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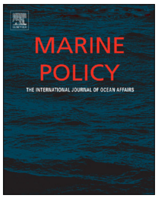

Using ecological modelling in marine spatial planning to enhance ecosystem-based management

Ateret Shabtay[a,*], Michelle E. Portman[a], Eyal Ofir[b], Yohay Carmel[c], Gideon Gal[b]

[a] *Faculty of Architecture and Town Planning, Technion, Haifa, Israel*
[b] *Kinneret Limnological Laboratory, Israel Oceanographic & Limnological Research, Israel*
[c] *Faculty of Civil and Environmental Engineering, Technion, Haifa, Israel*

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ABSTRACT

Growing awareness of the role of marine spatial planning (MSP) in promoting sustainable development and ecosystem-based management highlights the need to use decision-support tools, and specifically ecological modelling tools, to consider the future impact of planning and management on the marine environment. However, how these tools can be incorporated into planning and their expected contribution is not always clear. Here, an Ecopath with Ecosim and Ecospace food-web model was used in a hypothetical planning process to examine the integration of food-web tools in specific stages of MSP. The model was used to examine spatial alternatives and management strategies for Orot Rabin coastal infrastructure facility in the Israeli Mediterranean coast, in an attempt to assess how such facilities might promote marine conservation. The results revealed the effect of different management protocols on the ecosystem, and provide the maximum allowable catch for sustaining the biomass of vulnerable fish species in the area, which can be used in MSP to address specific marine conservation goals. The model led to counterintuitive understandings regarding the management of the area. It demonstrated that intensive development under specific management strategies may promote conservation goals better than some management strategies directed towards ecological and recreational purposes. This study confirms the potential usefulness of food-web models for MSP; it specifies the stages and means by which planners can use models. Furthermore, it is suggested that tool's development should be planning-oriented and should include more applications to serve planners who aim to promote ecosystem-based management and marine conservation goals.

1. Introduction

At the national and international level, marine conservation goals are often addressed through marine spatial planning (MSP). The aim of this process, which deals with allocating the uses of a space that includes marine protected areas, is to reduce conflicts between different uses and between the various uses and the continued protection of the marine environment [20]. However, the increasing human activity in the marine environment challenges marine planning to adapt and find creative solutions to potentially negative interactions between uses and the environment, while promoting marine conservation goals and ecosystem-based management [18,19,42]. For example, MSP attempts to explore marine conservation opportunities beyond the boundaries of marine protected areas (MPAs) (e.g., [24,34,44]), and even within areas dedicated to human activity [46]. Questions remain on how to consider and explore conservation opportunities as part of the planning process. Decision-support tools and spatial prioritization tools are often suggested for use in MSP, to handle multiple conflicts between human activity and marine ecosystems, and to secure the protection of valuable, unique and vulnerable marine habitats and populations [11,40,56]. At the same time, further methodological advances are required in order to devise comprehensive MSP, in which marine conservation goals constitute the basis for all developments [30].

Advances in this direction include the use of ecological models as decision-support tools to explore the effects of human activity on ecosystems as a whole. The main advantage of incorporating such models into planning and management procedures is that they allow users to predict not only the cumulative impact of human activity on the environment over time and space, but also the indirect impact of management on the environment [26,33]. In addition, recent advances in the design of food-web modelling tools has increased their diagnostic capabilities, and the ability to account for uncertainty (e.g., [35,54]). The significant progress in the ability of food-web modelling tools to assess cumulative impacts on the environment led to their application

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[*] Correspondence to: Faculty of Architecture and Town Planning, Sego Building, Technion, Haifa 32000, Israel.
E-mail address: ateretshabtay@gmail.com (A. Shabtay).

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for various purposes. Alexander et al. [1] used food-web model to examine the effect of the structure and management of renewable energy installations on a marine ecosystem. In addition, Pastorok et al. [36] demonstrate the importance of using ecological modelling in chemical risk assessment. Notwithstanding, ecological modelling tools have limitations. One of the most significant limitations of the modelling approach to planning is the difficulty of interpreting model results for the purpose of planning and management [12,26]. The incorporation of ecosystem modelling results into the MSP process is still lacking.

This study focuses on a marine infrastructure area of a coastal power station to which public access is limited; this managerial policy supports populations of highly vulnerable marine species [47]. Our assumption is that the MSP process can be aided by food-web modelling. The goal of this study was to examine how food-web modelling can be used as part of a MSP process, to explore the possibility of promoting marine conservation goals within an area that is subjected to intense human impact. To this end, the marine ecosystem within the area of Orot Rabin coastal power station was modelled and used in a hypothetical MSP process. The model was used to examine the effects of different spatial alternatives and management schemes on the marine ecosystem.

2. Methods

Ecological modelling was incorporated into the planning process in order to provide a means for predicting the possible effects of spatial and temporal uses and their management on the marine ecosystem. The process followed the Ehler and Douvere [20] step-by-step guide for MSP. Stages selected in the planning process were identified as suitable for considering alternatives whereby marine conservation goals can be maintained and supported within developed marine areas (See [11]).

A food-web model of the area of the marine infrastructure in question was developed. The area, to which public access is limited, was found to provide a suitable habitat for several vulnerable fish species. Based on the food-web model, hypothetical planning process was applied, with a 15-year planning horizon. Within this framework, different management scenarios of the infrastructure enclosure were examined, according to the pre-set, relevant stages of the planning process. Incorporating the model as a decision-support tool in the planning process allowed determination of the best way to adapt the infrastructure enclosure to serve as a multiuse area, while including marine conservation among the added uses.

2.1. *The planning process*

In the MSP process, 2 of the 10 stages were identified as suitable for examining the promotion of marine conservation goals (stages 6 and 7 in [20], see Table 1), within areas of marine infrastructure. Then a food-web model was used to predict the effect of different spatial alternatives and management schemes on the food-web.

2.1.1. *Defining and analyzing future conditions (Stage 6 in MSP process)*

This stage is the sixth of ten stages [20]. The business-as-usual scenario (BAU) was simulated as a reference, as well as two spatial alternatives, each under three management strategies. Each spatial alternative represents the incorporation of a different target: (1) The spatial alternative that prioritises 'Ecology and recreation' (ER) emphasises development guided by marine conservation needs, following the conservation targets outlined by the Israel Nature and Parks Authority – INPA [28], which highlight educational and recreational activities in MPA areas; 2) The spatial alternative that prioritises ‘Intensive development’ (ID) emphasises development of the area for further energy production and for the benefit of other industries that rely on ports.

2.1.2. *Preparing and approving the spatial management plan (Stage 7 in MSP process)*

Decision-support tools are often used in MSP in the seventh stage, to examine different management scenarios [11,40]. The seventh stage of the planning process (Table 1) was followed to examine the selected spatial alternatives under three management strategies: exclusive, cooperative, and inclusive management. Exclusive sectoral-management represents operation of the area according to sector needs only. Cooperative management represents operation of the area according to sector needs while promoting benefits of additional sectors from the area. Inclusive management represents operation of the area by multiple sectors, to allow maximum benefit for each sector. Thus a total of seven scenarios were employed: two spatial alternatives under three management strategies (=6), and the BAU scenario, which served as a baseline, for comparing measures from each of the simulated scenarios.

The spatial alternatives and the related management strategies are detailed in Table 2. The ER alternative focused on the natural components of the area, choosing to exclude artificial structures constructed for energy-production purposes, while allowing recreational activities such as swimming, snorkeling, SCUBA diving and sport fishing. In the ID alternative, the focus was on the construction of additional structures, to enhance production and port activities. Management strategies adjust the activity in the area according to the level of other sectors' involvement. The rationale for each spatial alternative and management strategy is described in Appendix 1.

2.2. *Study site*

The Orot Rabin Power Station is located on the coast of the Israeli Mediterranean Sea near the city of Hadera. It encompasses a marine area of approximately 1.5 km^2 and includes submerged and above-water structures (Fig. 1). The shallow area has a depth of approximately 5 m and includes an intake basin, into which seawater is pumped to cool the power station turbines. The intake basin is bordered by breakwaters from the west, south and partly from the north, to minimize turbulence which might cause pumping disruptions. Seawater in the intake basin is not treated in any way before uptake by the turbines, and water flows freely in and out of the basin.

The intake basin encompasses the tugboat harbour, a dock for military vessels and another dock for small maintenance and security patrol boats. The coal jetty, where ships unload coal for the operation of the power station, is the deepest area, at a depth of approximately 29 m. The jetty is located 3 km west of the power station and from there a

Table 1
Ehler and Douvere [20] stages of marine spatial planning where ecological modelling tools could be used for achieving marine conservation within areas of human activity.

Planning stage according to Ehler and Douvere [20]	Stage order	Stage description
Defining and analyzing future conditions	Sixth	Planners project the current existing human activities over space and time and then predict future demand for space by variety of existing and future activities. Based on these predictions, planners examine alternative future scenarios for the area.
Preparing and approving the spatial management plan	Seventh	Planners examine management alternatives for the area and select management measures for evaluation. At the end of this stage, planners prepare a comprehensive management plan.

Table 2

Planning and management scenarios examined, in a 15-year planning horizon (time frame).

Planning stage	Defining and analyzing future conditions; Identifying alternative spatial scenarios	Preparing and approving the spatial management plan		
	Spatial alternative	*Management strategy*		
		Exclusive	**Cooperative**	**Inclusive**
	Ecology and recreation (ER)	– All artificial structures including coal conveyor are removed except for 3 artificial reefs which function as an underwater SCUBA diving park. – Intake basin is transformed to swimming area by adding south-western breakwater. – No fishing is allowed in the area; however, illegal fishing equals 6% of the catch (estimated based on Edelist et al., 2013, Rotchild, 2015).	– Artificial structures remain at the bottom of the jetty – No-take zones in the area of the jetty, the artificial reefs or the intake basin. – Fishing effort doubles	– Artificial structures remain at the bottom of the jetty – Recreational fishing is permitted in all areas. – -Fishing effort is limited to 0.08 t per year (about the same as illegal fishing in ER exclusive scenario) – No fishing is allowed during breeding season.
	Intensive development (ID)	– Coal jetty and conveyor are expanded. – No fishing is allowed in the area of the study site due to safety and security considerations. – Conveyor and jetty piles and other essential artificial structures such as docks, are treated with antifouling substances.	– Coal jetty and conveyor are expanded. – Green engineering of the new constructions will increase benthos settlement twofold. – Public and fishers access to the area is prohibited. – Illegal fishing remains at the current estimated rate.	– Coal jetty and conveyor are expanded. – Recreational fishing is allowed all year in the area of the conveyor and the coal jetty. – Fishing effort increases twofold. – Artificial structures are removed from under the coal jetty.

◆ Breeding season of vulnerable species observed within the power station is April to August [51].

conveyor transports the coal to the station. The sediment in the study site is mostly sand with scattered rock. Artificial substrate in the study site comprises mainly concrete, steel and rock and includes the breakwaters, harbour and docks, and the piles of the coal jetty and the coal conveyor. During the construction of the coal jetty and conveyor, in the early 1980s, heavy waste such as concrete blocks, steel cables and steel nets were illegally thrown to the seafloor under the coal jetty. During the past decade the Ministry of Environmental Protection has encouraged the Israel Electric Corporation (IEC) to remove these artificial structures from under the jetty. The site borders with popular recreational beaches on both sides; however, the area is managed by the Israel Ports Authority which limits maritime and general public access to territories within its jurisdiction, usually up to a distance of 100 m from the port's structures. Therefore, fishing activity in the areas is illegal and uncommon, though it does take place to a limited extent, presumably less than if the area were openly accessible to fishers.

2.3. *Food-web model*

An Ecopath with Ecosim (EwE) model with the Ecospace module extension (ver. 6.5) was used for the study site, in order to examine the spatial alternatives and the management strategy scenarios listed in Table 2.

The Ecopath model creates a static mass-balanced snapshot of ecosystem resources and their interactions [41], based on biomass, production, and consumption parameters. Ecosystem resources are species or groups of species in the form of functional groups, which represent ecological guilds: the interaction between the 'guild members' results in a flow of biomass between them [7]. The parameterized Ecopath models are based on a set of equations, detailed and explained in Christensen and Walters [8] and Christensen et al. [7]. Using the Ecosim model allows for a simulation of food-web changes over time, as a response to fishing and environmental forces. The simulation is based on a set of time-dependent equations, which represent the biomass growth rate of each functional group, from the baseline, which is the mass-balanced Ecopath model [7–9]. A third module, *Ecospace,* allows simulation of ecosystem changes not only over time but also over a 2D spatial domain, as it dynamically allocates biomass across a raster grid map, which indicates the number of habitats to which functional groups and fishing fleets are assigned. This allows alternation of trophic interaction rates, based on species habitat affinities and the location of those habitats (see de Mutsert et al. [17], Steenbeek et al. [49], and Christensen et al. [6]).

2.3.1. *Input data and sources*

The Ecopath model in this study is comprised of 14 functional guilds, which were grouped based on the Corrales et al. [14] model of the Eastern Mediterranean area. The species in each group were observed in surveys performed by Shabtay et al. [47] and Frid and Belmaker [23] in the areas pertinent to the current study. The functional guilds included 2 groups of primary producers, 3 groups of invertebrates, 6 groups of osteichthyes, 2 groups of chondrichthyes, and one group of detritus. The currency used in this study was wet-weight biomass in tons (t) km^{-2} as well as wet-weight production, consumption and catch in $t * km^{-2} year^{-1}$ for all functional groups. All parameters used for the Orot Rabin Power Station food-web model (biomass, production, consumption, ecotrophic efficiency, and fishing catch) are presented in Table 3.

2.3.1.1. Biomass estimates. Biomass was estimated using data collected mostly from surveys preformed in the power station area. The surveys provided accurate data on the abundance of benthic primary producers, invertebrates, fish, and ray species in different locations within the power station area [47]. To calculate biomass, abundance data were multiplied by average wet weight of each species. To estimate wet weight of benthic invertebrates and primary producers, alcohol-

Fig. 1. Coastal infrastructures of Orot Rabin Power Station along the Israeli Mediterranean coast.

preserved specimens from The Steinhardt Museum of Natural History, Tel Aviv University were measured. Each species' wet weight was estimated by weighing 10–30 specimens from each species which were collected in area of the power station. For fish and ray species, average wet weight was calculated from the database of Frid and Belmaker [23]; only data from sampling points located within 100 m of the power station's structures were included.

Biomass of all other groups was calculated based on secondary data not directly measured in the area of the power station: Phytoplankton biomass was calculated from measurements conducted by the IEC [27] and the Israel Oceanographic and Limnological Research (IOLR) monitoring program [29] in the area of the power station. Zooplankton biomass was calculated from the Corrales et al. [14] model. Shark biomass was calculated from the database of Barash [2]. Although not a functional guild, detritus is essential component in EwE models (a functional group in ExE terminology) and therefore is incorporated into the model using the same currency as other functional groups. Detritus biomass was calculated using the empirical equation from Pauly et al. [39] and Torres et al. [53]:

$$\log D = -2.41 + 0.954\cdot \log PP + 0.863 \log E \qquad (1)$$

where D is detritus biomass, PP is annual primary production measured by IOLR [29], and E is the average depth of the photic zone.

2.3.1.2. Production. Production per biomass (P/B) of each group is equal to the sum of each species total mortality which is the sum of fishing mortality F and natural mortality M. F is the ratio between catch and biomass. M of each species was calculated for all fish groups following Pauly [37] and validated by comparison to Corrales et al. [14].

2.3.1.3. Consumption. Consumption, Q, of each species of finfish was calculated using an empirical equation following Pauly et al. [38]:

$$\log\left(\frac{Q}{B}\right) = 6.37 - 1.5045T' - 0.168 \log W_\infty + 0.1399Pf + 0.2765Hd \qquad (2)$$

where $T' = 1000/$mean seawater temperature, (K°), W_∞ is the body weight (g) taken from Frid and Belmaker [23] surveys in the area of the study site, Pf (apex and/or pelagic predators and/or zooplankton feeders) equals either 1 for predators or 0 for all others, and Hd (herbivores and detritivores) equals either 1 for herbivores or 0 for carnivores.

Table 3

Parameters used in Ecopath model of Orot Rabin Power Station. TL is the trophic level calculated by the model, P/B is the production per biomass per year, Q/B is the consumption per biomass per year, P/Q is production/consumption. **Bold-** calculated by the model.

	Functional group	TL	Biomass (t/km^2)	P/B	Q/B	Ecotrophic efficiency	P/Q	Fishery removal (t/km^2/y)
1	Phytoplankton	1	32	88		**0.09**		
2	Benthic primary producers	1	3.47	5.5		**0.09**		
3	Zooplankton	2.05	1.2	18.3	**294.41**	0.95	**0.06**	
4	Benthic invertebrates	2.35	5.13	0.77	2.58	**0.93**	**0.30**	
5	Cephalopods	3.30	0.2	0.84	9.28	**0.82**	**0.09**	
6	Flatfish	3.08	0.01	1.45	3	**0.92**	**0.48**	1.92E−4
7	Rocky fish	2.97	0.12	1.00	2.95	**0.98**	**0.34**	0.045
8	Demersal fish A[a]	3.19	0.10	2.28	4.39	**0.95**	**0.52**	0.147
9	Demersal fish B[b]	3.83	0.07	0.66	3.72	**0.94**	**0.18**	0.005
10	Herbivorous fish	2.00	0.11	0.82	2.37	**0.81**	**0.34**	0.013
11	Pelagic fish	3.42	0.2	1.06	2.5	**0.83**	**0.42**	0.104
12	Rays	3.58	0.18	0.28	1.29	**0.43**	**0.22**	0.021
13	Sharks	4.15	0.10	0.26	1.90	**0.01**	**0.14**	3.0E−4
14	Detritus	1	3.93			**0.03**		

[a] Demersal fish feeding on invertebrates.

[b] Demersal fish feeding on fish.

Table 4
Diet composition matrix for Orot Rabin Power Station food-web model.

	Prey/predator	3	4	5	6	7	8	9	10	11	12	13
1	Phytoplankton	0.7	0.3	0	0	0	0	0	0.1000	0	0	0
2	Benthic primary producers	0	0.1	0	0	0.2000	0.08	0	0.8998	0.0020	0	0
3	Zooplankton	0.05	0.2	0.15	0.02	0.0220	0.15	0	0	0.4	0	0
4	Benthic invertebrates	0	0.1	0.85	0.77	0.7001	0.654	0.276	0.0002	0.0492	0.5825	0.001
5	Cephalopods	0	0	0	0.01	0.0010	0.066	0.2	0	0.035	0.1747	0.001
6	Flatfish	0	0	0	0	0	0	0.063	0	0	9.71E−05	0
7	Rocky fish	0	0	0	0	0	0	0.1	0	0.095	0.0097	0
8	Demersal fish A[a]	0	0	0	0	0.0015	0	0.15	0	0.0176	0.0097	0.07
9	Demersal fish B[b]	0	0	0	0	0	0	0.01	0	0.0439	0	0.07
10	Herbivorous fish	0	0	0	0	0.0015	0	0.1	0	0.05	0	0.07
11	Pelagic fish	0	0	0	0	0	0	0.051	0	0.08	0	0.1
12	Rays	0	0	0	0	0	0	0	0	0	0	0.01
13	Sharks	0	0	0	0	0	0	0	0	0	0	0
14	Detritus	0.25	0.3	0	0.2	0.0738	0.05	0	0	0.0006	0	0
	Import	0	0	0	0	0	0	0.05	0	0.227	0.2233	0.678
	SUM	1	1	1	1	1	1	1	1	1	1	1

[a] Demersal fish feeding on invertebrates.

[b] Demersal fish feeding on fish.

For benthic invertebrates and cephalopods, consumption was calculated based on the model of Corrales et al. [14], using our biomass data. For zooplankton, consumption was estimated by Ecopath given an ecotrophic efficiency of 0.95 based on other small nearshore area models (e.g., [43,55]).

2.3.1.4. Diet composition. The diet of groups was calculated using diet preferences of each species, following Corrales et al. [14]; see Table 4.

2.3.1.5. Fishing. Although it is prohibited, fishing activity does occur within the area of the power station and therefore was incorporated in the model. The Israel Port Authority, which enforces the prohibition, reportedly detects minor illegal artisanal fishing activity in the area of the coal conveyor (Port captain, personal communication, 2015). Therefore, data from Frid and Belmaker [23] was used. The data include a detailed listing of all species caught in the area of the power station using both gill nets and trammel nets over a 1-year survey period. Here all the catch rates reported in the Frid and Belmaker [23] study was used as a single fleet type. Currently there is no indication of sport fishing taking place in the area; however, it is likely to occur under different management strategies. Therefore, in the Ecopath model we incorporated this fishing type with a negligible catch value of 0.002 $t/km^2/y$. In scenarios that allow sport fishing, fishing effort of unit is assumed to equivalent to 0.083 $t/km^2/y$ which is 6% of the trammel net fishing in BAU (For more details, see Appendix 2).

2.3.1.6. Model balancing. A critical stage in the development of an Ecopath model is the stage of balancing the model. A balanced model means that the food web (and the energy transformation within it) is correctly and fully represented in the model. For more details, see Darwall et al. [15] and Heymans et al. [25]. The small size of the study area (1.063 km^2) is one of the limitations of this study. To simplify the use of the model we assume a closed model that allows feeding of mobile groups outside the study area. Therefore, the feeding source for some of the species, such as pelagic fish, demersal fish B, rays, and sharks, was assumed to be outside the study area (see import value in Table 4) and the balancing process was began by increasing the value of the diet that these groups consume outside the area of the model. At the next stage, a top-down strategy [25] was followed similar to that found in previous studies that used EwE (e.g., [3,14,53]). The balanced Ecopath model was the basis for the scenarios examined using Ecospace.

2.3.1.7. Validation. To validate the model, fish biomass data [47] in two areas of the power station was used: the coal jetty, where no fishing occurs, and the conveyor area, where illegal fishing was reported by the Ports Authority. The time-dynamic module of EwE was operated with varying fishing effort in the conveyor area. It was found that a fishing effort of 15 nets per year resulted in biomass differences between these two areas that are similar to those reported by Shabtay et al. [47]. This result was well within the range of the fishing effort estimated by the Ports Authority.

2.3.2. *Ecospace*

An Ecospace model that was based on the Ecopath and Ecosim models was constructed. Ecospace is a spatial module that allows spatial-temporal dynamic modelling. The relatively small study area enabled us to construct the model using high-resolution data. Grid cell size represented an area of 10 × 10 m; spatial data, such as depth, temperature (from [27]), and habitat type (from [47]), were assigned to each cell.

Four habitat types were defined within the region represented by the Ecospace model: sand, breakwaters, piles, and artificial substrate. The first, sand, represents the areas where the bottom is sandy. The second habitat is found in areas of the breakwaters, which are made of boulders. The third type includes areas of habitat located on or near steel piles of the jetty and the conveyor. Each pile is about 4 m in diameter; they are located in pairs, every 40 m along the conveyor, and every 20 m along the jetty. The last habitat type, artificial substrate, consists of areas where various artificial structures are present such as concrete blocks, steel nets, and steel cables. Depth, temperature and habitat data were mapped using ArcGIS 10.2 and imported it into Ecospace (Fig. 2).

2.4. *Using Ecospace for MSP*

In Ecospace, spatial alterations of the existing state (sixth stage of MSP) included the addition or subtraction of hard substrate elements such as breakwaters, conveyor piles, and other artificial structures. Management scenarios (seventh stage of MSP) included fishing effort alterations, spatial fishing restrictions, seasonal variation in fishing, and fouling communities' habitat preferences. Changing biomass of benthic primary producers and benthic invertebrate groups was required to simulate an increase in fouling communities' biomass as a result of green engineering, when it was not accomplished through the usage of habitat preferences in Ecospace. This required changes to biomass of the fouling communities in Ecopath. Changing biomass values of the groups caused only minor changes to other model parameters, namely to the zooplankton group's consumption value, which decreased by 14%.

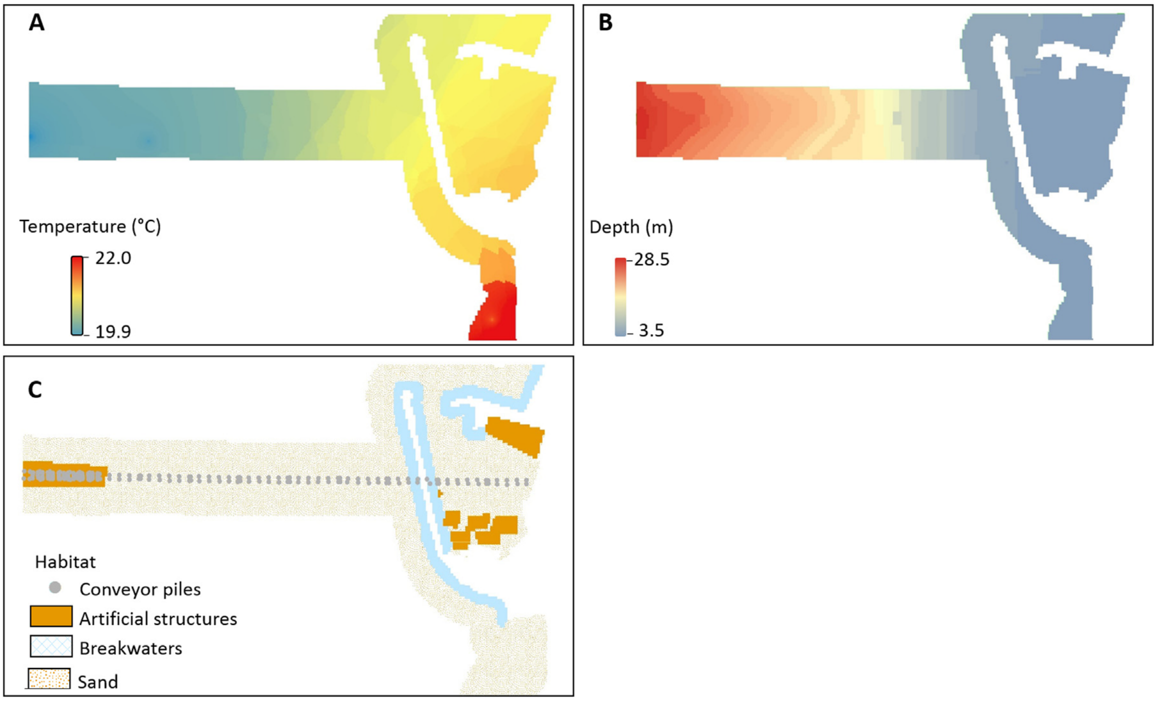

Fig. 2. Depth, temperature and habitat data mapped using ArcGIS 10.2. A. Sea surface temperature (SST) at the Orot Rabin Power Station in April 2016. **B.** Depth at Orot Rabin Power Station. **C.** Habitats in the area of Orot Rabin Power Station as used in Ecospace.

Changes in the biomass of demersal fish B and pelagic fish were used as an indication of the effect of each scenario on the marine environment, because both groups include species characterized by high vulnerability. In addition, the average trophic level, based on the trophic level in each cell of the grid, was used as an ecological indicator, to describe changes to the ecosystem (see [13]). Target groups' biomass changes between the different scenarios were tested using ANOVA. The data were normally distributed and the variances were equal so no data transformation was needed. All statistical analyses were performed using R software [45].

3. Results

3.1. EwE Ecopath model

The food-web flow chart (Fig. 3) is an output from Ecopath and is based on the information used to construct the model. It demonstrates (1) that benthic invertebrates have a significant role in the food web, and (2) that primary producers make up most of the biomass in the area. Demersal fish B and pelagic fish groups were used in our study to estimate the contribution of each scenario to the achievement of marine conservation goals. The flow chart demonstrates the role of these groups as predators situated in a relatively high trophic level and also their significant contribution as a food source for apex predators.

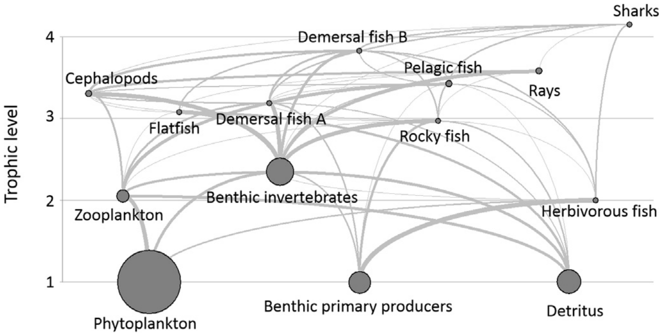

Fig. 3. Flow diagram of the Ecopath model for Orot Rabin Power Station. Circle size and line width are proportional to the group's biomass, and magnitude of the trophic flow, respectively.

3.2. MSP scenarios

The scenarios were assessed in terms of the differences in the biomass of demersal fish B and pelagic fish in each scenario relative to the BAU. Different fishing efforts in each scenario enabled us to estimate the minimal and maximal catch that would result in a decrease, and in an increase, of the biomass of each species-group, respectively. Changes in sport-fishing catch seemed to especially affect the biomass of the pelagic fish group. The maximum values of catch expected to allow an increase in pelagic fish biomass over a period of 15 years is 0.334 t/km^2/y (0.332 t/km^2/y and 0.002 t/km^2/y (for trammel nets and sport fishing, respectively)). The minimum level of catch that would lead to a decrease in pelagic fish biomass over a 15-year period is 0.415 t/km^2/y (0.332 t/km^2/y and 0.083 t/km^2/y (for trammel nets and sport fishing, respectively)). In total, the three scenarios were expected to lead to a similar increase in biomass of the pelagic fish group: the ER alternative with exclusive and with inclusive management strategy; and the ID alternative with exclusive management. The ER alternative with the cooperative management strategy resulted in the largest decrease in fish biomass (Fig. 4).

A fishing catch of 0.334 t/km^2/y (0.332 t/km^2/y and 0.002 t/km^2/y for trammel nets and sport fishing, respectively) was the maximal catch expected to cause an increase in demersal fish B group's biomass. A fishing catch of 0.08 t/km^2/y (0.0664 t/km^2/y and 0.016 t/km^2/y for trammel nets and sport fishing, respectively) was the minimal catch expected to cause a biomass decrease in the group's biomass. The ID alternative with the exclusive management scenario was the only scenario that resulted in a biomass increase of the demersal fish B group, while all other scenarios resulted in biomass decrease of the group (Fig. 5).

Aiming to benefit both species-groups' biomass, the scenario which would provide the greatest biomass increase for both groups was

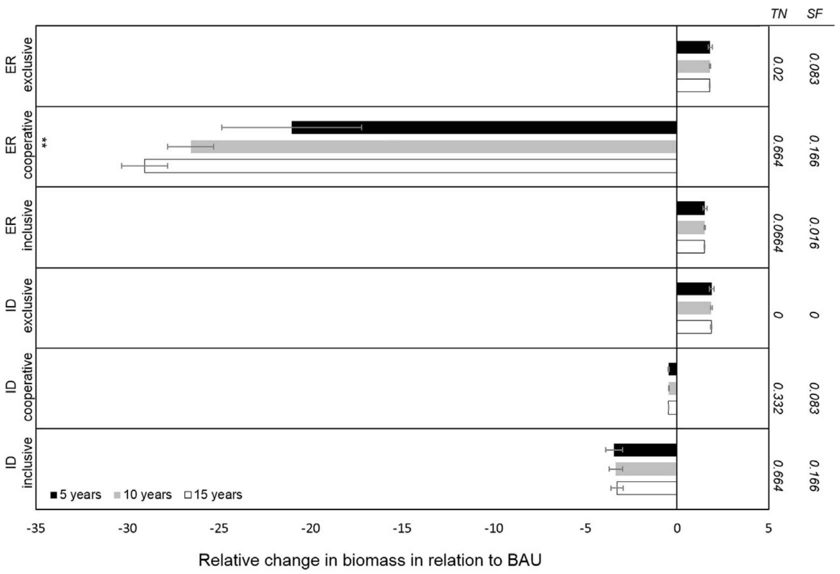

Fig. 4. Monthly average (± S.E.) of pelagic fish relative change in biomass in the different scenarios in relation to the BAU scenario. The fishing catch rate allowed for each fishing type in each scenario is listed above the bars. **TN**- trammel net fishing catch (t/km^2/y). **SF**- sport fishing catch (t/km^2/y).**-scenarios that differed significantly from all other scenarios ($F_{(5,\ 1074)} = 6711$, $P < 0.01$).

determined. The scenario of ID alternative with exclusive management, is the only scenario that is expected to result in an increase in the biomass of both, pelagic fish and demersal fish B (see Figs. 4, 5). The ER alternative with exclusive and inclusive management resulted in a biomass increase of only the pelagic fish, while all other scenarios caused a decrease to both groups' biomass.

Despite the expected biomass increase of demersal and pelagic fish groups, the ID alternative with exclusive management is expected to cause a decrease in zooplankton, flatfish, and herbivorous fish groups' biomass and especially to the benthic invertebrates group, which is expected to demonstrate a biomass increase in all other scenarios. The scenario of ER alternative with cooperative management, which is expected to result in the greatest decrease in the biomass of demersal and pelagic groups is also expected to result in significant decrease in the biomass of cephalopods, flatfish, demersal fish that feed on invertebrates, rays, and sharks. These groups' biomass is expected to decrease to a lesser extent also in the ID alternative with inclusive management scenario.

In addition to effects on species-groups' biomass, the mean trophic level (TL) of the food web was examined, as an indication of the state of the ecosystem. The highest mean TLs were obtained in the scenarios of ID alternative under exclusive management and under cooperative management. All other scenarios resulted in a relatively similar mean TL of the BAU along 15 years (Fig. 6). The spatial pattern of the TL in the area of the power station in all scenarios is presented in Fig. 7. In all scenarios, the highest trophic level was observed around artificial structures, conveyor piles and breakwaters. Fishing restriction affected the spatial distribution of trophic levels more moderately.

4. Discussion

Our prime goal of this study was to examine how food-web models can be integrated into the MSP process to enhance ecosystem-based management and to help achieve marine conservation goals in areas subject to intense human use. Specifically, the use of EwE was explored in MSP that considers conservation opportunities within infrastructure

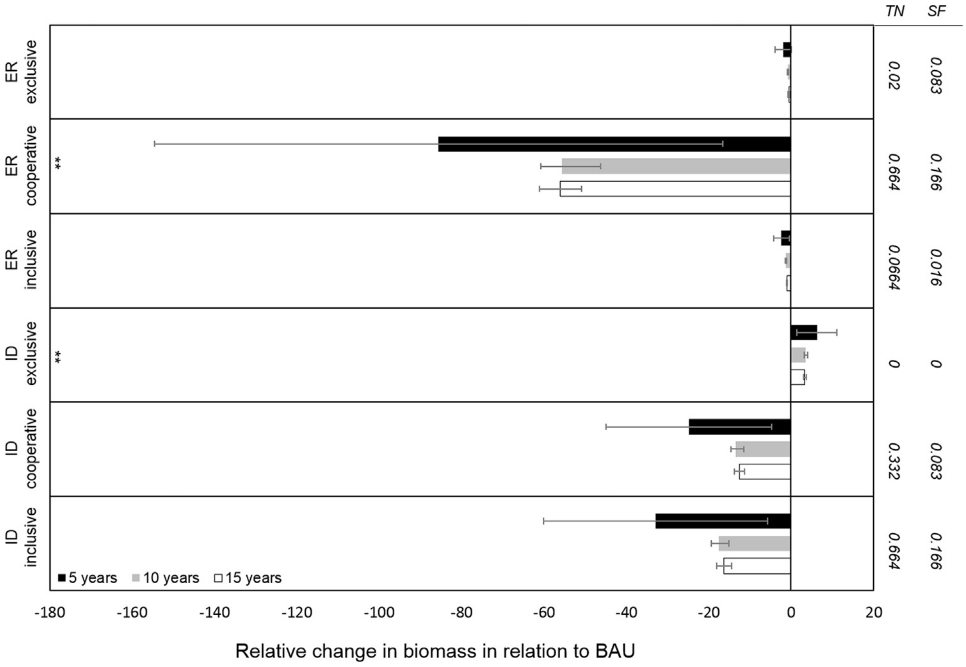

Fig. 5. Monthly average (± S.E.) of demersal fish relative change in biomass in different scenarios in relation to the BAU scenario. The fishing catch rate allowed for each fishing type in each scenario is listed above the bars. **TN**- trammel net fishing catch (t/km^2/y). **SF**- sport fishing catch (t/km^2/y). **-scenarios that differed significantly from all other scenarios after 15 years ($F_{(5,\ 1074)} = 8419$, $P < 0.01$).

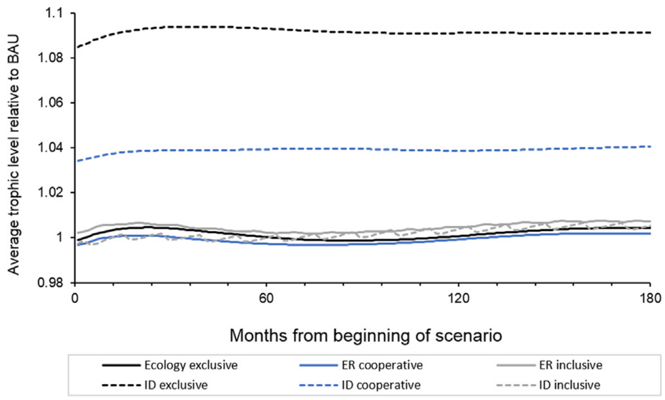

Fig. 6. The relative mean monthly TL in the Orot Rabin Power Station over the entire simulation period (15 years). The values are relative to the BAU scenario.

areas where public access and fishing is limited or prohibited.

The advantage of using quantitative and qualitative decision-support tools in the MSP process to better address environmental issues is well recognized. Coleman et al. [11] describe the possibilities and advantages of using decision-support tools in MSP. They conclude that the ability of these tools to develop and compare alternative scenarios is a major strength. Nonetheless, in this study, the construction of a food-web model required resources such as time, data, and knowledge of the modelling software. Similarly, Pınarbaşı et al. [40] have shown that decision-support tools, including food-web modelling, are being used for the sixth and seventh stages of MSP mostly by scientists and not by planners. Stelzenmüller et al. [50] claim that often, the direct use of decision-support tools for MSP by planners is unlikely, as these tools are highly specialized and are more suitable for use by scientists. Therefore, it appears that the use of EwE in MSP for large regions with multiple users and complex interactions is viable if data and knowledge resources are readily available to the planning team, or if a food-web model already exists for the area in question and is accessible to the planners.

Alternatively, food-web models could be used in planning with fewer resources, to address specific issues, such as determining the benefits of allocating a space for a specific use or exploring the optimal integration of specific uses. Filgueira et al. [21], for example, suggested that ecosystem modelling, specifically physical-biogeochemical models, be used in MSP to optimally locate shellfish aquaculture. More recently, Fretzer [22] suggested that EwE food-web model could be used to assess the environmental impact of terrestrial projects which might have negative impacts on the environment. As a sequel to these findings, the results of the current study demonstrate that food-web modelling can be used in MSP to promote marine conservation goals [46].

In the scenarios examined in this study, an attempt was made to reflect the variable aspects of managing an infrastructure site and region, taking into account the site's primary use and the different sectors involved in its management. Here, the main focus was on the effects of fishing, and substrate type and abundance on the ecosystem. However, food-web models provide means for incorporating many variables, including human activity variables (e.g., [32,52]). These variables would likely be of concern when implementing a marine spatial plan, thus reflecting the human impact on the ecosystem more accurately.

The study presented here demonstrate how EwE, primarily designed as a fisheries management decision-support tool, can be used for other purposes. Yet, acknowledging the divergence from their original purpose, the use of food web models for MSP should be conducted cautiously [31,48]. Therefore, planners wishing to use food-web models to explore conservation options within areas of human activity, should be mindful about: 1) setting response and forcing function types and values to describe affiliation of species to human activities, and, 2) examining areas of a certain human activity which does not fully overlap and represent the whole habitat of a target species [25]. Increased use of food-web models for planning will make it increasingly easier for new projects to rely on data from previous projects, which in turn, may motivate software developers to further adjust the models for use in MSP.

Once the Ecopath model was constructed, Ecospace was successfully used in our case study for the MSP stages listed in Table 1. Spatial alternatives which differed from the existing state were successfully implemented, readily considered and could perform directly in Ecospace, eliminating the need to import them from GIS-based software. Management strategies were readily examined with Ecospace when it included alterations in fishing efforts and fishing restrictions. However, other elements of the management which were not directly related to fishing were more difficult to examine, because they would have required additional changes to the Ecopath model. Theoretically, each aspect of management could be incorporated as a fleet in the Ecopath model or as a driving function in Ecospace. Nonetheless, planners can only examine those management strategies that have been defined and included in the earlier modelling stage.

An additional stage of MSP which could benefit from the use of ecological modelling is the 10th stage, which deals with monitoring and evaluating performance (See [20]). This stage formulates the monitoring scheme that will be used to evaluate the plan and later to adapt the plan and/or management accordingly. The use of decision-support tools for this stage of planning is rare and is mainly conducted by the authorities of specific sectors and not by planners [40]. However, based

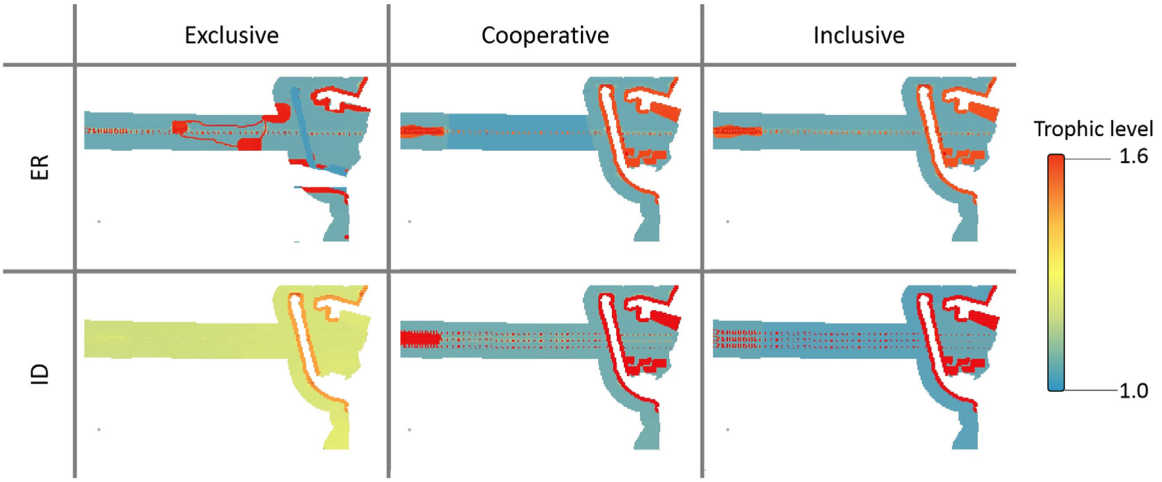

Fig. 7. Spatial distribution of trophic level in the area of Orot Rabin Power Station at the end of the 15-year scenarios.

on the examination of the management scenarios, we note that changes in biomass of groups or species can be examined directly using Ecosim or Ecospace and does not require construction of a new Ecopath model, complex calculations, or indirect conclusions based on other variables. In Ecosim and Ecospace, evaluation of the future state could be compared with expected results, but it could also be incorporated as a time series, to better forecast changes to the ecosystem in future years and to adjust the plan based on unexpected changes to the ecosystem.

The use of the food-web model of Orot Rabin Power Station in our hypothetic planning process enabled us to examine fine changes to the ecosystem, which were caused as a result of spatial and management alterations. The results suggest that the demersal fish B group is highly sensitive to sport fishing, which is currently not practiced in the area. The demersal fish B group includes three species of *Epinephalus* genus that are endangered according to the International Union for Conservation of Nature (IUCN) and hence are targeted for marine conservation efforts along the Israeli Mediterranean coast (see [47]). The results of the model demonstrated that also the pelagic fish group is sensitive to fishing if it were to exceed the catch rate that is currently assumed in the area. It is suggested that the predicted impact of altered fishing rates on the two species-groups indicates that the area of the power station, with its artificial structures and access prohibition, functions as a protective island in a heavily exploited environment [47], and that scenarios in which the management significantly differ from BAU may not contribute to conservation efforts for these groups Using the model made it possible to demonstrate in quantitative terms both the great value that this small area holds for marine conservation and the beneficial effects of its current management. Furthermore, the model demonstrated that even if the area continues to be developed and managed for energy production purposes, these beneficial effects on marine conservation are likely to remain stable.

The use of EwE also revealed the significant impact of management on the ecosystem, demonstrating that in both of the spatial alternatives (ER, and ID), exclusive sector management is expected to be even more beneficial for marine conservation purposes than cooperative management. Cooperative management is promoted in MSP as mitigating and compromising and often results in allocation of multiuse areas [16,18]. In addition, cooperative management may indirectly promote marine conservation through enhancing sectors' commitment to common goals pertaining to marine environmental protection [4,5,10,57]. Yet, the results of this study, suggest that exclusive management of a sector that strictly prohibits fishing in its area succeeds in enhancing the average trophic level of the area and maintaining or increasing biomass of conservation-targeted species. This was observed even in the scenario of exclusive management of the area under intensive development, whereby the prevalence of fouling groups considered detrimental to benthic primary producers and benthic invertebrates (which, as shown in Fig. 3, constitute an important component of the ecosystem) decreased by 50% (see Table 2 and Appendix 1). Therefore, it is suggested that, counterintuitively, exclusive management of a sector, even if not fully committed to marine conservation, may contribute to conservation of specific species. Hence, the planning process should be examined and assessed on a case-to-case basis, which can be done effectively and efficiently using ecological modelling tools, as shown.

5. Conclusions

Food-web models can be successfully incorporated into MSP process. The use of EwE, and specifically Ecospace, the spatial module of EwE, highlights the advantages of incorporating a food-web model into the MSP process. Planners may use food-web models in the sixth and seventh stages of MSP to explore the effects of spatial and management alternatives on the marine ecosystem. Moreover, food-web models can be used in planning, to explore the effect of management on groups targeted for conservation and on other ecological indicators, such as average trophic level in the area of the plan. The use of a food-web model in a MSP process can serve to mitigate the negative impacts of human activity on the marine environment, using quantitative terms to help identify the human activity management strategy that would be most beneficial for the area's ecological conservation. Supporting specific stages in the MSP process through the use of such models may promote science-based and ecosystem-based planning and management. In addition, the use of EwE in this study demonstrates how to perform detailed assessments of the plan's expected impact on the marine environment. However, effective use of this modelling tool for planning purposes requires constant monitoring and subsequent adjustments of the management conditions.

The use of food-web models make it possible to consider and evaluate nearshore marine infrastructures' contribution to marine conservation goals. The use of ecological modelling to examine the effect of infrastructure management on the marine environment can help define (in quantitative terms) the ecological advantages that a particular infrastructure provides, thereby leading to its eventual designation as an environmentally valuable area. Thus, ecological modelling may present marine spatial planners with unexpected opportunities for promoting marine conservation, subsequently resulting in creative spatial distribution of human activities in the seascape.

Food-web models are not, however, 'ready-to-use' tools for planning. Such models do not deliver complete solutions, but rather they are the starting point for deliberation and require resources such as knowledge, data, and time, to be effectively integrated in the planning process. When these resources are scarce, food-web models could be used to examine issues in specific marine infrastructure enclosures, as presented in this study. These tools could be further developed. A valuable addition, for example, would be the incorporation of prioritization features, to allow planners to examine spatial alternatives based on the goals of the plan (e.g., [33]). Such software developments, oriented toward planning or management beyond fishing management, could provide an important contribution to marine conservation.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.marpol.2018.06.018.

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