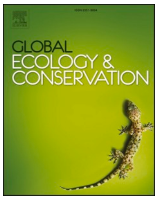
Global Ecology and Conservation 38 (2022) e02240

Contents lists available at ScienceDirect

Global Ecology and Conservation

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



Coastal ecosystem services and climate change: Case study for integrated modeling and valuation

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ARTICLE INFO

Keywords:
Social–ecological systems
Ecosystem services valuation
MIMES (Multiscale Integrated Model of Ecosystem Services)
Climate change scenarios
Brazil

ABSTRACT

Since the publication of global studies about ecosystem health and their importance to society, understanding and valuing ecosystem services (ES) has been gaining attention. Measuring undesired drivers that impact these services is crucial for planning sound socio-economic policies. This work explores how the coastal ES from Ubatuba, Brazil might behave following climate and tourists' management scenarios. A new model, embracing ecological functions and their interactions with the city was built and through benefit transfer methods, the value of ten ecosystem services was calculated. Results show that all ES will be affected by the climate scenarios and by tourism reduction. The conclusion is that the region can provide these 10 ES with an economic value of 622 M dollars (± 3.6 M dollars) from 2010 to 2100. When climate change is considered, the values most likely decline from −1.23% (±2.96%) or −7.5 M dollars (±3.8 M dollars) to −2.34% (±3.88%) or −14 M dollars (± 6.3 M dollars) depending on the scenario. Results also show the possibility of an increase in the aggregate ES values due to the climate scenario effect, but it is less likely to occur. Controlling the population visiting the area is the main policy advice from this research which can lead to positive effects on the ES provision in all scenarios.

1. Introduction

The contribution of ecosystems to the economy and wellbeing of society (ecosystem services - ES) has gained much attention as an academic research agenda for estimating trade-offs in managing natural resources. This interest has produced an applied body of knowledge for consultants, agencies, and practitioners allowing them to gain insight through broad global reviews of the state of ES (MEA, 2005; TEEB, 2010) and the economic value they represent to society (Costanza et al., 1997; Boumans et al., 2002; De Groot

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https://doi.org/10.1016/j.gecco.2022.e02240
Received 15 April 2022; Received in revised form 12 July 2022; Accepted 21 July 2022

et al., 2012; Costanza et al., 2014). The relevance of the field has been growing and the corollary is the creation of the International Platform on Biodiversity and Ecosystem Services (IPBES) as an international institution "with the goal of strengthening the science–policy interface for biodiversity and ecosystem services, for the conservation and sustainable use of biodiversity, long–term human well–being and sustainable development" (Diaz et al., 2015b).

While most ES research has focused on upland systems (Hyytiäinen et al., 2021), our interests are on coastal ecosystem services as they directly affect the economy and well-being of more than 2 billion people (Martinez et al., 2007) and indirectly the whole planet by controlling the climate, production of oxygen, production of food, allowing navigation, providing recreation, and stormwater protection, and more recently in providing energy from waves and offshore wind platforms. Marine and coastal areas are responsible for 60% of all economic value of the ecosystem services provided by the Biosphere (Costanza et al., 1997; Costanza et al., 2014). Yet, with human population growth in the 20th century, associated impacts like an increase in resource harvest, negative effects of resource extractions, and coastal pollution, the uncertainties on the reliability of the provision of coastal ecosystem services at the long and short-range have been increasing (Garrison, 2012). Thus, managing the marine environment and especially the coastal zones are crucial for human wellbeing.

During the last decades of the 20th century, most of the planning and policies regarding oceans and coastal areas were initiated by governments (Burroughs, 2011). Currently, perspectives with ES in mind consider resource management in the more plural context of trade-offs, formed by distinct but complementary forces, acting at the same time, inside the government, but also spread throughout communities. Applying this new perspective of ecosystem-based management (Burroughs, 2011), requires a governance system that adapts itself to changes in the environment. Thus, knowing how the ecosystem works and to what extent it varies is fundamental. Nonetheless, considering the perspective of different scenarios (e.g., climate change or frequency of tourists) can make the whole difference when the future of coastal socioecological systems is being planned.

The Brazilian coast is of great interest for tourism, especially when coastal areas are close to highly populated regions. The city of Ubatuba represents a great attraction for tourism in Sao Paulo state due to the combination of proximity to metropolitan regions with the great environmental quality of its beaches. The city has more than 200 km in tropical beaches that are part of a marine protected area. Also, more than 60% of its territory are inside an estate park (Parque Estadual da Serra do Mar) and a national park (Parque Nacional da Serra da Bocaina), what makes this city unique in terms of environmental quality (Fig. 1). The problems faced by this city are usually related to tourism (Oliveira et al., 2022) due to excess of visiting population and lack of infrastructure to deal with the

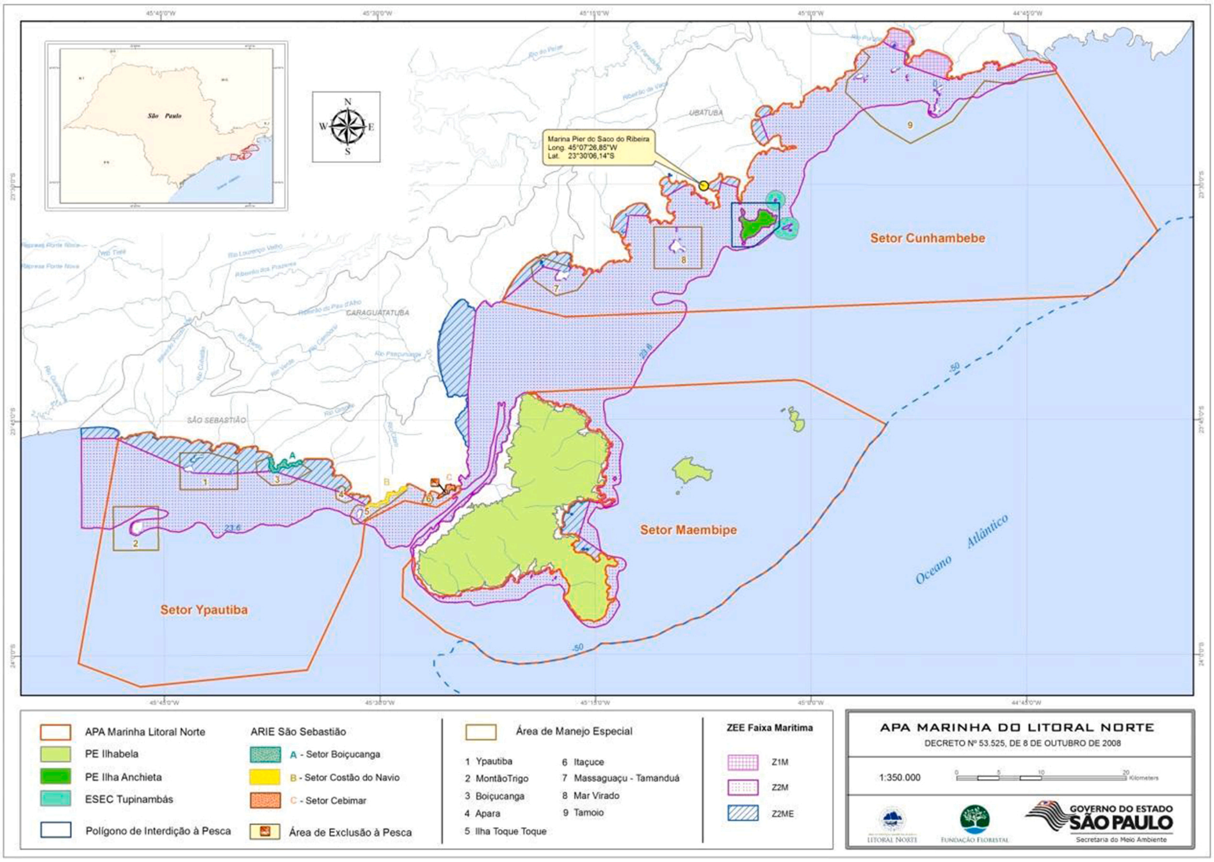

Fig. 1. Ubatuba and the limits of the marine protected areas. Source: Fundação Florestal, SP.

associated impacts, specifically sewage disposal.

To tackle these problems, this paper shows the application of a Multiscale Integrated Model of Ecosystem Services (MIMES) for Ubatuba. MIMES (Boumans et al., 2015; Oliveira et al., 2022) is a dynamic modeling framework that embraces coastal socio-ecological variables in a comprehensive model, designed to understand and simulate variations, in time and space, on the socioecological systems through the coupling of its features. The model description, limits, and caveats are described in Oliveira et al. (2022). In this paper, we present how we used MIMES for ecosystem services valuation.

2. Methods

2.1. Site description

The case study was developed in a Southeast Brazilian coastal city, Ubatuba, located a few hours from São Paulo, the largest city in the country, and therefore with high influence of tourist population. The city is formed by 200 km of beaches that cover all west frontiers. Ubatuba had its origins during the XVI century with the Portuguese arrival and making conflict with the Tupinambás natives that lived in the region. 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 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). For a complete description of the site see Oliveira et al. (2022).

2.2. Ecosystem services model

The MIMES model was used to simulate trends in the production of ten ES, including the landing of 8 fish groups for a period of 90 years (2010–2100). The other two ES deal with biogeochemical cycles involving photosynthesis (oxygen production and carbon sequestration), and sewage nutrient loading. Each ecosystem service studied has its behavior described (see the Appendix A) showing the base case behavior in the long range and the effect of the scenarios on this trend.

All the economic analyses of the base case (BC) model are presented separately with graphs (Figs. A1 – A10) showing the ecosystem services production along with its variations due to climate scenarios (RCP2.6 and 8.5). The reactive tourist scenario is shown in almost all ecosystem services, but it is suppressed from the graph representation when its results are indistinguishable from the BC (e.g., CO_2, O_2).

We used the benefit transfer method for the economic valuation (de Groot et al., 2012). Market values for four different fish groups were provided by the Instituto de Pesca of São Paulo State, Brazil. For the oxygen production and carbon sequestration, it was considered that the population of phytoplankton produces oxygen at a maximum rate of 0.06 $g/gww/m^2$ each hour, and carbon dioxide intake happens at the same rate (Teixeira, 1979; Falkowski, 1994). Therefore, the economic valuation of these ecosystem services was made using normalized values in which the benefit transfer value corresponds to the maximum normalized ES value. The values were obtained from the TEEB database or a specific database when relevant (Table 1).

The model uses producers' population data (Rocha, 2003) and standard carbon absorption data (Falkowsi, 1994; Teixeira, 1979) to infer the amount of carbon absorbed in the area. Falkowski (1994) considers between 1 and 10 mg of C fixed per m^3, depending on chlorophyll concentration and with light in saturation. Teixeira (1979) found values for Ubatuba that are compatible with those from

Table 1
Data and sources for economic valuation of ecosystem services.

Service	Avg. price	Unit	Value for model	Unit.	Reference	Source
Crustaceans' production	17.24	Reais 2017[a]	5.18	The average dollar from 2010 – 2017	kilogram	1
Mollusk production	10.23	Reais 2017[a]	3.07		kilogram	1
Cart. Fish production	7.6	Reais 2017[a]	2.28		kilogram	1
Bone Fish production	2.6	Reais 2017[a]	0.78		kilogram	1
Carbon Sequestration	5.85	Euros 2017[a]	6.38		ton	2
Sewage Depuration	58	Dollars 1990[b]	70.84		Hectare per year	3, ID 837
Nutrient Cycling	118	Dollars 1997[c]	70.82		Hectare per year	3, ID1040
Oxygen production	38.3	Dollars 1997[d]	2.29		Hectare per year	3, ID1039
Mineralization	118	Dollars 1997[c]	7.08		Hectare per year	3, ID1040
Water quality perception	0.22	Dollars 1990[a]	0.27		Hectare per year	3, ID837

1 – Fisheries Institute report (Report obtained in 16/08/2017 at 10h44min Filter: period (01/2000 – 02/2017); City (Ubatuba)

2 – https://br.investing.com/commodities/carbon–emissions–historical–data

3 – De Groot et al. (2010a, 2010b).

[a] Average dollar price from 2010–2017 (USD 1 = R\$3,33). Euro in 2017 = R\$3,60

[b] Monetary update used a discount rate of 6% each year

[c] Nutrient cycling and mineralization are 50% of total nutrient cycling ID1040. Mineralization is only 10% of the final value to balance its disproportionality.

[d] Total value for gas regulation by oceans. It was considered 10% of that for oxygen production

Falkowski (between 0.87 and 10.7 mg of C per m^3 per hour). Those values were incorporated in the model adopting a middle value of 6 mg of C (21.6 mg of CO_2) per hour when chlorophyll concentration (meaning phytoplankton and bacterioplankton population) is at the maximum. When the producers' population diminish, carbon capture diminishes proportionally.

Sewage depuration was calculated using the Enterococcus mortality calculated in the appropriate sub–model and applied to the volume of sewage that is, in turn, dependent on the number of people in the city discounted by the amount that is treated (50% of treatment according to CETESB, 2016). The economic valuation of this service uses maximum values (Table 1) that are normalized to the variations of mortality. The model considers these organisms arrive in great quantities with the sewage in rivers but also with rainwater once accumulated material on land is carried to the coast through overland runoff. It is considered 1% of the sewage produced is solid (detritus) and from this detritus 50% are feces. For each ml of feces, the number of bacteria was calculated using the formula I (Rocha, 2003):

$$W = N^*V^*SG^*10^{-6} \quad (mg/l)$$

Where:

W = wet weight of sewage
N = number of cells. (10^6 according to Lin and Lee, 2001)
V = average volume of each cell (0.06 μm^3)
SG = specific gravity (1.1 according to Rocha, 2003)

Considering that 50% of sewage is treated (CETESB, 2014) in the area with higher population density, the rest follows untreated until reaching the coast. With this, the model adopts a death rate of Enterococcus based on the light and temperature of the coastal water (Batista and Harari, 2017; Mancini, 1978) when these bacteria reach the water.

Nitrogen cycling regards the assimilation of this element by aquatic biota. This service is one part of the nitrogen cycle that appears in the model (mineralization is the other). It was considered that nutrient cycling happens only in the areas adjacent to the beach, where sewage deposition happens and then mineralization is the nitrogen cycle part that happens in the deeper areas of the coast, where nitrogen from organism metabolism is deposited in the water and cycled through biota. That distinction is useful to avoid double counting, and the maximum value (Table 1) is therefore divided by two, once this maximum value applies to whole nitrogen cycling. For nitrogen cycling and mineralization economic values obtained in the ESVD came from Costanza et al. (1997) that attributed to nutrient cycling a value (118$ per hectare per year) that we considered being astronomical. For their work, a value like that made sense because they calculated it in a role of soil creation and agriculture use. In our work, this value would put mineralization values much above any other service (because it happens in a huge polygon area), biasing the analysis. This is one of the key differences between marine and terrestrial ecosystem services valuations. Therefore, the option taken was to reduce the economic value of mineralization by 90% in a way that this service occupies the same scale of nutrient cycling service, considered a related ES. Then mineralization has a small value but operates in a huge area and nitrogen cycling has more accentuated value but happens on small scale. Both maximum values were normalized to ES seasonal variability.

Water quality perception is an ES that showed relevance for the region in previous research (Amazonas et al., 2021) whose values were not studied so far. This service regards the perception of the water quality by tourists and therefore it is applied only to coastal areas adjacent to the beach. When the volume of detritus surpasses a determined threshold (defined as the worst value of the first year of the simulation), the water gets turbid. This increase in turbidity is considered perceptible to tourists and then the water quality is diminished. For the economic valuation, we used the maximum reference value (Table 1) normalized to the quality losses that detritus produce. The model starts with the maximum value of water quality perception, and to every event that diminishes the water quality (meaning detritus surpassing a proscribed threshold), part of the quality is lost, and the economic value associated with this service (Table B1) as well. The threshold was established as the worst case of the first year of the simulation.

2.3. *Ecosystem service valuation*

Each ecosystem service's maximum values were adapted from the *Ecosystem Services Valuation Database* (Van der Ploeg and De Groot, 2010), the platform that is kept and updated from the Ecosystem Services Partnership. Each value is followed by an ID that can be used to verify the origin and value of each data. For each economic valuation not already in the U.S. dollar, an average price for the dollar from 2010–2017 was calculated using daily data.

For price attribution in fisheries, an adaptation of the model's classes of fishes was done to match with the groups presented in market price reports (from Instituto de Pesca). Instituto de Pesca is a reference institution for market values of fisheries in São Paulo estate, Brazil. This institute provides prices for cartilaginous fishes, bone fishes, mollusks, and crustaceans. We attribute the 8 groups of fish to each market group (Table 2).

Table 2
Modeled groups and markets groups correspondence.

Market group	Model groups
Mollusks	Bivalves
Crustaceans	Brachyuran and Penaeidae
Cartilaginous fishes	Piscivorous rays and piscivorous fish
Bone fishes	Pelagic–feeding fish, benthic–feeding fish, and pelagic fish

2.4. Scenarios

As described in Oliveira et al. (2022), climate scenarios were developed using two contrasting scenarios described by IPCC (2014): RCP 2.6 and RCP 8.5. Data used here were adaptations of 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). Details about the climate scenarios can be found in Oliveira et al. (2022). The names RCP 2.6 and RCP 8.5 are references to the lower and higher climate forcing and must be understood as "RCP-like" scenarios due to these numerical differences. These scenarios are compared with the current situation, which is built with data from 2010-2017 and referred to as the base case.

The second system scenario (reactive tourist) used in the model came from previous research (Amazonas et al., 2021) in the area, and tackles the great concern from tourists regarding the water quality. Therefore, it was considered that water and sand cleanliness is relevant to tourists when choosing the beach they will visit. The model uses a microorganism (*Enterococcus*) concentration as a proxy for water quality. This indicator has been used for decades to monitor water quality. Tourists cannot see these microorganisms in the water, but if the water quality is not adequate for usage, 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. It was considered that beyond a certain concentration limit tourists react to water quality and start to move to a different location. For this study, the concentration limit was established in 1.6 mgww/m^2, which means twice the worst value found in the first year of simulation.

The model uses three economic scenarios (utopian, selfish, and balanced) that will depend on the discount rate used in each case for the future economic value of the goods and services. The utopian scenario uses a discount rate of zero, meaning the money does not change its value over time. This scenario is called utopian because the flows of ecosystem services today must have the same value for future generations.The selfish economic scenario is the opposite. It considers a discount rate of 12% each year, reflecting a scenario where all economic value of the goods is explored in the shortest range possible, preferably during this generation's lifespan (40 years). The balanced scenario then is in the middle. It uses a discount rate of 6% and with that, it tries to balance price and conservation once it claims the resources are going to last more than one generation.

3. Results

3.1. Economic valuation of individual ecosystem services

Ecosystem services values are presented in Fig. 2 with respective variations due to systemic and economic scenarios. The results of each valuation are also present in Appendix B. A description of each ES behavior along the simulation is provided in the Appendix A.

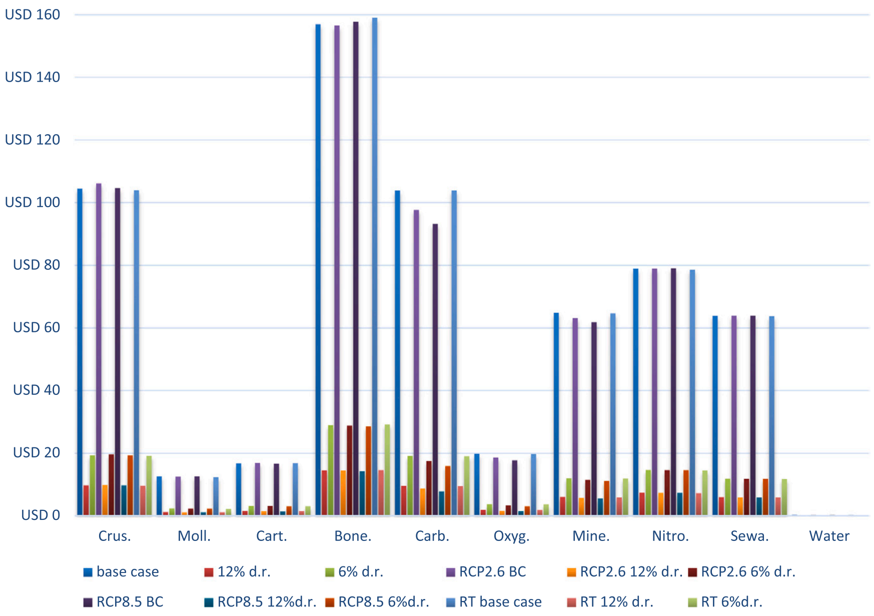

Fig. 2. Comparative values for each ES in different scenarios. Values in millions of dollars. Crus – crustaceans' production; Moll – mollusk production; Cart. – cartilaginous fish production; Bone – bonefish production; Carb – Carbon sequestration; oxyg. – Oxygen production; Mine. – mineralization; Nitro. – nitrogen cycling; Sewa. – sewage depuration; Water – water quality.

3.2. *Economic valuation of the aggregated ecosystem services*

The economic valuation of the 10 ES studied (Table 3 and B1-B3) are shown in the base case scenario and for both the systems scenarios (climate change and reactive tourist). Each line presents the total value for that scenario summed along the simulation time, followed by the standard deviation for that estimate. All Tables present data for the three economic scenarios based on their differences in discount rates.

Our findings show the Ubatuba coastal zone will provide ecosystem services with an economic value of 622 M USD (±3.6 M USD) for the city from 2010–2100. This value is equivalent to 7 M USD every year, or ~19,000 USD every day for the whole area. When this base case is compared with the possibility of extracting all ecosystem services in the short–range or their substitution for a different activity, results would bring great losses. In the worst economic scenario, selfish, the ES provision is reduced to less than 10% when compared with nature kept healthy. Economic loss (−564 M USD) would represent 90.73% (±0.59%). Even when the balanced economic scenario is considered, 81.55% (±0.59%) of ES are lost with values around −507 M USD.

If management was considering only the baseline, then the conservation effort costs *vs.* benefits would allow the city to spend 7 M USD each year on environmental conservation and still profit. This value corresponds to 6% of the gross income of the city (R$402 million) (Ubatuba, 2018).

When climate change scenarios (Tables B1 and B2) are considered, the situation gets worse. In the best scenario (RCP2.6), economic losses are −1.23% (±2.96%) with values of −7.5 M USD (±3.8 M USD) for the utopic scenario. If the selfish scenario is considered, then losses grow for −1.94% (±2.95%) adding –1.1 M USD (± 0.35 M USD) to the previous losses of – 564.5 M USD. In the balanced scenario, losses are −1.79% adding –2.0 M USD (±0.7 M USD) to the −507.3 M USD previously lost.

For RCP8.5, the situation is more serious (Table B2) with losses of −2.34% (±3.88%) that correspond to values of −14 M USD (±USD 6.3 M USD) for the utopic scenario. To different economic scenarios, losses reach −5.29% (±3.81%) for the selfish scenario (adding – 2.9 M USD ± 0.5 M USD to the – 564.5 M USD previously lost). For the balanced scenario, losses are −4.42% (±3.84%) (adding –4.8 M USD ± 1.1 M USD to the −507.3 M USD already lost).

For the reactive tourists' scenario (table B3) the situation is not as bad in all economic scenarios. For the utopian scenario, losses are −0.14% corresponding to −0.9 M USD. For the selfish scenario, losses are −0.40% with an additional value of −0.2 M USD to be added to those −591.3 M USD lost for this economic scenario. For the balanced economic scenario, losses are −0.33%, corresponding to −0.4 M USD to be added to the already lost −530.7 M USD of the adoption of this economic scenario.

4. Discussion

One of the highest impact papers in the field of ES valuation (Costanza et al., 1997) assesses coastal ES on a global scale by using a standard value per hectare and applying it in the whole area (benefit transfer). Results show USD 4050 per hectare per year (1997 dollar) for coastal areas in general and USD252 for the open ocean. In 2012 these values were revised, through a broad literature review, where authors (de Groot et al., 2012) searched for local scale valuations to reduce the effects of benefit transfer. The results for the same ecosystems are Int$ 28,917/ha/year (Values in 2007 'International' $/ha/year, i.e., translated into US$ values based on Purchasing Power Parity (PPP) and contains site-, study-, and context-specific information from the case studies (Costanza et al., 2014)) for coastal areas and Int$ 491/ha/year to open ocean. Rao et al. (2015) assessment still found values of USD 0.51 to 2529.9/ha/year for a 2013 dollar, reinforcing those variations are the rule when talking about the economic valuation of ES. The average value found in the present work was USD 43.70 (±USD 0.26)/ha/year (average 2010−2017 dollar price) for Ubatuba coastal area.

Despite being inside the range proposed by Rao et al. (2015), this value is far from those stated by Costanza et al. (1997) and for de Groot et al. (2012). There are several reasons for that: first, our values are the integration of different values and some of them were not

Table 3
Economic totals due to different economic scenarios for ecosystem services (aggregated) from 2010–2100.

Ecosystem Services	Scenario	Daily sum (Mil. dollars)	SD (10 K USD)	Daily sum (Mil. dollars) with 12% D.R.	SD (1 K USD)	Daily sum (Mil. dollars) at 6% D.R.	SD (1 K USD)
Crustaceans	BC	104.4	19.0	9.7	181.1	19.3	361.0
Mollusks	BC	12.6	27.0	1.1	25.4	2.3	50.6
Cart. Fish	BC	16.7	3.3	1.5	3.1	3.0	6.2
Bonefish	BC	157.0	30.0	14.5	286.1	28.9	569.6
Carbon	BC	103.8	0.3	9.6	0.6	19.0	0.5
Oxygen	BC	19.8	0.07	1.8	0.1	3.6	0.1
Mineralization	BC	64.8	0.1	6.0	0.3	11.9	0.4
Nitro. Cycling	BC	78.9	0.3	7.3	0.5	4.6	0.7
Sewage dep.	BC	63.8	0.3	5.9	0.7	11.8	1.0
Water quality	BC	345.0	0.001	0.003	0.003	0.006	0.005
Total		**622.0**	**366.00**	**57.7**	**340.0**	**114.8**	**676.00**
Total of losses				– 564.5		– 507.3	
Percentage				−90.73%	0.59%	−81.55%	0.59%

BC for base case scenario. D.R. for discount rate.

considered in the whole area (e.g., sewage depuration and nutrient cycling) that were considered only on the marine areas adjacent to the beach; second, the values from Costanza et al. (1997) and for de Groot et al. (2012) consider a different set of ecosystem services (e.g., regulation against perturbation, biologic control, habitat/refugee, raw materials) despite the exaggerated value of nutrient cycling that we have reduced to 10% of the proposed value (see Table 2). De Groot et al. (2002) also found discrepant values for this ES (between USD 87 and 21,100 /ha/year). Since the present study used the direct benefit transfer method, some variation in the value is expected, following changes in locations and society.

Climate change, depending on the model considered, tends to reduce the value of ecosystem services (Sumaila et al., 2011; Grimm et al., 2016). On the simulations presented in this work, climate change has different impact rates in all ES which include eventually increases in ES values in these scenarios. We hypothesize it is a regional effect on ES, producing a normal distribution of effects that most likely would be negative, but with possible results on the positive axis of the curve.

Results for **Crustaceans production** show a small gain in production for both climate change scenarios with a small loss for reactive tourists' scenario. Metzger et al. (2007) call attention to the synergic effect of the increase in CO_2 concentration on the water with an increase in water temperature to have negative effects on the survival of the crab (*Cancer pagurus*). Other niche variations are documented for crabs due to changes in environmental conditions as conquering new habitats due to change in water temperature (e.g., Nabout, 2009; Neumann et al., 2013; Vianna, 2019); change in feeding behavior due to changes in the rainy season (Alberti et al., 2007; Vianna, 2019) with possible effects on local food web; change in reproductive rate due to increase in temperature (Celentano and Defeo, 2016) for the crab *Emerita brasiliensis* in Uruguay.

All these synergistic effects and variations in feeding behavior, mortality rates, etc., were not captured by the present model, which makes the result for Crustacean's productivity conservative. Our results point to a slight increase in crustacean ES value in both climate change scenarios. This result comes from the fact that with the increase in precipitation frequency embedded in the model (corroborated by Reboita et al., 2022), more detritus will be carried from land to the ocean, feeding these animals and increasing their population. Variations in the food web due to climate change effects were also reported by Alberti et al. (2007), Heath et al. (2012), and Vianna (2019).

Mollusks' production results from the model show their population is slightly affected by climate change and tourism scenarios. In a global study, Narita et al. (2012) calculated the economic losses associated with variations in the production of Bivalves to be around USD100 billion globally until 2100. Climate change can influence the bivalve population because of the change in the patterns of rain, salinity, and even the frequency of extreme events (Brugère and de Young, 2015). Short-time intense changes in temperature (heatwaves) are also related to mass mortality of gastropods (Hemraj et al., 2020). In some cases, mollusk production is being limited by nutrients in the water (Guyondet et al., 2015) which appears to be the case in the present study for the reactive tourist scenario.

The **cartilaginous fish's** most evident result points to production reduction due to climate change RCP8.5 scenarios. Rosa et al. (2014) show the necessity of major research to enlighten the synergies in temperature increase associated with pH decrease for the survival of cartilaginous fishes and point to the low survival rate of one tropical shark (*Chiloscyllium punctatum*) due to water temperature increase. Each species will react to climate change in a particular way depending on its genetics, niche, adaptability, etc. (O'brien et al., 2013) but species with similar biology probably will behave in similar ways.

Using predictive population models for cartilaginous fish in the Great Barrier Reef in Australia, Chin et al. (2010) found that species that were closely related to coastal environment and land (in opposition to those that live in the open ocean) probably will suffer more the consequences of climate change (temperature and current changes). Our aggregation of information from the work of Rocha (2003) and the fisheries data does not allow us to make any conclusion regarding these habits. But in an Ubatuba's survey, Silvério (2010) identified four main species landed on the harbor (*Sphyrna lewini* – Tubarão Martelo, *Prionace glauca* – Tubarão azul, *Rhizoprionodon lalandii* – Tubarão–de–bico–fino–brasileiro e *Isurus oxyrinchus* – Tubarão–mako). If we consider that those species more related to the coast would be strongly affected by climate change (Chin et al., 2010), then that would likely be observed happening in hammer shark (Tubarão–martelo) and the Brazilian fine–billed shark (Tubarão–de–bico–fino–brasileiro) which would corroborate the results of the current model in the RCP8.5 scenario.

The **bonefish** group is strongly diverse and probably climate change will have different effects on each species of this group. From a broad perspective, one can imagine that climate change will affect movement speed (Nowell et al., 2015), physiology, development rates, reproduction, behavior and survival rates (Brander, 2010), habitat degradation (Sumaila et al., 2011), and increase in respiratory rates (Roessig et al., 2004). Consequently, all economies depending on fisheries will be affected.

Countries with a high dependency on fisheries and with limited economic capacity for adaptation to climate change impacts are more vulnerable. In a global study, some African, tropical Asia, and two South American countries (Peru and Colombia) appear among this vulnerable list (Allison et al., 2009). Another study made in 67 exclusive economic zones, responsible for 60% of global fisheries, presents an increase of productivity in higher latitudes and decrease of productivity in lower latitudes, with an average variance of 3.4% (Barange et al., 2014), which are coherent with the simulations of the present work.

Every day, oceanic phytoplankton transform more than one hundred million tons of **carbon** in the form of CO_2 into organic compounds (Behrenfeld et al., 2006). The trend of decreasing primary productivity has been observed since 1999 (Op. cit.); other authors in a multi–decadal study (1998–2018) claim that there is no decreasing trend (Kulk et al., 2020); different authors (e.g., Henson et al., 2010) also claim that observed variations cannot be certainly attributed to climate change because usually, decadal variations happen naturally. For Ubatuba, this service shows a clear decreasing rate pattern for both climate change scenarios, steeper for RCP8.5, which are in accordance with Behrenfeld et al. (2006). Navarrete et al. (2022) also show the relevance of local currents in Phytoplankton productivity, and this calls attention to the limits of the current model that has not embraced this effect on primary productivity.

Oxygen production service shows that the region produces between 100 and 450 tons of this gas every day. These values are compatible with those suggested by Emerson et al. (2008) of 0.4208 ± 0.2367 g/m^2/day that applied to the total study area (1.58E+09 m^2) would produce 665.08 ± 374.5 tons per day.

The discussion about primary productivity on carbon sequestration is also pertinent to oxygen production as both services are the fruit of primary productivity. Joos et al. (2003) states a clear tendency in the decrease of the global dissolved ocean concentration and raise the hypothesis that this diminishing in O_2 concentration is related to rearranging in global maritime currents. Other authors agree with that decreasing trend and estimate losses between 4 and 7% of O_2 concentration in the oceans until the end of the 21st century (Matear and Hirst, 2003). Limburg et al. (2020) state that the oceans have already lost between 1 and 2% of their oxygen production since the middle of the 20th century and the numbers of locals that have registered worse conditions are growing.

For **nitrogen cycling** and **mineralization,** the dumping of sewage and solids on the ocean has been studied for several years, particularly from a project created by IGBP (International Geosphere–Biosphere Program) in 1993 named "land–ocean interactions on the coastal zone" (LOICZ) (Ramesha et al., 2015). One of the main products of LOICZ is the volume that shows a synthesis of global continental flows (Liu et al., 2010) where nitrogen load to the ocean is calculated in 1350×10^9 mol/year which is a number three times larger than the previous mainstream literature (Meybeck, 1982).

Current consensus (Rockstrom et al., 2009; Steffen et al., 2015; Gerten et al., 2020; Waltham et al., 2021) observes that nitrogen dumping on oceans (so does Phosphate) happens much above tolerable limits. Agriculture, due to fertilizers and through legumes for fertilizing plantations, activates a large amount of nitrogen that was passively stocked on the atmosphere or in fossil fuel deposits that eventually reach the coasts.

This global mobilization of nitrogen is around 120 million tons every year (Rockstrom et al., 2009), and considering that a good part of this nitrogen ends up in the ocean, makes this mineral a menace for global sustainability because (associated with phosphorus) it causes algae blooms, leading to eutrophication and hypoxic dead zones in the ocean. The same authors (Op. cit.) in their seminal study about planetary boundaries for human development showed that the nitrogen cycle must be reduced to 25% of current values to operate in a safe space. This same work was updated (Steffen et al., 2015) to include regional goals to previous global ones, focusing on the control of fertilizers production and distribution on the planet. The global production limit in this new work is 73Tg (73 million tons) of nitrogen, which is more than the previous goal from Rockstrom et al. 2009 and pose a huge challenge for the current 120 million tons.

In our study, mineralization is decreasing in each climate scenario due to the reduction of phytoplankton biomass. Nitrogen cycling presented negligible values for both scenarios.

Sewage depuration service discussion can profit from the discussion of nitrogen cycling because they both represent problems with the same origin, the lack of treatment in wastewater. But despite the small overlap, this part is focused on the ecological processes responsible for the mortality of the biological portion of the sewage and the economic implications of climate change.

The variation in sewage depuration values was negligible in both climate scenarios and for the reactive tourist scenario which might point to a limit of the model in considering this ES. Sewage depuration values on ESVD are proportional to the area of the coast dedicated to the depuration of sewage. Considering our case, the area did not change in both scenarios, just the normalized value of the amount of sewage deposited in the water, which can explain the low variation of the results due to scenarios.

Water quality perception shows that the region loses quality due to climate change. Despite the economic values associated with this service being very small when compared to the rest of the ES analyzed, this is an indirect index for tourist satisfaction and therefore it can be used to understand tourists' behavior and plan for public policies (Ghilardi–Lopes et al., 2015).

Other authors already showed that environmental quality is as important as price policies for tourists to choose their destiny (Otrachshenko and Bosello, 2015) and more recently Qiang et al. (2020) showed that tourists stay for short periods on beaches where the water quality was not satisfactory, with consequent economic impacts of 28–32% compared to clean beaches. Our results were far more conservative (0.24%) despite pointing to the same direction.

The **aggregate of all ES** analysis shows that the best option for the city is to keep nature providing these services as long as possible. Any economic scenario that brings future values to the present is showing an average loss of one order of magnitude in the economic yield of ES. In the utopian scenario the yield is 622 M dollars ± 3.6 M dollars then when compared to the selfish scenario would be reduced to 57.6 M dollars ± 340 K dollars and for 114.8 M dollars ± 676.5 K dollars when compared to the balanced scenario.

The losses from climate change on ES provision vary from –7.5 M dollars (±3.8 M dollars) to –14.2 M dollars (± 6.3 M dollars) dollars in the best scenario (utopic) along the century for RCP2.6 and RCP 8.5 respectively.

5. Conclusions

The initial hypotheses of Ecosystem Services provided on the region of study would be different in the future due to climate change and due to the possibility that the tourists would change their behavior according to the water quality were both tackled by scenarios studies and the associated valuation.

All ten studied ES (Crustaceans` production, Mollusks production, Cartilaginous fish production, bonefish production, carbon sequestration, oxygen production, mineralization, nitrogen cycling, sewage depuration, and water quality) showed individual variations between the climate scenarios RCP2.6 or RCP8.5 or due to the reactive tourists' scenario. These variations spectrum was from very small (−0.08 ± 0.00%) for water quality in RCP2.6 to big (10.2% ±0.01% for carbon sequestration under the RCP 8.5 scenario) percentages compared to the base case.

Six of these services show a decrease in the offer due to climate change in the RCP 2.6 scenario, four presented some gain. For RCP8.5 it was five and five. It is necessary to say that most of the ES provisions forecast did not point to unidirectional results as loss or gain because when uncertainties were associated with the evaluated mean value, these values present a Gaussian curve with legs on the positive and negative side. The conclusion is that most probably there will be losses in ES due to most means occupying a negative position, but some positive effects can also be obtained and must be confirmed in future studies of the region.

The overall picture is that Ubatuba coastal zone will provide ecosystem services with an economic value of 622 M dollars (± 3.6 M dollars) for the city from 2010–2100. When climate change scenarios are considered, the situation gets worse. In the best scenario (RCP2.6) economic losses are −1.23% (±2.96%) with values of −7.5 M dollars (±3.8 M dollars) for the utopic scenario. If the selfish scenario is considered, losses grow for −1.94% (±2.95%) adding – 1.1 M dollars (± 352 K dollars) to the previous losses of −564 M dollars. On the balanced scenario, losses are −1.79% adding −2 M dollars (±701 K dollars) to the −507 M dollars previously lost.

For RCP8.5 the situation is more serious, with losses of −2.34% (±3.88%) that correspond to values of −14 M dollars (± 6.3 M dollars) for the utopic scenario. To different economic scenarios, losses reach −5.29% (±3.81%) for the selfish scenario (adding – 2.9 M dollars ± 578 K dollars to the −564 M dollars previously lost). For the balanced scenario, losses are −4.42% (±3.84%) (adding −4.8 M dollars ± 1.1 M dollars to the − 507 M dollars already lost).

For the reactive tourists' scenario, the situation is less worsening in all economic scenarios. For the utopic scenario, losses are −0.14% corresponding to −898 K dollars. For the selfish scenario, losses are −0.40% with an additional value of −249 K dollars to be added to those −591 M dollars lost for this economic scenario. For the balanced economic scenario, losses are −0.33%, corresponding to −407 K dollars to be added to the already lost −530 M dollars of the adoption of this economic scenario.

Controlling the population visiting the area can have a positive effect on the water quality, carbon sequestration, and oxygen production, remove the pressure of services like sewage depuration and nitrogen cycling and increase yield in some fisheries (cartilaginous and bonefish) despite the losses in crustaceans and mollusk fisheries. The city of Ubatuba is recently (since July 2022) implementing a visiting tax, with diver objectives to deal with the impact of the tourist population. This tax will certainly increment the administration resources to deal with the impacts of the visiting population but also might discourage part of the tourism and therefore reduce its impacts on biodiversity and ecosystem services. This policy is in high adherence with the products of this study. Future research can analyze how this policy unfolded.

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.

Acknowledgements

The authors would like to thank the anonym reviewers for their collaboration in the paper and for the editors of the journal. The authors also 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.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.gecco.2022.e02240.

Appendix B. Valuation tables

See Tables B1-B3

Table B1

Economic losses due to different economic scenarios for RCP2.6 on aggregated ES provision from 2010–2100.

n	Ecosystem Service	Scenario	Daily sum (M US$)	SD (1K US$)	Losses (1K US$)	SD (1K US$)	Totals rate	SD	12% d. r. (M US $)	SD (1K US$)	losses (1K US$)	SD (1K US$)	totals rate	SD	6% d.r. (M US$)	SD (1K US$)	losses (1K US$)	SD (1K US$)	totals rate	SD
1	Crus.	RCP 2.6	106,10	1895,80	1710,30	473,00	1,64%	0,45%	9,80	176,50	159,10	43,90	1,64%	0,45%	19,60	350,00	316,30	87,40	1,64%	0,45%
2	Moll.	RCP 2.6	12,50	408,60	-83,90	301,90	-0,67%	2,40%	1,10	37,70	-7,70	27,80	-0,67%	2,39%	2,30	75,10	15,40	55,50	-0,67%	2,39%
3	Cart.	RCP 2.6	16,90	259,40	153,20	257,20	0,91%	1,53%	1,50	23,90	14,00	23,70	0,91%	1,53%	3,10	47,70	28,00	47,30	0,91%	1,53%
4	Bone.	RCP 2.6	156,50	3266,60	-459,40	1055,30	-0,29%	0,67%	14,50	301,40	-43,70	94,60	-0,30%	0,65%	28,80	600,60	-86,10	190,50	-0,30%	0,66%
5	Carb.	RCP 2.6	97,60	9,30	-6158,90	8,90	-5,93%	0,01%	8,70	2,60	-843,80	2,60	-8,81%	0,03%	17,50	3,30	-1561,10	3,20	-8,18%	0,02%
6	Oxyg.	RCP 2.6	18,60	1,60	-1167,60	1,40	-5,90%	0,01%	1,60	0,40	-159,70	0,40	-8,76%	0,02%	3,30	0,50	-295,80	0,50	-8,14%	0,02%
7	Mine.	RCP 2.6	63,10	2,00	-1680,80	1,70	-2,59%	0,00%	5,70	1,00	-230,80	1,00	-3,83%	0,02%	11,50	0,90	-426,70	0,90	-3,56%	0,01%
8	Nitro.	RCP 2.6	78,90	9,00	72,30	8,50	0,09%	0,01%	7,30	1,70	6,20	1,60	0,08%	0,02%	14,60	2,80	13,20	2,60	0,09%	0,02%
9	Sewa.	RCP 2.6	63,90	6,30	59,70	5,10	0,09%	0,01%	5,90	1,00	6,50	0,70	0,11%	0,01%	11,80	1,40	12,40	1,00	0,11%	0,01%
10	Water	RCP 2.6	0,30	0,01	-0,30	0,01	-0,08%	0,00%	0,03	0,01	-0,03	0,01	-0,10%	0,02%	0,06	0,01	-0,05	0,01	-0,09%	0,01%
		Total	**614,40**	**3,80**	**7,50**	**3807,80**	**1,22%**	**2,96%**	**56,13**	**352,13**	**-1099,93**	**352,15**	**-1,96%**	**2,95%**	**112,56**	**700,83**	**-1984,45**	**701,26**	**-1,76%**	**2,95%**

Table B2

Economic losses due to different economic scenarios for RCP8.5 on aggregated ES provision from 2010–2100.

n	Ecosystem Service	Daily sum (M US$)	SD (1K US$)	Losses (1K US$)	SD (1K US$)	Totals rate	SD	12% d.r. (M US$)	SD (1K US$)	losses (1K US$)	SD (1K US$)	totals rate	SD	6% d.r. (M US$)	SD (1K US$)	losses (1K US$)	SD (1K US$)	totals rate	SD
1	Crus.	104,60	2282,50	239,60	1179,90	0,23%	1,13%	9,70	211,40	5,70	107,70	-0,06%	1,11%	19,30	420,90	8,20	215,60	0,04%	1,12%
2	Moll.	12,60	246,10	58,00	123,40	0,46%	0,98%	1,10	22,60	4,90	11,50	-0,43%	0,99%	2,30	45,10	2,00	22,90	-0,09%	0,99%
3	Cart.	16,60	270,90	-122,40	268,80	-0,73%	1,60%	1,40	24,70	49,30	24,50	-3,19%	1,58%	3,00	49,10	69,10	49,00	-2,24%	1,59%
4	Bone.	157,70	5901,50	808,20	5026,90	0,51%	3,20%	14,20	536,80	278,10	545,10	-1,92%	3,13%	28,60	1075,00	-281,30	912,40	-0,97%	3,16%
5	Carb.	93,20	11,40	-10592,90	11,00	-10,20%	0,01%	7,80	10,60	-1766,90	10,60	-18,45%	0,11%	15,90	9,80	-3116,80	9,80	-16,33%	0,05%
6	Oxyg.	17,70	2,40	-2004,20	2,30	-10,13%	0,01%	1,50	1,80	-333,10	1,80	-18,27%	0,10%	3,00	2,10	-588,50	2,10	-16,19%	0,06%
7	Mine.	61,80	3,70	-2912,90	3,60	-4,50%	0,01%	5,50	2,30	-489,90	2,20	-8,13%	0,04%	11,10	2,70	-862,20	2,70	-7,20%	0,02%
8	Nitro.	79,00	7,90	157,60	7,40	0,20%	0,01%	7,30	1,20	14,30	1,00	0,20%	0,01%	14,60	1,50	29,70	1,40	0,20%	0,01%
9	Sewa.	63,90	5,00	124,80	3,40	0,20%	0,01%	5,90	1,70	13,10	1,50	0,22%	0,03%	11,80	2,70	24,90	2,50	0,21%	0,02%
10	Water	0,30	0,00	-0,50	0,00	-0,16%	0,01%	0,03	0,00	0,01	0,00	-0,16%	0,01%	0,06	0,00	-104,83	0,00	-0,17%	0,01%
	Total	**607,40**	**6338,11**	**-14244,70**	**6338,16**	**-2,35%**	**3,88%**	**54,43**	**578,01**	**-2900,00**	**578,02**	**-5,33%**	**3,81%**	**109,66**	**1156,44**	**-4819,73**	**1157,05**	**-4,40%**	**3,84%**

Table B3

Economic losses due to different economic scenarios for Reactive Tourists on aggregated ES provision from 2010–2100.

n	Ecosystem Service	Daily sum (M US$)	SD (1K US $)	Losses (1K US$)	SD (1K US $)	Totals rate	SD	12% d.r. (M US$)	SD (1K US$)	losses (1K US$)	SD (1K US$)	totals rate	SD	6% d.r. (M US$)	SD (1K US$)	losses (1K US$)	SD (1K US$)	totals rate	SD
1	Crus.	103,90	1154,30	-433,00	1576,50	-0,41%	1,51%	9,60	106,90	-86,70	147,10	-0,89%	1,51%	19,10	212,80	-145,20	292,20	-0,75%	1,51%
2	Moll.	12,30	708,50	-263,40	652,80	-2,09%	5,18%	1,10	65,30	-25,60	60,20	-2,21%	5,17%	2,20	130,20	-50,30	119,90	-2,17%	5,17%
3	Cart.	16,80	156,20	56,30	152,50	0,34%	0,91%	1,50	14,40	3,50	14,00	0,23%	0,91%	3,00	28,70	7,90	28,00	0,26%	0,91%
4	Bone.	159,00	4141,40	2081,80	2755,70	1,33%	1,76%	14,60	382,50	172,70	253,90	1,19%	1,75%	29,20	761,90	355,60	506,00	1,23%	1,75%
5	Carb.	103,80	3,50	17,80	1,90	0,02%	0,00%	9,50	0,70	6,10	0,20	0,06%	0,00%	19,00	0,90	9,40	0,70	0,05%	0,00%
6	Oxyg.	19,70	0,90	2,90	0,50	0,01%	0,00%	1,80	0,10	1,00	0,00	0,06%	0,01%	3,60	0,20	1,60	0,20	0,04%	0,01%
7	Mine.	64,60	0,70	-128,00	0,70	-0,20%	0,00%	5,90	0,20	-46,30	0,10	-0,77%	0,00%	11,90	0,40	-68,90	0,00	-0,58%	0,00%
8	Nitro.	78,60	2,60	-198,90	1,50	-0,25%	0,00%	7,20	0,60	-50,70	0,40	-0,69%	0,01%	14,50	1,00	-85,50	0,70	-0,59%	0,00%
9	Sewa.	63,70	3,30	-155,50	1,60	-0,24%	0,00%	5,90	0,40	-40,00	0,60	-0,67%	0,01%	11,70	0,70	-67,40	0,80	-0,57%	0,01%
10	Water	0,30	0,00	0,80	0,00	0,24%	0,00%	0,03	0,00	0,20	0,00	0,67%	0,01%	0,06	0,00	0,30	0,00	0,57%	0,01%
Total		**622,70**	**4360,05**	**980,80**	**4360,12**	**0,16%**	**5,75%**	**57,13**	**402,75**	**-65,80**	**402,85**	**-0,12%**	**5,74%**	**114,26**	**802,22**	**-42,50**	**802,29**	**-0,04%**	**5,74%**

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