Ecological Modelling 468 (2022) 109953

Contents lists available at ScienceDirect

Ecological Modelling

journal homepage: www.elsevier.com/locate/ecolmodel

Socio-ecological systems modelling of coastal urban area under a changing climate – Case study for Ubatuba, Brazil

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ARTICLE INFO

Keywords:
Socio–ecological systems
Ecological models
MIMES: Multiscale integrated model of ecosystem services
Climate change scenarios
Brazil

ABSTRACT

Understanding the complex dynamics between society and nature is a critical contribution of ecological modelling. Integrated views of human-nature relations as well as tools and frameworks for studying these relations are gaining ground. A socio-ecological systems (SES) perspective therefore embraces both social and environmental factors that uses nonlinearities, feedbacks, models, and multi-level networks for understanding and studying those phenomena. When undesired drivers as climate change are also taken into account, the most urgent question is how these critical socio–ecological systems will behave given the stresses they endure. This work had the objective of creating a new simulation of a coastal SES from Brazil that is able to integrate several climatic and social variables through a dynamic and coupled model, and forecast its behavior in the future according to scenarios. Specifically, a systems dynamics simulation model using MIMES (Multiscale Integrated Model of Ecosystem Services) was developed for Ubatuba, a coastal city highly dependent and influenced by tourism. Results showed good correspondence between the model and the data when testing several environmental inputs (wind speed and direction, cloud cover, sea surface temperature, precipitation patterns). The model simulated the population dynamics of 15 biological groups from 2010 to 2100 under different scenarios. Climate change will reduce most of populations in a range from −0.13% (± 0.0%) to −10.31% (± 0.0%). There are groups where the influence of climate change is not significant (Bivalve, Brachyuran, pelagic feeding fish and benthic feeding fish) with variations from 0 to 2% and others with moderate significance (Phytoplankton, Zooplankton, and Enterococcus) with variations >2%. Tourists reacting to water quality degradation is very relevant in Enterococcus population (with a reduction of 34%). Results show the urban activities strongly influencing the biological populations and that these impacts depend on the scenario context. This suggests a policy that limits the number of tourists and increases the water quality at the same time. Therefore, the model's spatial simulation of this complex socio-ecological system can be used to develop an integrative decision-making tool to help the city manage its natural capital and adapt to its changes.

1. Introduction

The study of socio-ecological systems has been gaining momentum since the perception of society intertwined with its natural environment (Liu et al., 2007; 2015) and its relevance for sustainability, economics, and governance. Integrated perspectives of research increase the potential to understand natural phenomena and relation with social well-being, reinforcing the importance of systemic paradigms of research towards a holistic perspective to complement conventional approaches (Schlüter et al., 2012, 2019).

A systems perspective on research embodies notions of complexity, non-linearity, feedback, emergent behavior determined by self-organization and other characteristics of complex adaptive systems (Sterman, 2000). Embracing climate change as a scenario suits these integrative approaches mostly due to the nature of its influence in the biosphere: pervasive, multi-level, and non-linear (systemic). Therefore, the potential for application of a systems perspective in research and practice is not only increasing in intensity but also in urgency.

Modeling is a relevant tool for learning and simulating socio-ecological systems (Ford, 1999; Sterman, 2000; Meadows, 2009;

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https://doi.org/10.1016/j.ecolmodel.2022.109953
Received 5 November 2021; Received in revised form 5 March 2022; Accepted 7 March 2022
Available online 13 March 2022

Schlüter et al., 2012, 2019). Through simulation, it is possible to model population dynamics to test the nature of the coupling between society and the environment, making forecasting possible. One goal is improving the possibility of investigating how new interventions, practices, projects, or policies would unfold. System dynamics started in the 1960s with the seminal work from Forrester at MIT (Industrial Dynamics, 1961). Since then the science around system dynamics has expanded worldwide and reached a high degree of development. One of the main advantages of these models is the capacity to integrate a systems' complexity in the simulation, as described by Forrester (1994) "It can accept the complexity, nonlinearity, and feedback loop structures that are inherent in social and physical systems". The method is responsible for enhancing learning about complex systems (Sterman, 2000).

For coastal areas the necessity of integrated nature-society investigations and governance are blatant since the recognition of the historical and current abuses of marine environment capacities (Halpern et al., 2015; Altman et al., 2014; Börger et al., 2014; IOC-UNESCO, 2020) and the huge importance of oceans on the provision of food, minerals, climate control, transport, etc.

To aid management in formulating, regulating, and guiding the governance of coastal areas, we aim to design a simulation that mitigates complications associated with the complexities inherent in a multi criteria perspective on ecosystem management by means of an ecological model that considers population dynamics and ecosystem services, that has value to management.

MIMES (Boumans et al., 2015) is a very interesting tool for planning and management. The MIMES model is built on causalities, with complex adaptive systems background, embodying feedbacks, path dependencies, and nonlinearities from the environment in a highly interdisciplinary and integrated simulation. For the present study, a new MIMES model[1] was created from scratch, developed specifically for the study area, which is a timely novelty for South American coastal areas.

This paper presents the Integrated MIMES model for Ubatuba, a case study for a Brazilian coastal city, with description of the data integration, model building and scenarios, discussing the simulation development, caveats and limits.

MIMES is the acronym of *Multiscale Integrated Model of Ecosystem Services* (Boumans et al., 2002; Altman et al., 2014; Boumans et al., 2015). This model is based on system dynamics and has been used in several cases (Boumans et al., 2002; Batker et al., 2010; Altman et al., 2014; Boumans et al., 2015). Each MIMES model is unique, built specially for the case and questions the user intends to study. For this Brazilian area, a new MIMES model was built.

MIMES is slightly different concerning regular system dynamics studies. Remarks should include the interaction with GIS systems, the use of arrays, and the great complexity of these models. MIMES goals (Boumans et al., 2015) are:

- Build integrated models of social–ecological systems to guide the process of decision making
- Build ecological economics models focused on integration of knowledge regarding ecosystem functioning and the provision of ecosystem services, under the human well-being perspective;
- Create computer infrastructure as a modeling tool that can incorporate stakeholder input and biophysical dynamics for valuation of ecosystem services and decision–making:
- Simulate ecosystems and socio–economic systems in space;
- Simulate these systems over time, and simulate the interactions between these systems through the coupling

In addition to extending MIMES to a new application, the current model presents modifications in relation to previous versions of MIMES: (1) scenarios were directly coded in the model, instead of being reloaded as scenario parameters; (2) a new sub model for sewage depuration was developed from scratch; (3) precipitation sub model was built in a more accurate fashion; (4) fisheries sub model was built using variable fishing rates; (5) oxygen dissolution algorithm was improved with wind and productivity participation. Items 2 to 5 are new features that addresses limitations of previous versions of the model.

SES modeling represents one frontier in scientific development, to which spatially explicit and dynamic modeling "represents the cutting edge of research in this field" (Costanza et al., 2014). It is believed that increasing the application and development of dynamic integrated models can enhance the knowledge and practice in the field and help "addressing the challenges for analysis and governance resulting from the intertwined, diverse and complex adaptive nature of SESs" (Schlüter et al., 2019).

The objectives of this work were fourfold: (1) to integrate available socio-ecological data of the city Ubatuba into a dynamic and comprehensive model, enhancing the knowledge and understanding about the integrative social–ecological challenges; (2) to formalize the causal premises assumed for the system, the ecological attributes behavior and their interactions with human sphere; (3) to simulate these interactions in time and space; and, (4) to discuss the problems the area can face due to climate change.

2. Methods

The research translated into this paper has the overall structure (Fig. 1):

This paper is part of a greater piece formed by four papers. The present one introduces and describes a new ecological model of ecological population dynamics for coastal Ubatuba There are three more papers that represent applications of the model described here: 2nd) economic valuation of ecosystem services; 3rd) resilience index description using *Homo economicus* as standard and 4th) advanced index development with Culture Theory perspectives. These applications were separated into specific papers due to the length constraints and to reach different audience with relevant information.

2.1. Area description and spatial definition

Ubatuba is a coastal city on the northern São Paulo State coast, Brazil (Fig. 1). The city is formed by 200 km of beaches that cover all west frontiers. Eastern limits are the Serra do Mar mountain range, with altitudes greater than 1300 m. The northern limit is Paraty (RJ state), and south Caraguatatuba (SP state), also two touristic cities but with different profiles. Ubatuba had its origins during the XVI century with the Portuguese arrival and making conflict with the Tupinambás natives that lived in the region. Around XVIII century, the city was producing cachaça (a sugarcane strong alcohol beverage) and sugar to fuel the national market, but this production was about to decline due to the development of commerce in Santos region (the main Brazilian harbor since then), and also the faster development of other productive areas such as the Paraíba river valley (Fontanelli, 2019). Following the decline of sugarcane, coffee production rose, allowing the construction of the main buildings in the city (counselors chamber and the main church)[2]. At the end of the coffee cycle, Ubatuba did not have great economic development from the end of the 19th century to the first decades of the 20th century. The economy started to grow significantly again during the 1950s and 1970s when roads connected the city and tourism activity started to push economic activity locally (Diegues, 1974).

Nowadays, the city has 80% of its land covered by tropical forests, which includes the biggest protected area in São Paulo State, the State

[1] The model can be downloaded at: https://drive.google.com/drive/folders/16XTYcEtoXhKpcSFvHy4U68CEifO_COfp?usp=sharing

[2] https://www.ubatuba.sp.gov.br/a-cidade/ Accessed in 29/07/2020

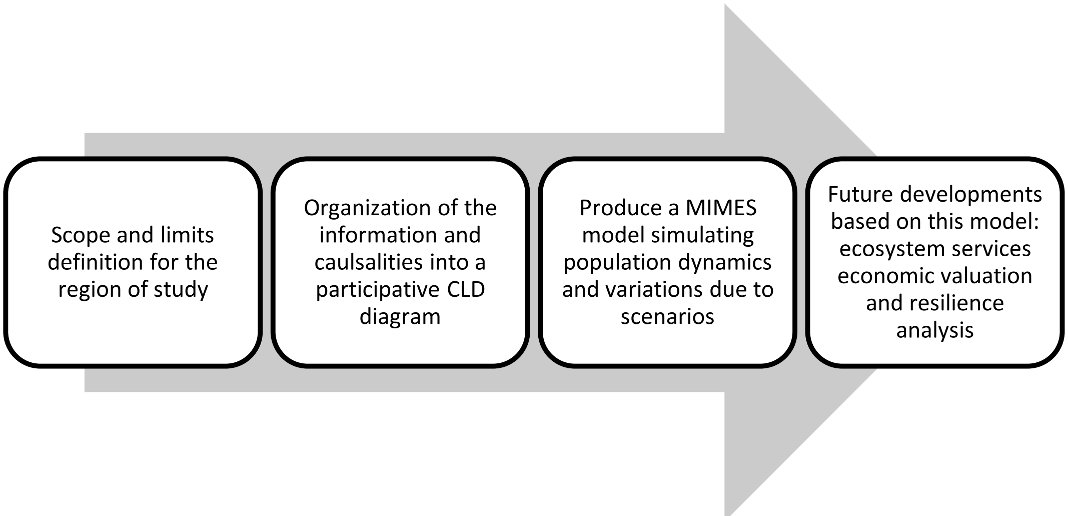

Fig. 1.

Park of Serra do Mar, which overlaps a national park (National Park of Serra da Bocaina), in the extreme north of the city. The marine area has other protected areas such as the APAMLN protected area and the Anchieta Island State Park (PEIA).

Model boundaries follow the political limits of the city. The focus of this study is to embrace the structure and processes that happen in the water, despite the relevance and exuberance of the local forest. For the space limits, it embraces the continental area of the city, two main islands (Mar Virado and Anchieta), and also the marine area (Figs. 2 and 3) until 50m depth, with limits following the northern sector (Cunhambebe) of the APAMLN protected area.

Considering the possible future uses of the model for this protected area policymaking, the area embodied in the model was delimited to match the north sector of the main marine protected area in the region (APAMLN). This marine protected area also occurs in two other regions of the São Paulo coast (Fig. 2). The idea is that future developments of the model could be created to embrace the other regions.

Due to the connectivity between both land and ocean, coastal areas are influenced by events that happen in these two realms. The shape of the coast, wave heights and other traits are determined by several processes from geological activity to wind speed and direction (Garrison, 2014). Several of these factors influence coastal water quality and beach sediments. Some variables change slowly (such as sea level during global glaciation periods), while others change rapidly such as wave height or concentration of gases and minerals. These fast changing variables and their causes can be modeled stochastically as cloud cover (Bergemann et al., 2017), mangrove inundation frequencies and communities (Gao et al., 2021) and waves (Idier et al., 2020). The present study used stochastic simulation, bounded by historical data, to some determinants of the marine population as wind speed and direction, cloud cover, and precipitation patterns. The results and accuracy are discussed in the discussion session.

2.2. Causal loop diagram – CLD

As a precursor step, a casual loop diagram (CLD) was constructed using expert knowledge inside the research group in Brazil. The CLD (Fig. 4) is a representation of the main aspects subsequently integrated into the model. With a main emphasis on water quality we see it is influenced positively by some ocean ecosystem services such as waste depuration and dilution. The main attributes of these services are on the right side of the model, represented by the variables depuration, bacteria activity, and dissolved nitrogen (DIN). Some of these variables are influenced by temperature and sunlight and then influence phytoplankton growth, dissolved oxygen, consequently influencing zooplankton population, fish, and flag fauna (animals that can be attractive for scuba diving).

The left side of the CLD shows the main variables of the social sphere, represented by resident and visiting population (tourists), influenced positively by affluence (State Gross Domestic Product - GDP) and negatively by water quality decrease (due to sewage disposal).

CLDs are very useful because they represent the formalization of the mental models and theory of a determined situation of interest. Despite their limitations, such as the absence of numerical simulation, CLDs are already an interesting tool for making individual assumptions of system's behavior and feedbacks clear and ready to be challenged by others assumptions about the same system. The next step increases the complexity of the model with the translation of these relations and feedbacks in terms of the numerical simulation (with stocks and flows).

2.3. Considerations about the model structure and data sources

The basic idea of the model (Fig. 5) presents all environmental attributes captured by the simulation in a reader friendly image. Causalities are represented by arrows connecting variables. Environmental variables (precipitation, sea surface temperature, wind, cloud cover, and light) are exogenous and influence several water attributes (primary productivity, transparency, oxygen concentration, etc.). Primary productivity holds the whole food web starting from zooplankton and most of other species at the coast (some of them also get food from detritus or suspended materials). All the macro fauna species are connected through a food web of prey-predator relations. Fisheries represent a main way society benefits from the coast.

Human population is formed by residents and tourists (Fig. 5). They interfere with the ecological population dynamics trough waste production that is transformed in nutrients at the water. Climate data are the determinant of some particles (the simulation's group formed by the Plankton community plus Enterococcus and sediments) growth with water nutrients. These data can be influenced by scenarios. At the water, particles interact with nutrients, climate and water conditions to grow. These particles are the base of a macro food web, with eleven groups of species that are interlinked through the food web and water conditions. The interactions among all these organisms and the water create the ecosystem services that come back to the population as benefits. Food web interactions happen between organisms from the same sub model (particles and species) and different sub model as well. Feeding between sub models are relevant to sustainability of the food web and resilience of the system as discussed in Dragicevic and Shogren (2021).

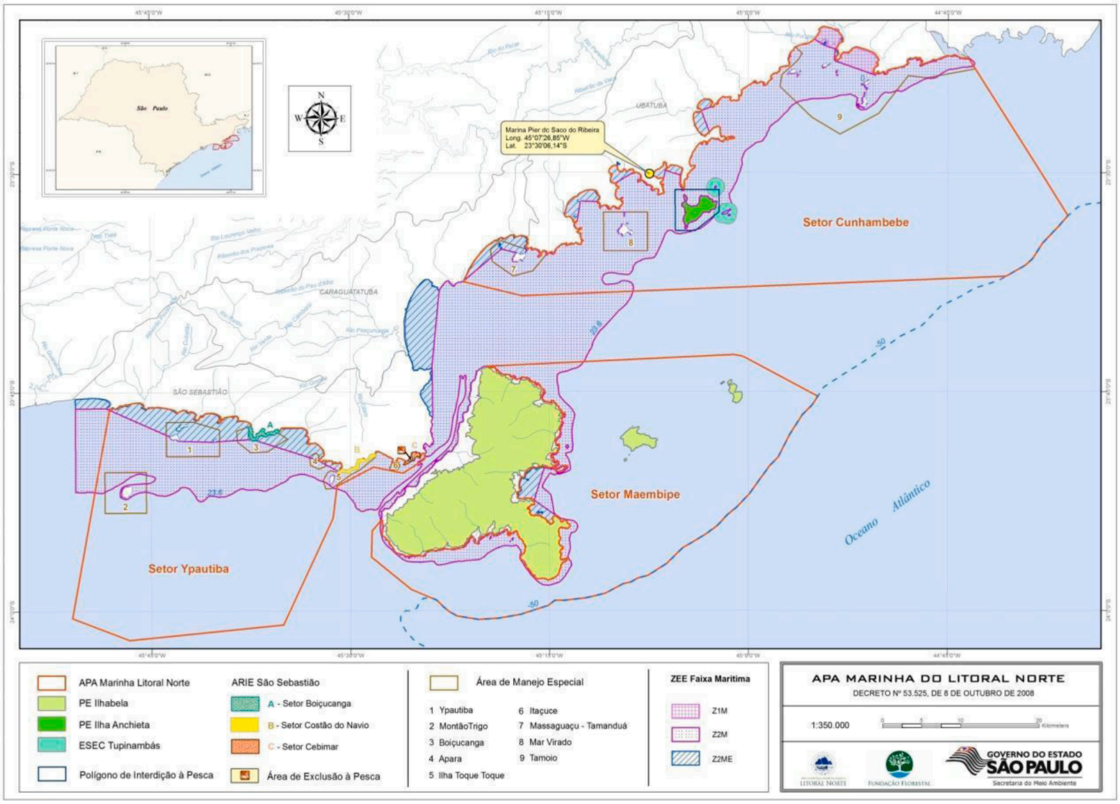

Fig. 2. APAMLN and its limits. The marine portion of the model uses the spatial definition of the northern portion of APAMLN protected area. Source: Fundação Florestal.

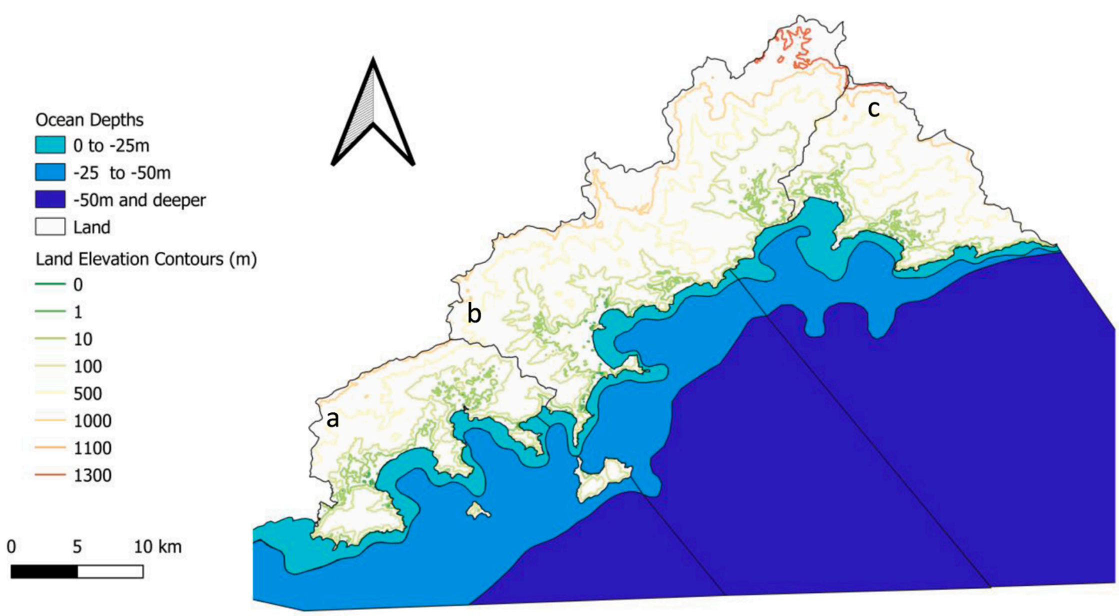

Fig. 3. Spatial definition of the city and coast. Elevation curves of Ubatuba and the marine portion of the model. The ocean represents different depths (bathymetry lines in 10, 25, and 50m depth). Polygons a (intermediate), b (high) and c (low) show land basins with different population densities. The two islands are barely populated (despite being visited by tourists).

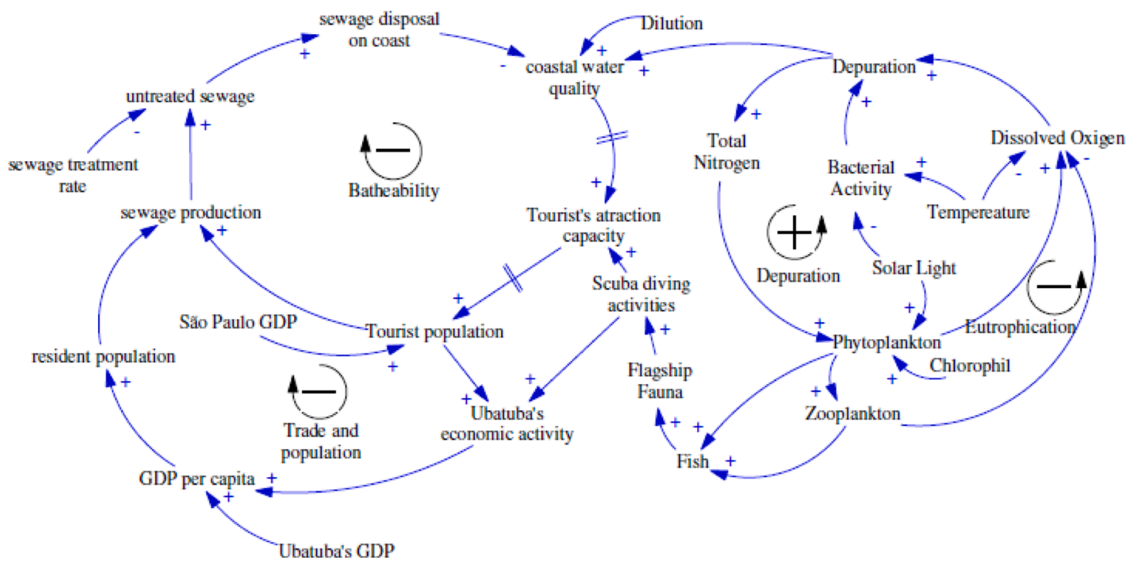

Fig. 4. Causal Loop Diagram for the relations among society and nature in Ubatuba. This CLD was built with participation of the research group in 2017. The idea was to show assumed causality between water quality and economic and population variables. This is representative of some boundaries the model adopted, as considering the ecosystem provision of the coastal area being provided only to this city.

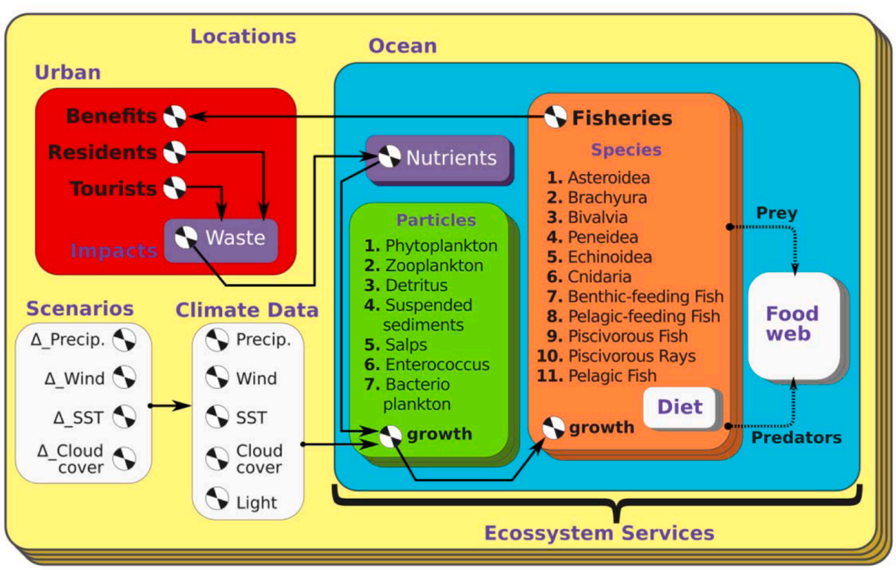

Fig. 5. Framework of the Ubatuba model.

Table 1
data sources.

Data	Source:
Sea Surface Temperature (SST)	personal communication from National Institute for Space Research (INPE - Brazil)
Cloud cover	European Centre for Medium–Range Weather Forecasts (ECMWF)
Wind speed and direction	European Centre for Medium–Range Weather Forecasts (ECMWF)
Precipitation	Ciiagro (www.ciiagro.sp.gov.br/dados/entrada.htm)
GDP	Bischof, 2014; IBGE cidades (https://cidades.ibge.gov.br/)
Fisheries	www.pesca.sp.gov.br/
Biodiversity	Rocha et al. (2003, 2007), Mesquita et al. (1993); Gaeta et al. (1999)
Local and tourist population	(SEADE Foundation) and São Paulo State Environmental Agency (CETESB -Companhia De Tecnologia Ambiental Do Estado De São Paulo, 2016)

Input data (Table 1) present data relative to the same period (2010–2017). When data estimates were present to future periods, they were used for calibration (as in population and tourism).[3]

The resident population is distributed along the 200km of shores. But, the northern part of the city is less densely occupied (CETESB - Companhia De Tecnologia Ambiental Do Estado De São Paulo, 2016; Fig. 2c). The central part of the city is occupied with high–density houses and small buildings (Fig. 2b). The southern part is an intermediary density (Fig. 2a). In the model we distributed percentages of the population to fill this pattern (70%, 25% and 4%, respectively).

Secondary data used as parameters for calibrating the model were obtained in the literature review (see calibration section), to include estimates of tourism and population growth (CETESB Companhia de

[3] http://www.ciiagro.sp.gov.br/dados/entrada.html Visited in 10 August 2017

Tecnologia Ambiental do Estado de São Paulo, 2014). The model assumes tourism follows a constant growth rate until the end of the simulation, except when a specific scenario (reacting tourists) is active. The time horizon of the model starts in 2010 because this represented the majority of data available.

São Paulo state population showed rapid growth in the 1990s, most of it due to migration from other states, and stabilizing in the 21st century (2010–2025) possibly signaling a demographic transition. Visiting and resident population estimates were obtained until 2040 (CETESB - Companhia De Tecnologia Ambiental Do Estado De São Paulo, 2016). This is most important for the model and local management once the city is dependent on tourism for the economy and this activity is the most related to environmental impacts on the coasts. Data from sewage treatment (CETESB Companhia de Tecnologia Ambiental do Estado de São Paulo, 2014) considered the city collects 100% of sewage but only 50% is treated. The same estimates consider Biological Oxygen Demand in 0.045 g/l per person per day.

2.4. Ecological model structure and equations

The MIMES architecture follows the architecture in model development described by Fitz et al. (1996) (see also Boumans et al., 2002; Boumans et al., 2015) who proposed the use of a unit model as a node for implementation into a spatial network to achieve spatial dynamic simulations. We developed unit models to model upland and marine areas coupled through the upland marine interactions signified in waste production from the land into the ocean and the production of ecosystem services in the ocean enjoyed on the land. The unit model for upland simulates human population dynamics (residents and tourists) and the trends in environmental awareness. The marine model simulates the food web dynamics among 11 major groups of species found in the region (Asteroidean, Brachyuran, Bivalves, Penaeidae, Echinoids, Cnidarian, Benthic-feeding fish, Pelagic-feeding fish, Piscivorous-fish, Piscivorous rays, Pelagic fish) and the fates of 7 classes of particles (phytoplankton, zooplankton, detritus, suspended materials, salps, Enterococcus and bacterioplankton).

The coupled unit models were used to simulate the Ubatuba coastal regions (Fig. 4) a collection of 3 upland and 9 marine areas. The model was coded into the Simile software and is made available upon requirement to the authors.

2.4.1. Upland dynamics

$$\frac{DP}{Dt} = (b-m) * P_t^r + \left(v - lP_t^{r,nr}\right) \tag{1}$$

The model generates the trends in population (P) for each of the upland areas, b and m are birth and mortality estimates for the resident populations (P^r), v is an estimate of tourist populations visiting and $lP_t^{r,nr}$ an estimate of populations of either residents or nonresidents (tourists) leaving. Sewage (S) is the impact of the upland to the marine systems in terms of Biological Oxygen Demand (BOD), Dissolved Inorganic Nitrogen (DIN), and Detritus.

2.4.2. Marine dynamics

The food web constructs the population dynamics and prey predator interaction among a total of 11 marine life forms in units of biomass (BM)

$$\frac{DBM^{1,11}}{Dt} = gm^{1,11} * gl_t^{1,11} * BM_t^{1,11} * \frac{1 - BM_t^{1,11}}{CCBM} - \left(mbm^{1,11} + c^{1,11}\right) BM_t^{1,11} - \sum_{1}^{11} \left(a^{(1,11),(1,11)} * BM_t^{(1,11),(1,11)}\right) \tag{2}$$

2.4.3. Growth

Where gm is the life form specific maximum growth rate, gl the environmental limitations of growth, based on oxygen and food requirements, and CCBM set the carrying capacity.

2.4.4. Mortality

The sum of natural mortality (mbm) and catch (c) rates on the population

2.4.5. Predation

The sum of biomass consumed through the food interaction with the other life forms. a represents the feeding rate of life forms 1 to11 in the role of predator on life forms 1 to 11 in the role of prey.

2.4.6. Marine particles

Besides marine life forms, the model considers the dynamics for marine particles (MP) and how such particles modify light, nutrients and conditions on Dissolved oxygen.

The particles are either organisms themselves such as Phytoplankton, Zooplankton, Salps, Enterococcus and Bacterioplankton, or non-organisms such as Detritus and Suspended Sediments.

$$\frac{DMP^{1,7}}{Dt} = gmp_t^{1,7} * glmp_t^{1,7} * MP_t^{1,7} * \frac{1 - MP_{t-1}^{1,7}}{CCMP_t^{1,7}} - \left(mmp_t^{1,7} + rmp_t^{1,7}\right) * MP_{t-1}^{1,7} - Consuption(Outflow - Inflow) \tag{3}$$

2.4.7. Growth

Gmp (0 for non-organisms) sets the maximum growth rate for particles, CCMP determines the carrying capacity and Gmpl is a growth limit set by a most limiting factor to either light (LL), Food (FL), Nitrogen (NL) or Oxygen (Ol)

$$gml_t^{l,n} = \min\left(LL_t^{l,n}, FL_t^{l,n}, NL_t^{l,n}, OL_t^{l,n}\right) \tag{4}$$

2.4.8. Mortality

Mmp and rmp are the parameters on mortality and respiration (in the case of detritus)

2.4.9. Consumption (not yet defined)

Outflow and Inflow move particles among the polygons and are not yet implemented in the model.

LL or Light Limit is determined by the availability of Light at body of water considered as one depth only. The PAR is calculated by simile depending on the latitude programmed in the model. The model then reduces PAR considering the influence of cloud cover (from 0 to 17% (Anthony et al., 2004). Another light reducing influence comes from the amount of particles dissolved in the water. The influence of particles in water transparency data came from Lorenzen (1972). The climate scenarios do influence the light limitation by changing the Julian day probabilities for cloud cover and therefore the effect of the seasonal sun angle on PAR.

Food limit come from the availability of phytoplankton (for zooplankton); from the sum of phytoplankton plus zooplankton (for Bivalves and salps) and for each population of prey each predator preys upon. Nitrogen limitation is only for primary producers (Phytoplankton and bacterioplankton). Oxygen limit is for every organism as a minimum requirement for living (5mg/l), otherwise the population starts to die.

2.5. Scenarios description

The model works with two systems-type scenarios (climate and reacting tourists) representing the biggest menaces to Ubatuba's SES (São Paulo, 2019a).

2.5.1. SES scenarios

Climate scenarios. Climate scenarios were developed using two contrasting scenarios described by IPCC (2014): RCP 2.6 and RCP 8.5. Data

Table 2
. Climate attributes change due to climate scenarios.

Year Attribute	2050 RCP2.6	RCP8.5	2100 RCP2.6	RCP8.5
SST (°C)	0.5	1.5	1	3
cloud cover	7%	15%	18%	34%
wind speed	7%	15%	21%	50%
precipitation	15%	30%	15%	30%

used here sometimes are different than that found in IPCC once some variables were not found at a satisfactory scale for the municipality level even in downscaling works (Chou et al., 2014a, 2014b). For example, some sources (São Paulo, 2019a) project SST alterations between 4° and 8°C due to climate change scenarios. Despite the values used for SST in the model having their origin in IPCC reports (IPCC, 2014, page 61), the values used here are approximations (Table 2). The names RCP 2.6 and RCP 8.5 are references to the better and worse scenarios and must be understood as "RCP-like" scenarios due to these numerical differences.

These climate scenarios bring variations in SST, wind speed, the amount of cloud cover, and the frequency and intensity of precipitation (Table 2). Alterations in precipitation were made instantly and starts to act with full intensity once the model is active (July 2017).

Tourism scenario. The second system scenario used in the model came from previous research (Amazonas et al., 2021) made in the same city that remarked on the great concern from tourists regarding the water quality. When asked about which factor was more important to tourist activities on the beach, 61% of tourists considered the water quality (followed by 33% on weather and 23% of sand cleanliness). This semi–structured interview, which reached 387 tourists during Summer 2016, also revealed that 83% of interviewees stated they would not come to the beach if it was not proper (meaning with good water quality) for batheability; 52% said they would not come if the water presented a different color and 74% said they would not come if the water was muddy with excess sediment. These results corroborated previous studies for the same region (e.g., Ghilardi–lopes et al., 2015).

Therefore, water and sand cleanliness are relevant to tourists when choosing the beach they will visit. The way tourists perceive this cleanliness and act accordingly is harder to tell. Since, the São Paulo State agency for batheability management (CETESB) uses a microorganism (*Enterococcus*) concentration as an indicator to monitor water quality, we do the same in the model. The CETESB communication program has been using this same proxy to raise awareness about water quality for decades. Tourists cannot see the microorganisms in the water, but if the concentration exceeds a threshold, then the environmental agency puts red signs on the beach and makes public announcements about the quality on their website, social media, and also in great circulation newspapers. So, it was considered a good proxy for scenarios most likely to reach tourists and influence their decision to move to a different location. For the purposes of this study, the concentration limit was established in 1.6 $mgww/m^2$ of *Enterococcus*, which means twice the worst value found in the first year of simulation.

Due to the reaction to poor environmental conditions, we considered that up to 15% of the visiting rate could be affected.

Consequently, in this scenario, tourism has a lower growth rate compared to the baseline situation (Fig. 6), reaching their maximum at 85% of the previous rate.

2.6. Model validation and calibration

Validation means the establishment of legitimacy, typically in terms of contracts, arguments, and methods (Oreskes et al., 1994). A valid contract is one that has not been shown to be incorrect yet; a valid argument is one that has not been refuted by peers to that finality.

It is a common practice among modelers to divide data into two parts, using the first part to calibrate the model and then certifying the results of the model are coherent with that time series, and posteriorly comparing the other results with the second part of the data, from which is usually inferred that if the results and the data were congruent, the model is valid, otherwise not. This practice is misleading (Oreskes et al., 1994; Sterman, 2000) and does not ensure the validity of the model because being an open system, the congruence of data and results are occasional.

Oreskes et al. (1994) claim that verifying or validating numerical models of natural systems is impossible. That happens for two reasons: first, these systems are open, which implies that there are variabilities in the system that were not captured by the model; second, some results, the more verisimilar they appear, can be originated in different models, and therefore it is not possible to know for sure which represents the reality (which one is true). Even if the model is congruent with data from the present and satisfactorily fits data from the past, there is no guarantee that it will explain future events for which no data is available yet. Finally, the model can be tested and declared false, but its veracity cannot be determined because it is embracing an open system.

Nonetheless, all modeled variables were compared to data using the information presented in Table A1 (Appendix 1), originally collected from Rocha et al. (2003 and 2007) and measured in grams of wet weight per square meter (gww/m2). The simulation of the input data as sea surface temperature, cloud cover, precipitation and wind speed and direction are available on the calibration topic in Appendix 1 (Table A1).

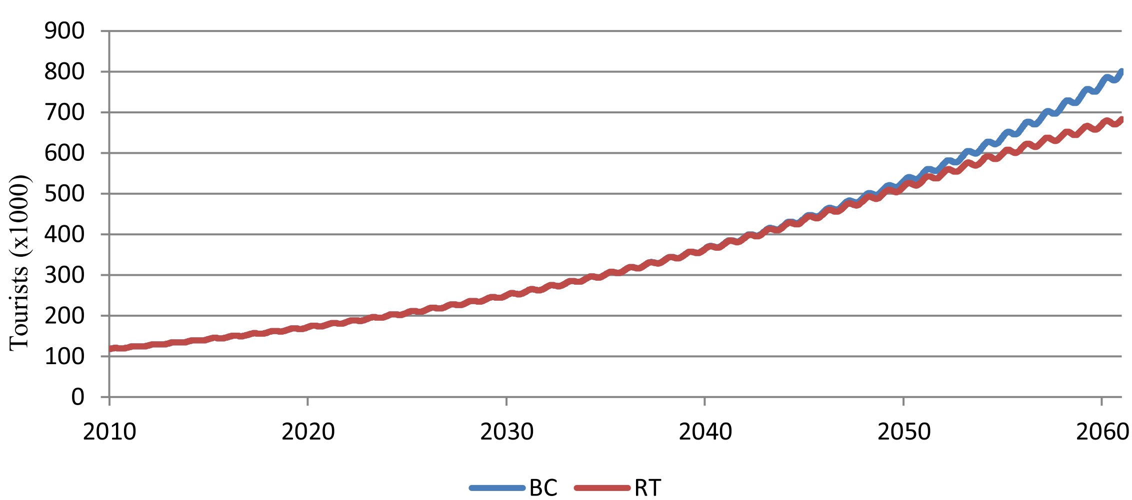

Fig. 6. Simulation of tourist growth from 2010 to 2060. Showing yearly visitations. Blue – normal case (base case), red means growth limited by tourist reaction (RT) scenario.

The model followed satisfactorily the seasonal oscillations presented by data and that is relevant due to the effect this seasonality will show in some ecological processes (sewage depuration, oxygen production, carbon sequestration) and future ecosystem services valuation.

In the present model, the comparison between what is produced in the model and data was done in all climate and biological population's data. For sea surface temperature, the correlation between data and the results of the model was ($r = 0.31$). For cloud cover the correlation was r=0.26. In relation to the variations of wind speed and direction we had u component $r = 0.15$ and v component r = 0.15 which are lower than more elaborated wind models (with correlations of 0.6 as in Valentin el al., 2013). The precipitation model correlation between data and the simulation was $r = 0.21$. These values are considered satisfactory when comparing to other MIMES models (Boumans et al. 2002, 2015) due to the main power of these models rely on the integration of multiple variables, not just individual simulations. Further comparison of accuracy with models for the same region remain difficult due to the lack of proper correlation information in the models for the same area (Galvão et al., 2006; Abessa et al., 2005; Heckler et al., 2013; Mazzuco et al., 2015; Dias et al., 2016; Marques et al., 2021).

In the end, what makes a good model is its capacity to test discrepancies in assumptions (mental models included). Good models are those that confirm or refute the hypothesis that has been created from other research methods and knowledge gathering. Good models can be used to answer "what if questions" and then make some forecasts, or even explore causal hypotheses in its past and future behavior. In short, good models are tools for learning (Sterman, 2000) and heuristics (Oreskes et al., 1994). For further information see Apendix 1.

3. Results

The graphs present results for the first year of simulation and for a long range forecast until 2100 where the scenarios of climate change and tourism can present their effect on these populations. When present, min and max indicate the model range of values based (see Table A1).

3.1. Water particles and fish populations

Phytoplankton simulations (Figs. 7 and 8) show the seasonal oscillation in this population and their numbers are well suited in the expected range (Table A1 in the Appendix).

This simulation shows the oscillation from summer to winter and the diminishing population with RCP8.5 in the long range. Reactive tourists' scenario was not different from the base case (not shown).

Zooplankton brings a higher value for its population in winter when compared to summer (Rocha et al., 2003). Our simulation (Fig. 9) could not reach this inverted oscillation and then zooplankton population decreases in winter when food (Fig. 7) decreases. In the long-range simulation (Fig. 10), zooplankton population suffers from stronger oscillations in winter. Also, the zooplankton population tends to be smaller due to the effect of RCP 8.5.

The population of Enterococcus is determined by the sewage deposition and the area where sewage depuration is happening (with less than 10m depth area) (Fig. 11).

Considering the local and tourist population growth, the enterococcus population increases along the century (Fig. 12).

From the model, individual results for each modeled group can be extracted (Table 3). The sum of daily population can be used to understand the differences between scenarios.

This table brings the simulation results for each interest group along the simulation period. Those values are discussed below. It is important to notice that these values and scenarios variations are the basis for the next papers once these biomass will be used for the economic valuation, trough benefit transfer method, and will be the basis for the development of the resilience analysis. Once each group biomass was investigated and simulated, we can infer about the ecosystem services production. For most of fisheries, the biomass is the basis on which the fishery will act and result in the fisheries ecosystem services. For carbon sequestration and oxygen production, the biomass of the producers (Phytoplankton) is the basis for the metabolism that control those gases cycle. From these populations, with some inferences of metabolism, results the nitrogen related ecosystem services (nitrogen depuration and mineralization) and from a representative organism (Enterococcus) unfold the sewage depuration service.

4. Discussion

Population data for phytoplankton, zooplankton, detritus, suspended material, salps, Enterococcus, and bacterioplankton did not present time series data against which the simulation could be compared. Thus, the model focused on delineating the maximum and minimum populations (when available) or some reference value (e.g., Fig. 7) and satisfactorily

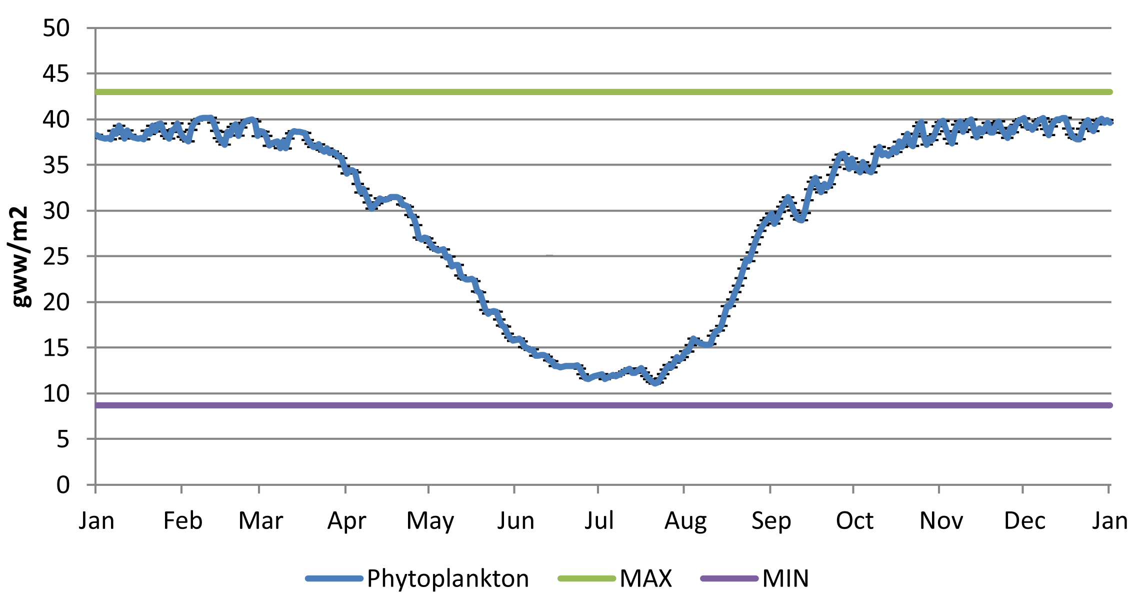

Fig. 7. Phytoplankton population during the first year of a 90-year simulation. This first year simulation shows phytoplankton population oscillating between the maximum and minimum limits, with daily stochastic variations. Standard deviation is very small.

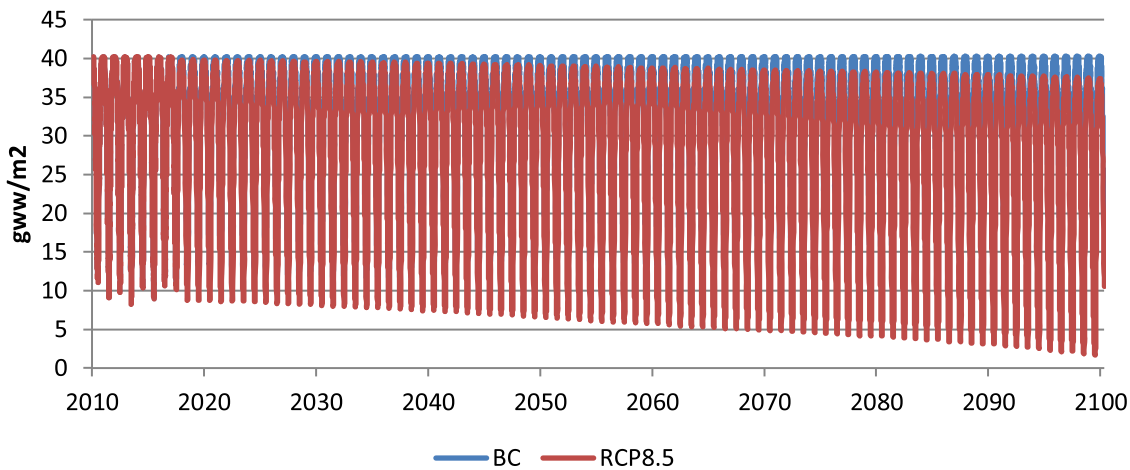

Fig. 8. Phytoplankton population from 2010 to 2100.

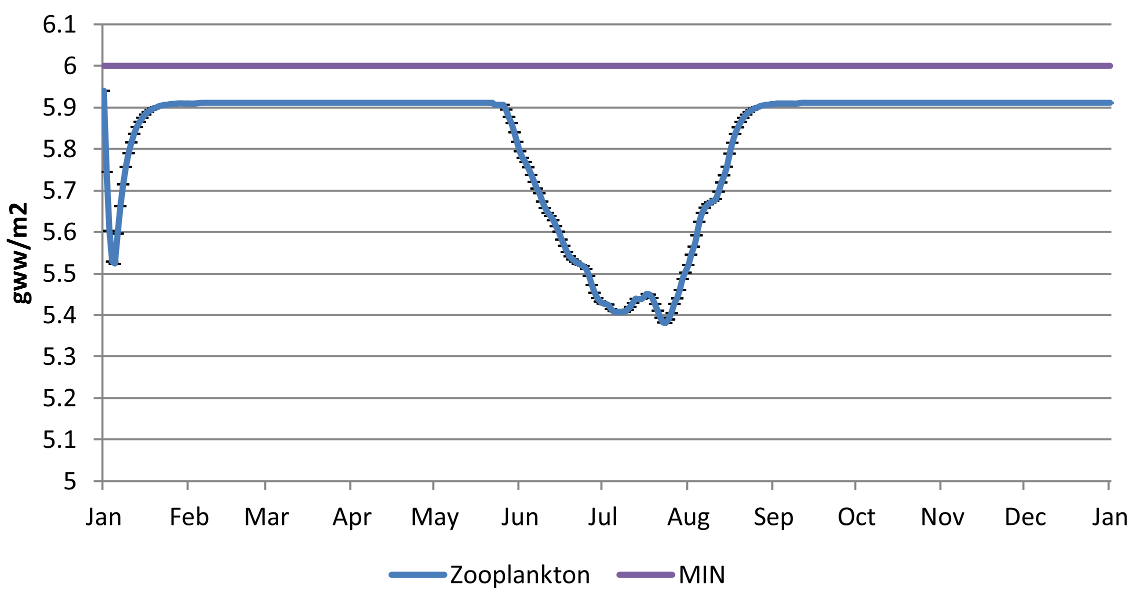

Fig. 9. Zooplankton population during first year of simulation. Zooplankton population for 2010. The simulation was very close to the desired reference value and presented a diminishing oscillation during winter.

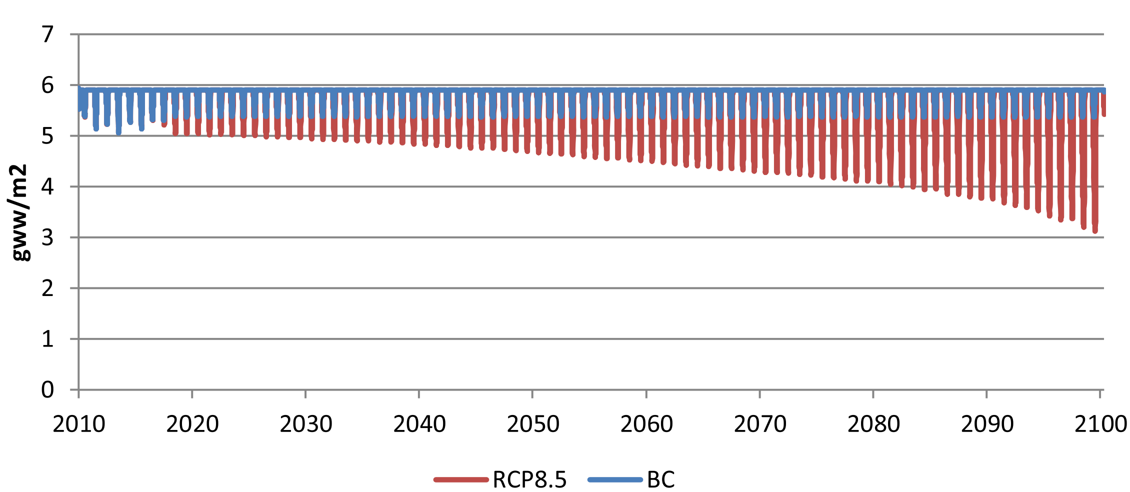

Fig. 10. Simulation of Zooplankton from 2010 to 2100.

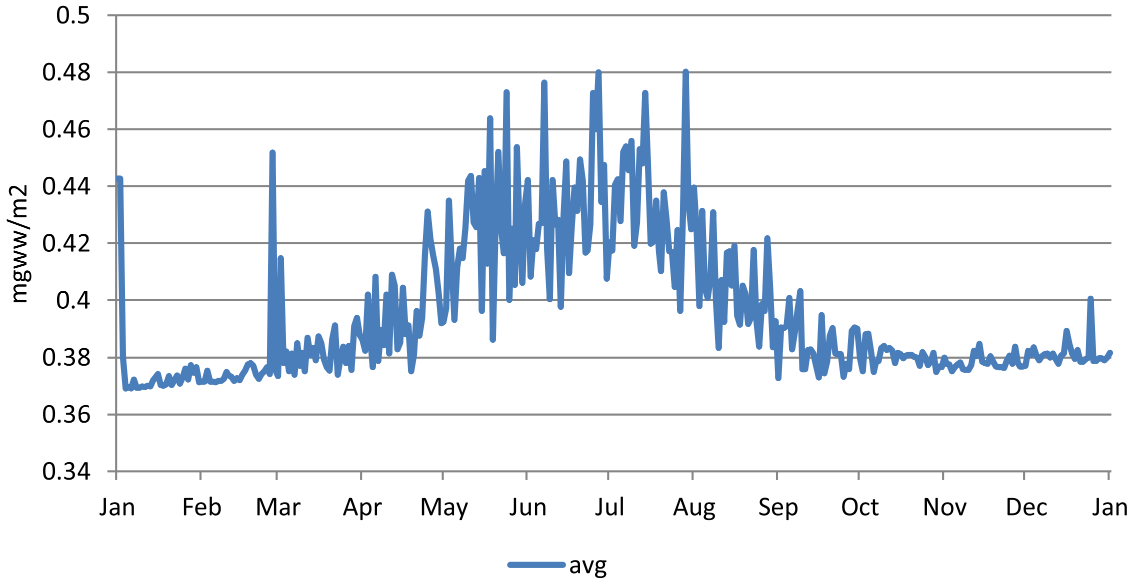

Fig. 11. Enterococcus population.

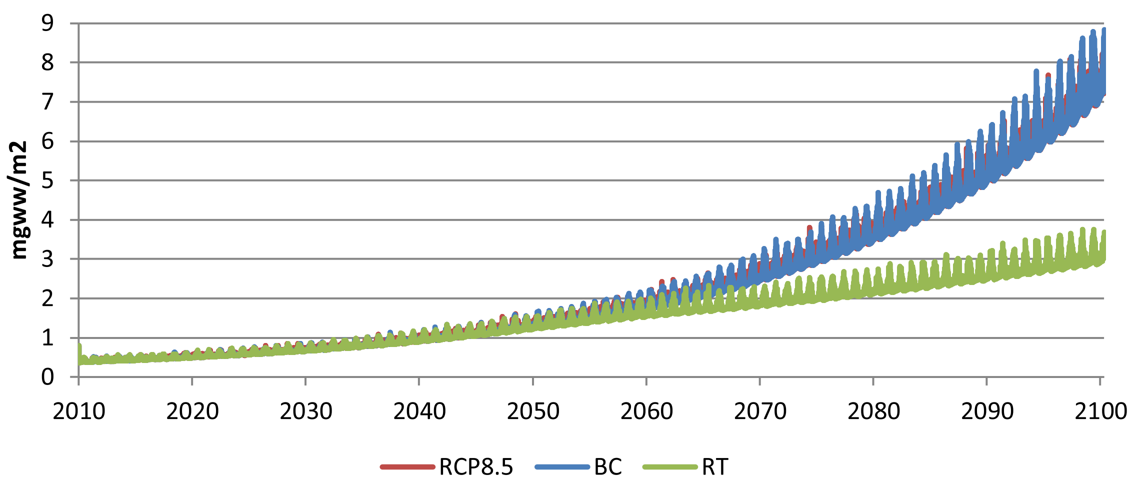

Fig. 12. Enterococcus population from 2010 to 2100. In this case the Reactive Tourists' (RT) scenario has strong influence in the population.

Table 3
Biological populations and variations trough scenarios. Values are the total sum of each population in gww/m^2 from 2010 to 2100. SD is calculated.

Population	BC	SD	RCP 8.5	SD	Var	RT	SD	Var
Phytoplank.	1011491	13.4	907182	30.6	-10.31%	1011685	13.4	0.02%
Zooplankton	192785	0.4	187258	2.7	-2.87%	192793	0.4	0.00%
Enterococcus	75583	37.1	73764.5	26.8	-2.41%	49704.3	21.2	-34.24%
Bivalves	9117.7	0	9091.2	0.2	-0.29%	9111.8	0	-0.06%
Brachyuran	729482	0.2	728516	8.1	-0.13%	728044	0.1	-0.20%
Benthic FF	42986.1	0	42477.5	5	-1.18%	42960.2	0	-0.06%
Pelagic FF	9598.9	0	9567.2	0.5	-0.33%	9594.5	0	-0.05%

follow those limits (Table A1). All values in the water particles sub model present clear seasonal variability, the causal reason for phytoplankton is the light availability (season); zooplankton varies due to phytoplankton variation that acts as food limit, presenting higher population in summer than winter; salps vary according to zooplankton and phytoplankton but only occurs in summer; detritus, suspended material and Enterococcus are directly dependent on tourists.

Zooplankton population simulation presented a different pattern when compared to the literature (Rocha et al., 2003). The authors reported higher values for the zooplankton population during winter, probably where the absence of salp's predation allowed these creatures to reproduce and reach these high values. The model has not captured this movement and the main limitation to zooplankton growth is food availability (phytoplankton) and therefore their behavior follows its variation.

Enterococcus population, however, was higher in winter when compared to summer. When compared directly with batheability data (CETESB, 2010 to 2016) these seasonal fluctuations cannot be detected easily. Nevertheless, in other research (Oliveira et al., 2020) using neural network analysis, this seasonality was detected in batheability data showing the difference between seasons in bacteria concentration along the whole coast of Ubatuba.

The vertebrate and invertebrate populations showed simulated values that are very close to the literature (Table A1). Invertebrates presented slight seasonal variability that follows their food source variations (detritus, suspended material, etc.). Superior groups, like vertebrates, have not shown the same amplitude in their oscillations presented by water particles or even by invertebrates. Vertebrate's oscillations are very discrete in the model and absent in reference literature (Rocha et al., 2003, 2007). The model developed by Rocha et al. (2003, 2007) did not reach seasonal variations in their vertebrate analysis and the present model brings this novelty.

These populations presented different behavior when compared to scenarios of climate change and reactive tourists. This variance was expected once these two types of scenarios act upon different set of variables in the model: climate scenarios change wind speed, precipitation patterns, SST, and cloud cover (Table 2) while reactive tourists change the number of tourists and therefore their effluents in water (nitrogen, enterococcus, suspended material). For climate change scenarios the biological population variation (Table 3) ranged from −0.13% (± 0.0%) to −10.31% (± 0.0%). These results (Table 3) allows the formation of groups where the influence of climate change are not significant with influences from 0 to 2% (Bivalve, Brachyuran, pelagic feeding fish and benthic feeding fish) and moderate significance with variations >2% (Phytoplankton, Zooplankton, and Enterococcus). These results are slightly different from that found in Lotze et al. (2019) for RCP8.5 17.2% (± 10.7%). These difference are understood as natural once those authors focused in open seas, where stratification was the main phenomena limiting primary productivity, and our case represents a coastal area with probably more influence from the mixing zone. Other comment is that the variations expected in Lotze et al. (2019) where comparing to the period of 1990−1999 and ours to the period 2010−2017.

In terms of feeding limitation, the reactive tourist scenario showed that most of the studied groups had variations smaller than 1% except for Enterococcus which had 34% decrease. This result shows that if a policy controlling the number of tourists where implemented the quality of water would increase sharply, which is one of the main factors that attract tourists for that city in the first place (Amazonas et al., 2021). Policies like that can be one way to reduce global inputs of sewage into the sea, especially nitrogen, and can contribute to reshape the ocean concentration into his boundaries (Rockström et al., 2009; Steffen et al., 2015).

4.1. Limitations and boundaries of the model

MIMES is a modeling framework that allows the inclusion of virtually every possible variable related to the problem understudy. As it was born from the System Dynamics body of knowledge, it is recommended to follow the best practices and guidelines from this field, which are well described in Sterman (2000). Considering that, and the fact that the present study focused on the city Ubatuba as a whole, and how it in interferes with the ecological coastal dynamics, some boundaries apply on the present work:

(1) We recognize underground water flows as potentially relevant for the area, but considering the lack of data, these flows were not considered to the present work.
(2) Agriculture is representative of only 3% of the City's economy, and therefore do not represent a significant flow of minerals to the water.

Natural forests can also contribute with some minerals to the coastal area, but due to lack of data they were not considered in the present case.

The spatial limitation used in the model, embracing the north sector of APAMLN seems appropriate due to the importance of this area in providing ecosystem services for the city, but future development of the model could improve some features of the model, named: (1) use smaller water polygons to enhance the definition of the results (2) embrace the types of substrate in the bottom of the sea for each of these polygons, allowing the simulation of benthic species distribution; This idea was made in Lorilla et al. (2020) with influence on conservation practices; (3) land polygons can be diminished using small scale data for population groups as determined by National Census data and therefore increase the accuracy of the model; (4) fish landings would be benefited by monitoring of fish vessels and productivity; (5) water quality monitoring in depths of 20m and 50m would increase the quality of information about this environments and the ES produced at these points.

The choice of the groups in the water particle sub–model and the fish sub–model were based on the best data available (Rocha et al., 2003, 2007) but some of them revealed useless for ES assessment as Echinoids or Asteroidean.

5. Conclusions

The objective of this paper was to build a new coastal ecology model that at the same time integrates some key elements of the Socio-economics of Ubatuba, Brazil, and then simulate them in time and space to better understand and forecast biological populations along the century and under different scenarios. We carried out this objective within the MIMES framework, a very integrative and powerful modeling technique that allowed us to embrace the main portion of the marine biota and simulate them in different scenarios.

This Ubatuba MIMES model embraces data from atmospheric sciences mostly collected by satellites (cloud cover, light availability, wind speed and direction, precipitation and sea surface temperature); and, through its causal structure, integrated this information with the biological and oceanographic information about the physical state of the coast (nitrogen concentration, oxygen, particulates and undesired microorganisms) and the food web (from primary producers to top predators). Human society influences the water quality through sewage dumping, which can vary according to scenarios.

Results show good correlation between data and the model outputs and thus the biological population forecast was done with good confidence. Climate change will reduce most populations along a range from −0.13% (± 0.0%) to −10.31% (± 0.0%). There are groups where the influence of climate change are not significant (Bivalve, Brachyuran, pelagic feeding fish and benthic feeding fish) with variations from 0−2% and other with moderate significance (Phytoplankton, Zooplankton, and Enterococcus) with variations >2%. Reactive tourist scenario shown to be very relevant in Enterococcus population (with a reduction of 34%). This can be translated into a policy that limits the number of tourists and increases the water quality at the same time. Further studies and applications of this model can measure the economic impact of this possible policy.

Spatial simulation of the groups and the interfaces between the number of residents and the biological populations can be used to develop an integrative decision-making system to help the city to manage its natural capital and adapt to its changes.

Implications of this work for the city management point to the necessity of a climate adaptation plan specifically designed to mitigate the effects of climate change in the reduction of the fish populations, carbon and oxygen exchanges and sewage depuration (Ecosystem services offer). It is also clear in the study the effects of tourist population in the ES provision pointing to the necessity of control of this visiting population. In terms of sewage management, this research has shown that despite the negative effects on the beach area, the nutrients provided are useful to sustain fish populations and therefore using pipelines to direct discharge away from beaches are better than removing all the nutrients from sewage, despite the overall negative effects to the oceans as such nitrogen pollution. This approach could feed the fishes at the same time that leaves the beaches clean for tourists.

CRediT authorship contribution statement

Bruno M. Oliveira: Conceptualization, Visualization, Formal analysis, Writing – original draft. **Roelof Boumans:** Visualization, Conceptualization, Formal analysis. **Brian D. Fath:** Writing – original draft, Formal analysis, Validation. **Joseph Harari:** Writing – original draft, Validation, Conceptualization, Formal analysis.

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. The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Bruno Meirelles de Oliveira reports financial support was provided by CAPES PROEX, CAPES Finance Code 001 and from IIASA-YSSP 2019 Program.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.ecolmodel.2022.109953.

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