beaumont et al., 2007). Governance needs to be able to work properly under a system that changes across time due to internal variations and also external influences such as climate change. Adaptive governance seems to be appropriate, once it connects individuals, organizations, agencies, and institutions at multiple organizational levels (Folke et al., 2005) and can be considered the way societies can manage to change accordingly to the behavior of the ecosystem. Therefore, to be served by the desired set of ecosystem services, in the short and long–range, within a certain level of confidence, requires a social system able to adapt itself to nature's regular behavior and changes. In other words, the SES must demonstrate resilience.

The resilience concept has been used in several disciplines from ecology to business to medicine. Resilience thinking and use by practitioners or scientists in the SES field started with Holling (1973), which has since blossomed into an interdisciplinary and important framework. In a brief review, Downes et al. (2013), found more than ten resilience concepts. Practical applications that results in increased resilience can be as simple as the implementation of a serial step-pool (Fattahi Nafchi et al., 2022). A recent broad review (Folke, 2016) evaluated it as a developing field inside the academy, but also as a movement outward academic research being embedded in environmental and sustainability planning by several countries and institutions.

Resilience is usually desired in a system when the provision of ecosystem services suits what society expects from that system. Sometimes resilience locks the system in a poor condition that is undesired by the community revealing a "duality of resilience" (Kharrazi et al., 2016). In other words, resilience is neither good nor bad, is a feature of the SES regarding change and identity.

There is a distinction between Specific Resilience and General Resilience that is commonly present in the literature. The first one is the answer to the question "Resilience to what?" meaning specific resilience is considered concerning a specific menace. On the other hand, general resilience is a general feature of systems, not a reaction regarding some specific threat. It is the capacity to deal with uncertainty, complexity, and surprises (Folke, 2016).

Operationalizing Resilience is a field in fast development, although modeling and measuring resilience is not a trivial task. Specific Resilience is easier to handle and there are several experiences in the literature (e.g., Bottero et al., 2020; Feldmeyer et al., 2020; Barreiro et al., 2021; Chen & Quan, 2021), but operationalizing the concept at a higher level is an operational challenge. Béné et al. (2016) also claim that "none [analyses] provides an approach or a methodology that enables us to measure resilience simultaneously at several levels". Additionally, resilience is a theoretical concept that was originally envisioned using models (Carpenter et al., 2001) and several attempts of measuring and modeling resilience are currently in development (Angeler et al., 2015; Bottero et al., 2020; Cristiano et al., 2020; Li et al., 2020).

In this line, the goal of this work was to integrate governance and ecological systems features (Biggs et al. 2012) into a Dynamic Resilience Index (DRI), meaning it is based on a dynamic model, while understanding the system as a social–ecological system (Carpenter et al., 2001; Boumans et al., 2002; Gunderson and Holling, 2002; Gunderson et al., 2010; Levin, 2013; Boumans et al., 2015). The DRI was developed and applied in Ubatuba, a Brazilian coastal city (Oliveira et al., 2022). The innovative part of the present study was to develop the system structure that connects all these social and ecological variables in a coherent model, and to analyse the results and inplications of resilience theory, through the model.

SESs modeling still does not have a unique framework for analysis and its methods represent an interdisciplinary attempt to reach some aspects of these dynamic, complex, and adaptive systems (Schlüeter et al., 2012). In this context, we claim a causality model such as the one used in the present study (MIMES – Multiscale Integrated Model of Ecosystem Services – see Oliveira et al., 2022; Boumans et al., 2015) is an interesting tool for this task, once its capacities of integration enhance the usual techniques used in resilience models and extrapolate disciplinary knowledge.

2. Methods

2.1. Foundations for the prototype development

Several authors have been studying what systems' properties interact forming the substrate from which Resilience emerges. Fiksel (2003) established a list of four components of Resilience:

Diversity – the existence of multiple forms and behaviors;

Efficiency – performance with modest resource consumption;

Adaptability – flexibility to change in response to new pressures; and,

Cohesion – the existence of unifying forces or linkages.

Additionally, Calgaro et al. (2014) and van der Veeken et al. (2016) built a framework for resilience analysis. Although it is focused on tourism activities, it is very comprehensive, brings the knowledge of complex adaptive systems to the core of the analysis, and shows that feedbacks and dependencies are crucial to understanding resilience.

Yet, a broader approach is presented by Biggs et al. (2012, 2015) with a deeper analysis and more detailed features underneath the resilience concept. Their understanding focuses on the resilience of ES, meaning the "capacity of a social–ecological system to continue providing some desired set of ecosystem services in the face of unexpected shocks as well as more gradual ongoing change". This comprehensive approach found resilience in seven components:

- (P1) Maintain diversity and redundancy – systems with high levels of biodiversity and redundancies tend to be more resilient in providing ecosystem services;
- (P2) Manage connectivity – ecosystem recovers from disturbances using internal links of species and social actors. In social networks connectivity can also provide new information and trust;
- (P3) Manage slow variables – identify slow variables and their feedback is a challenging effort, but understanding these general system features enhance resilient behavior;
- (P4) Foster Complex Adaptive Systems (CAS) thinking – comprehension of the need for integrated approaches, non–linearity, and uncertainty regarding ES production in SES enhance the ability to deal with changes and then increases resilience. This principle will be called "SES as CAsK", meaning the knowledge of the SES being a complex adaptive system;
- (P5) Encourage learning – studying how systems work reduces the uncertainties; experimentation and monitoring thus can enhance knowledge and fostering resilience;
- (P6) Broaden participation – participation enhances relationships, can build trust, can facilitate learning, and make collective action possible. All these are directly related to governance and resilience;

- (P7) Promote polycentric governance systems – provides a structure in governance that allows the other principles to develop and enhances participation and social networks.

Principles 1 to 3 are general systems features and principles 4–7 are more related to the governance of social–ecological systems.

All those principles have their particularities regarding field measurements, communication, and relations with ES production. The present paper offers a prototype model that assumes values for each of those subcomponents (independent variables) (Appendix A) to test and learn about the structure of variables underneath resilience. Although we do not know the instantaneous values of each independent variable (Fig. 1), we hypothesize the goals the dependent variable (resilience principles) should pursue: the goals society desires for them (see next section for more details). With that, the structure could be tested, and some insights were produced through the development and indication of a novel dynamic resilience indiex.

2.2. Model description

The model used to calculate the dynamic resilience index (DRI) is composed of two sub-models: one embracing the coastal ecosystem and its associated ecosystem services production (Oliveira et al. 2022); and the other, the resilience sub-model (Fig. 1). The ES model provides the situation of ten ecosystem services for the case study region, Ubatuba (crab production, clam production, cartilaginous fish production, bonefish production, carbon sequestration, oxygen production, mineralization, sewage depuration, nutrients cycling, and water quality). Fig. 1 represents the prototype translation of resilience theory as found in Biggs et al. (2012) to the numerical MIMES-type model. The integration of the two parts forms DRI (Fig. 2).

The first step to translate the theory into a model was the construction of a causal loop diagram (CLD) to represent the most relevant objects that were simulated and the causalities connecting them (Sterman, 2000). Considering this as a prototype model means that this translation of the theory in a causal loop diagram represents the author's understanding of the theory and validation occurred inside the research group only. For the sake of transparency about our assumptions during translation, every causal relation pointed in the CLD is followed by the phrase or word on a specific page of the paper (Biggs et al., 2012) used as a source of this interpretation (Appendix A).

The next step was translating the CLD into a numerical simulation. This experimental part is the core of the prototype because the computer simulation requires numbers for each variable. All variables had a spectrum of values, from zero to one. The latter does not necessarily mean the best for the SES. Sometimes when a variable assumes a higher value it can bring some undesired consequences as well. For example, low diversity can lead to brittleness (and consequent lower resilience), but very high diversity can lead, through feedback, to low redundancy and diminish resilience as well (Biggs et al., 2012 page 6).

To simulate the participation of the secondary variables (Tier ≥ 2) in the resilience principle's sphere, values were assumed considering their relative proximity to the main seven principles, depicted from the intermediary steps studied in the CLD. This way allows all variables to be relevant to the result, yet the participation is kept proportional to their relative importance given by the theory. Thereby all seven principles are considered tier 1 (varying from 0 to 1, starting with 0.5) and variables that influence directly one of these seven principles are tier 2 variables, whose highest value is 1×10^{-3}. Variables that influence tier 2 are considered tier 3 and have the highest value of 1×10^{-4} and so on (Fig. 1). Considering the model uses daily timesteps, these numerical assumption makes sense because direct influences (tier 2) on the core of the resilience attributes (the seven principles) will manifest their influence in the short term, while indirect influences, through feedback and slow addition of cumulative effects will act in the long term. Limitations of this approach are presented in the discussion.

The foundational principles from Biggs et al. (2012, 2015) are broad and therefore some difficulties appear when applying these principles. First, the principles, as the word means, are high–level understandings of what underpins resilience. As principles, they are generic and broad,

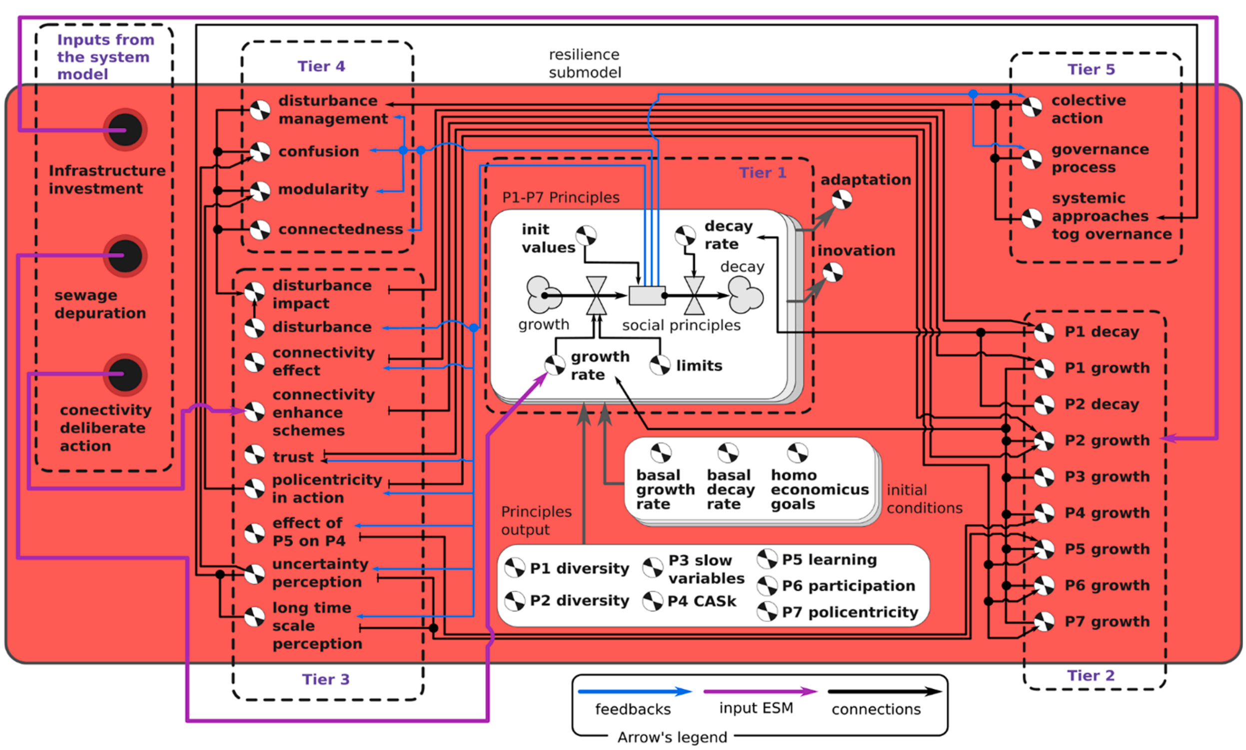

Fig. 1. Resilience submodel. Numerical Simulation of the resilience principles showing tiers of values of each variable. This stock and flow numerical simulation came from the causal relations described in the CLD (Appendix A).

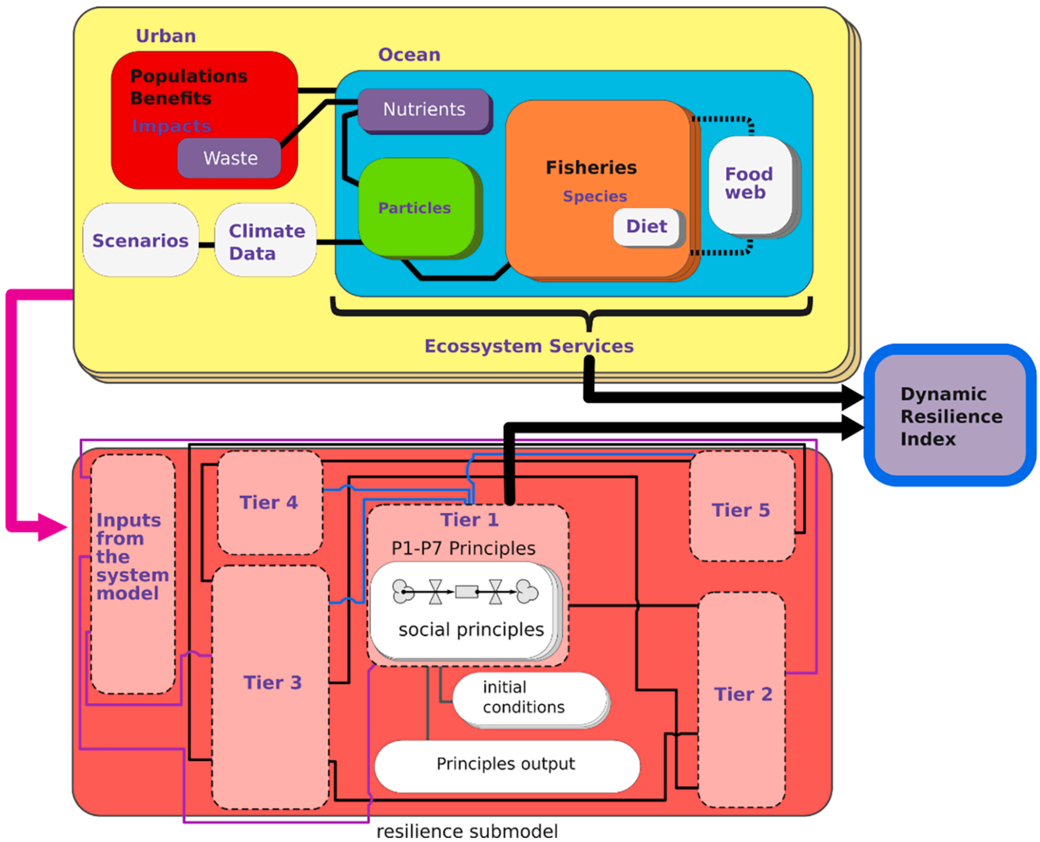

Fig. 2. The ecosystem services and resilience sub-models coupled. The ecosystem services sub-model provides inputs for the resilience sub-model in terms of infrastructure development, connectivity, and sewage depuration (Fig. 1). From the ecosystem model, ecosystem services will be incorporated into the DRI. From the resilience sub-model, the values of the seven resilience principles are integrated with the ten ecosystem services, forming the DRI.

and thus the initiative of measuring, or applying them in an operational approach, is difficult, as recognized by the authors (Biggs et al., 2012). Second, when describing those principles, the consideration of scenarios that lack resilience was probably the case because the text usually uses terms with growth connotations as "enhancing, foster, broaden" when applied to those principles. Therefore, when we translated the text into a numerical model, the results present more feedback related to growth than the decrease in variables (Fig. 1).

The third point is the lack of a cap limiting the principles. In Biggs et al. (2012, 2015) the growth for each principle is unlimited. However, the present paper considers that every principle has a limit that is the manifestation of a social goal, once it is determined and chosen by the society in that system. This understanding of resilience limits being socially determined is presented by several authors (Carpenter et al., 2001; Holling et al., 2002; Adger et al., 2009; Sundstrom and Allen, 2019). They conceive resilience limits as society's feature dependent on values and goals: something socially built and politically supported by part of society's decisions, but at the same time contested in desirability, effectiveness, and feasibility by other parts of the same society (Adger et al., 2009). Thus, the dynamic equilibria of social forces would bring the adaptation (or resilience) to a point determined by goals but influenced by those social interactions.

In the present paper, we followed orthodox economic theory and elected *Homo economicus* (Costanza and Folke, 1997; Costanza et al., 2000; Costanza et al., 2017) as a representative participant of the whole society. A follow-up on this assumption is already in preparation for a different paper, in which we will test the role of different social goals (through culture-theory worldviews) in determining the behavior of the SES and its resilience. As stated by Cetin (2015) "humans design their environments to reflect their relationships with nature and space". Therefore, with plural worldviews applied in this model, different implications in terms of resilience of this SES will appear and show the importance of participative decision making processes in creating and maintaining the whole set of desired ecosystem services.

The goals for each principle are described and numerically presented (Table 1). They can assume values from 0.04 (a number meaning zero, but necessary for the model to run numerically), narrow limits (0.4), a very limited position (0.6), acceptable limitation (0.9), high (1) and infinite (2) (this infinite happens only with the Learning principle because the authors assumed learning can always improve). The numbers represent the importance *Homo economicus* attributes to each principle of the resilience theory.

The last step in the simulation methods was to run a sensitivity analysis (Appendix B) to test the relative importance of these principles. The simulation runs daily values from 2010 to 2100 to be congruent with the ecosystem services model (Oliveira et al., 2022).

The story for the *Homo economicus* (Fig. 3) is that there is no need for response diversity and redundancy (P1 = near zero), the market is the answer to solving environmental problems. Thus, the market must stay

Table 1
Profiling of the goals for resilience principles for the *Homo economicus*.

Principles	*Homo economicus*
1. Response diversity	Almost zero (0.04)
2. Connectivity	Must be high (1)
3. Management of slow variables	Must be high (1)
4. SES as CAsK	Almost Zero (0.04)
5. Learning	Narrow limits (0.4)
6. Broaden Participation	Very limited position (0.6)
7. Policentricity	Very limited position (0.6)

SES as CAsK means the Knowledge of a Social-Ecological System taken as an Adaptive System.

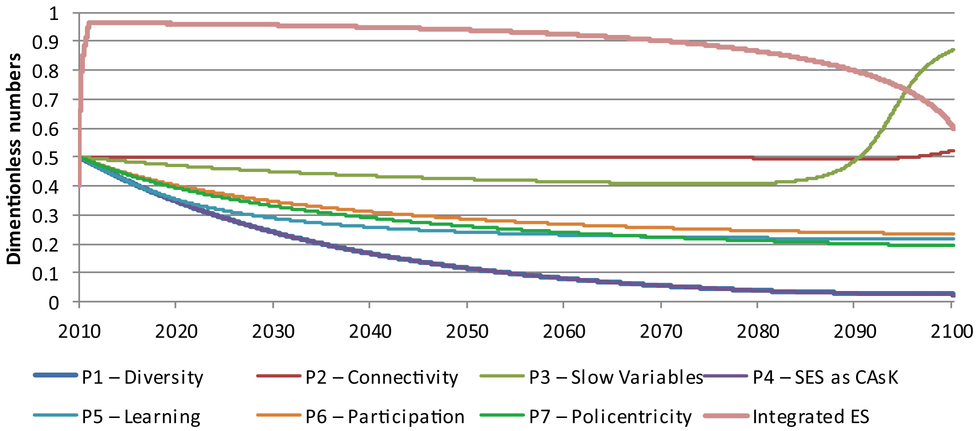

Fig. 3. Individual behavior of the DRI elements. The graph shows the seven principles individual behavior over time. Considering the *Homo economicus* goals, most of the principles exhibit a decrease in value at different rates, exceptions made for connectivity, and management of slow variables that counterbalance the trend exhibiting a growth behavior at the end of the simulation, reflecting thus the influence of the slow feedbacks in the system. The ecosystem services curve represents the integration of the ten normalized values using weights from Table 2.

connected to every possible point in the system (P2 = high) and slow variables such as "long economic cycles" must be managed properly (P3 = high) to avoid surprises or dissonances in the market equilibrium. The resource bases of the economic system are not complex (P4 = near zero) and can be managed by rational economic beings who know the ways of the market, and their preferences. With additional learning (P5 = narrow) regarding the right prices, the management will be appropriate. There is no need for participation of others unless it is necessary to maintain the good competition of the markets (P6 = very limited), and there is no need to spread the government in everybody's hands, once small groups, taking centralized solutions can leave the markets free to work (P7 = very limited).

2.3. Dynamic resilience index formula

The novelty of this paper is combining a dynamic ecosystem and ecosystem service model within the resilience framework to construct a dynamic resilience indicator. The index was built using the formula:

$$DRI = \prod_{i=1}^{7} P_i^{\gamma i} \prod_{j=8}^{17} ES_j^{\gamma j} \quad (1)$$

where DRI is the Dynamic Resilience Index; P1 to P7 are the resilience principles. ES embraces all ten ecosystem services extracted from the ecosystem model.

We adopted a Cobb-Douglas like function (Cobb and Douglas, 1928) (Eq. (1)) because it successfully integrates the ten ecosystem services with seven resilience principles in a feasible mathematical approach and also allows gaming with the weights of each element. Furthermore, this forumalation is consistent with similar approach already used in the MIMES framework (Boumans et al., 2002, 2015).

2.4. Weighting the cobb douglas equation

As the Cobb–Douglas-like function demands dealing with exponents ($^{\gamma 1\text{-}17}$), comes the question of which of those elements weigh more in the overall resilience of the system. Boumans et al. (2002, 2015) claim that the weighting values are intrinsically unknown and reflect aggregated individual preferences. Therefore, we used the same idea of representing the *Homo economicus* ideals, or worldviews for the weighting of the Cobb-Douglas equation (Table 2).

The weights assumed values ranging from negative values, associated with an undesired situation (−0.01), to positive weights representing grades of approval for each variable: very low (0.01), low (0.02), medium (0.05), high (0.07), and very high (0.1). Those values represent variations around the medium value of 0.058 for each of the 17 components of DRI, which sum totalizes 1.

The story in Table 2 is complementary of that describing the goal

Table 2
Homo Economicus weights for ecosystem services and resilience principles.

	Variable	*Homo economicus*
Resilience Principles	P1 – Diversity	0.01
	P2 – Connectivity	0.1
	P3 – Slow Variables	0.1
	P4 – SES as CAsK	−0.01
	P5 – Learning	0.05
	P6 – Participation	0.01
	P7 – Policentricity	−0.01
	subtotal	0.25
Ecosystem Services	Crustaceans production	0.1
	Mollusks production	0.1
	Cartilaginous fish production	0.1
	Bonefish production	0.1
	Carbon sequestration	−0.01
	Sewage Depuration	0.1
	Nutrient Cycling	0.1
	Oxygen Production	−0.01
	Mineralization	0.07
	Water quality	0.1
	subtotal	0.75
	TOTAL	1

attribution (Table 1). From the *Homo economicus* perspective, there is no need for response diversity (P1 = very low), the market is the answer to solving environmental problems. Thus, the market must stay connected to every possible point in the system (P2 = very high) and slow variables (e.g. economic cycles or water quality) must be managed properly (P3 = very high) to avoid surprises or dissonances in the market equilibrium and also to avoid losing the source of economic income. The resource bases of the economic system are not complex, and the understanding of it as complex is undesired (P4 = undesired); resource bases can be managed by rational economic beings, that know and learn about their preferences (P5 = medium). There is no need for participation of others unless it is necessary to maintain the good competition of the markets (P6 = very low) and there is no need to spread the government when centralized solutions can leave the markets free to work (P7 = undesired).

On the ES side, *Homo economicus* focus their governance efforts on those ecosystem services that provide an immediate economic yield, maximizing the bottom line. Thus, high values are given to production (Crustaceans, Mollusk, cart. fish, bonefish = very high) and to water quality and sewage depuration (very high) because they matter to tourism frequency. Nutrient cycling (very high) and mineralization (high) are bonuses from nature that can help to ensure better water quality and thus tourism. Carbon sequestration and oxygen production are global problems that could lead stakeholders to choose a different management system for the environment, against that one provided by markets, and so they are not welcome (undesired).

3. Results and discussion

The DRI calculation is based on the integration of ten Ecosytem Services with the seven resilience principles. The behavior of the integrated ES and the individual seven principles are presented (Fig. 3).

3.1. 1st insight: Resilience of what to what? resilience of the whole system in providing a set of ES against changes in slow variables

It is very common in resilience literature to establish the foundational question: resilience of what to what? Therefore, the analysis must specify the state of the system and to what this state is resilient against. This practice is usually grounded in Carpenter et al. (2001) and its metric is based on the size of the basin of attraction. Folke et al. (2010) called that specific resilience and, in an opposing concept, defined general resilience: "resilience to all kind of shocks, including completely novel ones". Also, the authors call the attention that reinforcing part of the system to be resilient against a determined perturbation can make the whole system loses resilience in other ways (Folke et al., 2010).

In this case, DRI answers both questions from specific and general resilience, because it has characteristics from both (see Walker et al., 2009): first, it is *a priori* unspecific about disturbances as it relies on slow variables that are varying through the long time series; second, when stressed with known shocks, it reacts accordingly.

3.2. 2nd insight: Resilience presents seasonal variations

The fact that the index is proportional to some ecosystem services that have a strong seasonal pattern, makes the index seasonal (Figs. 4 and 5). All fisheries in the model are seasonal as well, but their oscillation is small. Carbon sequestration, oxygen production, mineralization, and sewage depuration are strongly seasonal, and then their oscillation is reflected in the index as well.

The overall behavior of the curve (Figs. 5 and 6) shows the system losing resilience along with the simulation. That is coherent with expectations, considering the curve of the ES and the behavior of the resilience principles. What calls attention is the marked seasonality.

Oscillatory behavior has been shown before in the r to K phases of the adaptive cycle (described below) (Burkhard et al., 2011; Fath et al., 2015; Kharrazi et al., 2016), but they were random oscillatory movements not related to seasons. The difference between high resilience season (in this case summer) and low resilience season was around 10% of DRI, which is significant.

In this sense, this observation alerts a potential manager to the fact that certain systems are more resilient in determined seasons and less resilient in the others. For example, if disturbances can be delayed to hit the system during high resilience season, maybe those disturbances unfold in smaller impacts. This dynamic indicator highlights the importance of the temporal dimension of resilience in managing ecosystem services.

To enhance visual clarity and continue the observations of the index those oscillations were normalized. In this case, the resilience index curve starts with values around 0.8 and decreases along the century reaching almost 0.5 in 2100. This decrease reflects that the net result in the integration of ecosystem services with the seven resilience principles is negative throughout the century.

3.3. 3rd insight: The system is likely operating in the K phase

Holling and Gunderson (2002) showed that most ecosystems change over time in an evolutionary cycle (the adaptive cycle). It is a metaphor for how changes in systems occur through time and what is the role of resilience (Holling and Gunderson, 2002; Folke, 2006; Oliveira & Silva, in press). Our results for DRI show the resilience decreasing until the end of the simulation, which corresponds to the behavior of a system in the late K phase, (Holling and Gunderson, 2002; Fath et al., 2015; Kharrazi et al., 2016). Sundstrom and Allen (2019) attribute the decline in resilience in the K phase to the excess of connectivity. Our results show the connectivity being kept constantly high (when compared to the other principles) along with the simulation with a further increase at the end of the century (Fig. 3), which is consistent with observations in literature (list it again here).

Considering a system in the late K phase is coherent with declining resilience since some ecosystem service capacities (e.g., sewage depuration and mineralization) are being overwhelmed by long-term drivers such as the number of tourists. This is verified by the unconformities in water quality in terms of low dissolved oxygen, and high concentration of *Enterococcus* (CETESB 2019, 2020, 2021). It is also assumed in the model (Oliveira et al., 2022) that fisheries (all four groups) can sustain current yield throughout the century, but this assumption is a statement against the global alarms of fisheries decline. The actual drop in the DRI would be greater considering fisheries depletion.

3.4. 4th insight: Not all resilience principles have the same weight in resilience

The results of the sensitivity analysis are presented (Fig. 7, for additional explanations, see Appendix B) and show the participation of each principle is different. The higher μ^* of P2 (connectivity) and P1 (diversity) show that these two principles are mathematically more relevant for the objective.

In the sensitivity analysis, the following have medium impact:P3

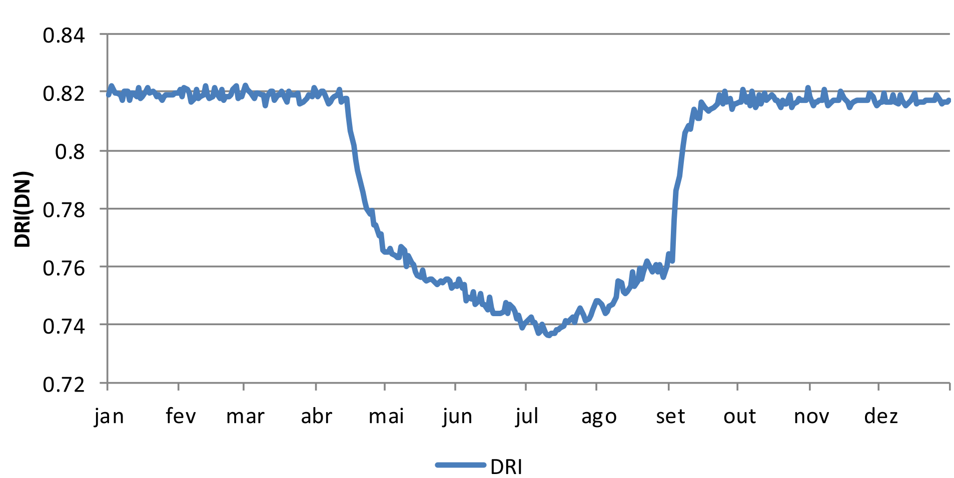

Fig. 4. Dynamic Resilience Index for 2011. DRI for the *Homo economicus* was simulated from January to December 2011, showing a marked seasonal oscillation.

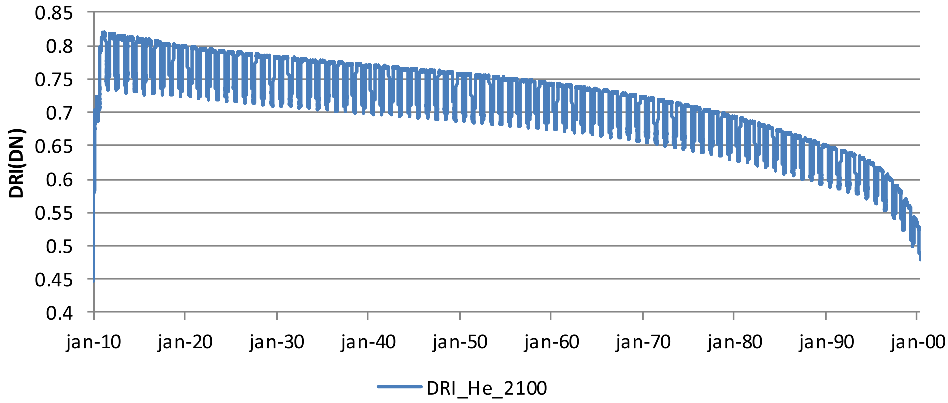

Fig. 5. Dynamic Resilience Index from 2010 to 2100. Simulated with seasonal oscillations from 2010 to 2100 for the *Homo economicus* DRI.

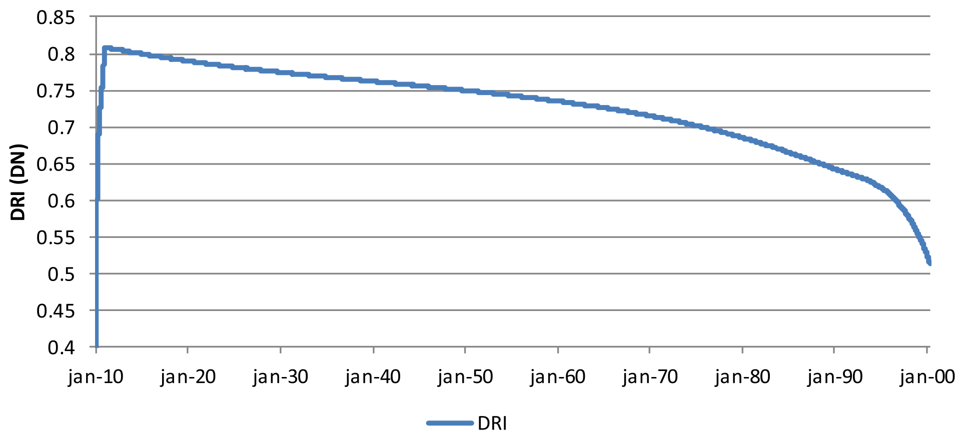

Fig. 6. Dynamic Resilience Index normalized. In this simulation, the oscillations of ES were normalized, and then the index appears clean along with the simulation.

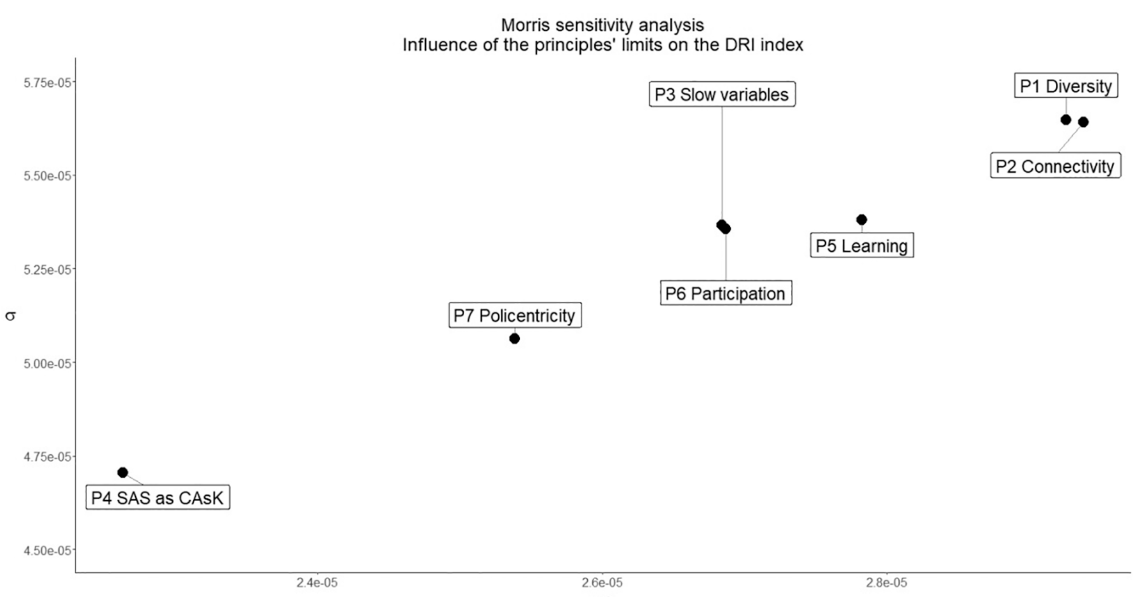

Fig. 7. Main contributions to resilience. X–axis (μ* - muStar) indicates the importance of its direct linear influence on the output. The higher is μ*, the more sensitive the output to this input. Y–axis (σ – sigma) indicates the indirect influence (influence through feedback).

(management of slow variables) with intermediate μ^* and intermediate σ; P5 (learning), with higher μ^* and intermediate σ; P6 (participation), with lower μ^* and lower σ and finally P7 (policentricity), with intermediate μ^* and higher σ. Those four principles (P3, P5, P6, and P7) form a distinct group of intermediary influences in resilience, with slight variances of direct (μ^*) and indirect (σ) intensity. The least influence is made by P4 (SES as CAsK) with low μ^* and low σ, which appear isolated in the left corner of Fig. 7.

That result is coherent with the model and theory (Biggs et al., 2012). This sensitivity analysis justifies why some of the principles that do not have a variable directly influencing their decreasing rate (P3 to P7) can also decrease: due to the feedback of other principles. That fact is also corroborated by P1 and P2 having higher σ, meaning they are more sensitive to an indirect influence of the input (principles values) than the others.

Regarding the management of resilience, those principles should be the focal point because they have more effect on the result with the same input change. This makes sense once the high leverage effects of response diversity and functional redundancy have been described by resilience theory (Biggs et al., 2012, 2015; Walker et al., 2002, 2009).

3.5. Limits and caveats of the simulation

The first limitation is regarding the numerical data for all the seven principles and they're at least sixteen auxiliary variables (Fig. 1). The goal of this research was not to measure those variables, assuming they can be measured, but to test the structure of the SES coupled with a dynamic systems model.

The second limitation is the use of *Homo economicus* as a model of society. While this approach conforms with standard economic theory, it has been shown unsatisfactory in many studies. We use it here as a baseline for comparison with other economic studies to build more sophisticated approaches. An analysis using other typologies for worldviews is in preparation.

The numerical modeling assumptions presented in this paper may be different from field data. The point of creating a prototype, or the first example of something from which latter forms are developed, was to understand how the relations between those variables unfold later in resilience. The numerical results might be different according to the data inserted in the model, but the overall behavior of the system will be roughly the same, considering behavior is the product of the structure (Sterman, 2000; Meadows, 2009).

The practice of creating numerical models from sociological theory using experimental data is a common practice in the field, being present in Janssen and Carpenter (1999), with a resilience simulation; Sterman (1985) with a system dynamics simulation of Kuhn's "the structure of scientific revolution"; Rahmandad et al. (2009) in which system dynamics were used for a numerical simulation of "learning", using the same level of abstraction. Robinson (2007) brings a great review of numerical simulation on sociology, rooting this practice since the 1940 s. Finally, we echo Midgley (1992) that pluralism is much deeper than a way to "promote openness and conciliation while at the same time preserving theoretical coherence": it is essential for system sciences.

4. Conclusions

This work presented an innovative socio-ecological systems indicator for measuring resilience over time called the dynamic resilience index (DRI). Far from exhausting the possibilities of calculations, the goal was to collaborate with the discussion regarding SES resilience on at least three points. First, is to formalize the principles underpinning resilience in an integrative although treatable mathematical dynamic index that should not substitute other types of assessments, but enhance the application of the concept and the operationalization of the theory. Second, it provides an understanding of system interdependencies and trade-offs assessed by the causal model and the numerical simulation that can be useful prioritizing management actions and in establishing comparative studies in the future. Third, the quantitative assessment resulted in insights that can be useful in adaptive management on coastal systems in general when the ecosystem services production are being taken into account.

From the DRI results, four insights were discussed, and they point to some theoretical properties of resilience that seem new compared to those found in the literature: resilience being seasonal (2nd insight); "diversity and connectivity" influence resilience with higher weight in the result (4th insight) compared to the other resilience principles. These results can also be relevant for practitioners due to the possibility of the higher resilience of the present system during the summer being a more-or-less general property of SES. In that case, determining the high resilience season can be useful for management. The second practical result is to reinforce the leverage behavior response diversity and functional redundancy principles have in determining the resilience of the system.

The other results seem to be more related to this case and probably have less potential for universalization as the general or specific classification of the index (1st insight), and the phase in which the system is (3rd insight).

Closing remarks refer to the use and application of resilience concepts through the measurement of DRI, which we argue, can enforce the awareness of society regarding complexities, uncertainties, and feedback of SES and thus promote the development of this scientific field. It could also, after some improvements, be used for developing a comparative standard for future simulations or land and coastal management comparisons.

CRediT authorship contribution statement

Bruno M. Oliveira: Conceptualization, Software. **Roelof Boumans:** Conceptualization, Software, Supervision. **Brian D. Fath:** Conceptualization, Supervision. **Benoit Othoniel:** Software, Validation. **Wei Liu:** Conceptualization. **Joseph Harari:** Conceptualization, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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