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Modeling the Effects of a Power Plant Decommissioning on an Estuarine Food Web

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Abstract While a number of studies have looked at the impingement and entrainment impacts of power generation facilities on recreationally and commercially important fish species, few have assessed the effects on forage species or the broader aquatic community. Here, we constructed a trophic-based ecosystem model for the Barnegat Bay, New Jersey estuary, which is home to the Oyster Creek Nuclear Generating Station. Utilizing this model, we developed two scenarios: a baseline scenario for 1981–2030 and a decommissioning scenario where the generating station substantially reduces its water withdrawals beginning in 2020. The effect on the biomass of an individual species tended to be small (<3 %), and the direction of the change varied by species. Trophic interactions played an important role in determining the overall change in a species' biomass, as some species directly impacted by the generating station had a reduced biomass in the decommissioning scenario due to increased predation mortality. The differences in results between the static mixed trophic impact analysis and the dynamic simulation analysis highlight the value of dynamic modeling in assessing management strategies.

Keywords Ecopath with Ecosim · Barnegat Bay · Trophic interactions · Power generation facility

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Introduction

The management of natural resources, particularly in marine systems, has historically occurred on a species or sector level. This single-species approach has had mixed success, with recent analyses suggesting that 61 % of the world's major fish resources are fully fished, 10 % are underfished, and 28 % are overexploited or depleted (FAO 2014). In response to perceived shortcomings in the single-species approach, management agencies began to utilize a multi-species approach in some circumstances, whereby the trophic interactions between a target stock and its prey were taken into account. The assumption was that a reduction in a predator's forage base would lead to reduced productivity of the predator and thus reduced biomass available to the fishery.

While the multi-species approach accounted for single predator-prey dynamics, it was broadly recognized that fish stocks of interest were impacted by more than this simple interaction and that there was a need to consider the effects of the broader environment when managing fisheries (Ecosystem Principles Advisory Panel 1999; Pew Oceans Commission 2003; U.S. Commission on Ocean Policy 2004). This led to the advancement of the concept of ecosystem-based management (EBM), an integrated approach that considers the interaction between ecosystem components and the cumulative impacts of a full range of management activities (Rosenberg and McLeod 2005). The broad definition of EBM thus describes a gradient of interconnectivity, from a focus on multi-species interactions across a range of trophic levels, including some abiotic factors, to a comprehensive view which includes human impacts other than fishing (Dolan et al. 2016).

Aquatic communities are subject to a myriad of anthropogenic influences, both direct and indirect. Indirect human-mediated impacts include alterations in temperature and water chemistry associated with climate change (Harley et al. 2006), changes in salinity due to alterations in freshwater flow (Gillanders and Kingsford 2002), and the ripple effects of increasing nutrient loads (United States Environmental Protection Agency 2006). In addition to the direct removal through commercial and recreational harvest, power generation can also negatively affect aquatic biota. Power generation stations require large volumes of water as part of the generating process or to cool equipment and are therefore often located adjacent to waterbodies from which they can withdraw water (Dempsey 1988). In open-cycle design, water is withdrawn from a waterbody, utilized within the plant, and then discharged into the same or nearby waterbody (Kelso and Milburn 1979). During this process, planktonic larvae and juvenile stages of fish and invertebrates are susceptible to injury or mortality associated with impingement on screens or filters located at the entrance to the plant or via entrainment through the plant's pumps and other equipment (Fletcher 1990; Mayhew et al. 2000; Newbold and Iovanna 2007; Barnthouse 2013).

While estimates of losses due to impingement and entrainment at power generation stations are often calculated as part of the permitting process, they are typically focused on commercially and recreationally important species, dubbed representative important species (Greenwood 2008; Ehrler et al. 2003; Saila et al. 1997; Heimbuch et al. 2007), with fewer studies of species that serve important ecological roles, such as forage fish (but see Summers et al. 1989). Thus, while there are calculations of the impacts of power generation on individual species through production forgone models (Rago 1984; EPRI 2004) or adult equivalency models (Goodyear 1978; Ehrler et al. 2003; Saila et al. 1997; Greenwood 2008), there is little understanding of how these removals impact the broader food web and what these losses mean for species that may not be directly affected by impingement or entrainment. This is of particular interest, given the age of many power generating stations within the USA which are transitioning to closed-loop cooling systems or are being decommissioned.

The effects on aquatic communities of reduced water utilization associated with closed-loop cooling systems or decommissioned generating stations are not well understood. One potential outcome is that those species most impacted by impingement and/or entrainment would increase in abundance as this source of mortality is reduced or removed, as would be predicted by a single-species model. Extending those increases across multiple species would suggest an increase in overall ecosystem biomass as well. However, as previously mentioned, this linear approach does not take inter-species interactions into account. For forage species, reduced impingement and entrainment mortality may be offset by an increase in predation mortality. This increase in predation mortality may be caused by an increase in predator abundance due to their release from impingement and entrainment effects.

In this study, we utilize a widely used trophic-based ecosystem model, Ecopath with Ecosim (Christensen and Walters 2004), to predict changes to an estuarine food web associated with the upcoming decommissioning of a nuclear generating station. We first develop a balanced static model of the estuary and then create a dynamic simulation of the system using 22 years of time series data. The dynamic model is then extended into the future under a *status quo* scenario and a scenario where water withdrawal volumes associated with the nuclear generating station are substantially reduced during the model run. The results of the two model runs are then compared and discussed.

Methods

Study Area

Barnegat Bay is a temperate lagoonal estuary located in central New Jersey, USA (Fig. 1). The estuary stretches nearly 70 km north to south and ranges from 2 to 6 km in width for a total surface area of 279 km^2 (Kennish 2001). With an average depth of 1.5 m, it has a volume of approximately 4.39×10^8 m^3. There are two main sources of tidal exchange: Barnegat Inlet in the center of the estuary and Little Egg Inlet at its southern terminus. A third source of ocean exchange is the manmade Manasquan Canal at the northern end, which connects the bay to the Manasquan River and inlet. The surrounding 1730-km^2 watershed is home to an estimated 580,000 year round residents (US Census Bureau 2012), with a summer population that swells to over one million with the influx of tourists. Land use is a mix of urban and suburban uses in the northeast and along the barrier islands, grading to less sparsely populated forested areas to the south and west (Kennish 2001). Portions of the E.B. Forsythe National Wildlife Refuge and the Pinelands National Reserve are located along the eastern and western sides of the watershed, respectively. The blue crab (*Callinectes sapidus*) fishery is the main commercial fishery within the bay, though there are still remnants of a historic hard clam (*Mercenaria mercenaria*)

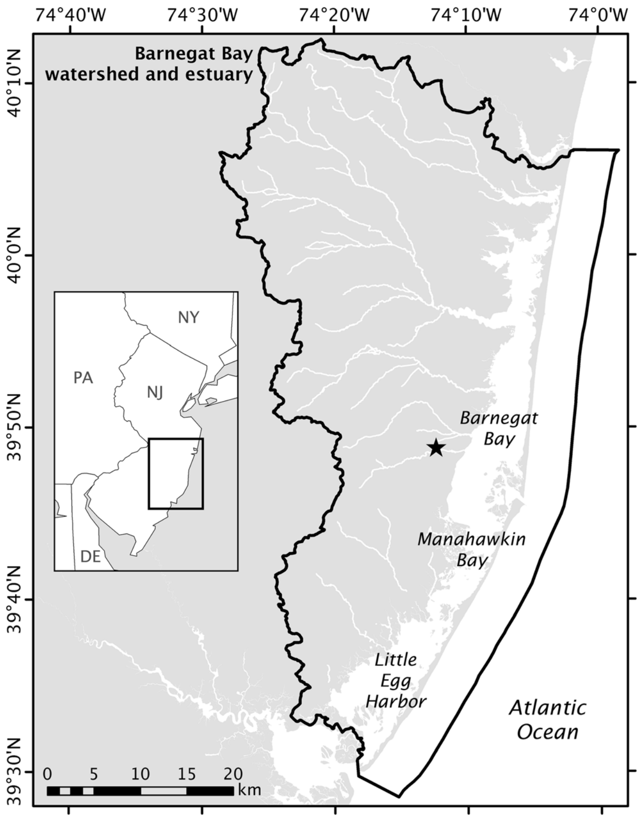


Fig. 1 Map showing the location of the Barnegat Bay estuary system. The location of the Oyster Creek Nuclear Generating Station is denoted by a *star*

fishery that was highly productive in the past (Bricelj et al. 2012). Commercial fishing, once an important source of income for local baymen, is now a minor component of the regional economy (Kennish 2001). The Barnegat Bay is a popular destination for recreational fishing, crabbing, and clamming. The bay suffers from symptoms of eutrophication, mainly due to nutrient enrichment through non-point source pollution (Bricker et al. 2007).

Located in the central portion of Barnegat Bay between Oyster Creek and Forked River is the Oyster Creek Nuclear Generating Station (OCNGS), the nation's oldest continuously operating nuclear power plant (Fig. 1). OCNGS, which commenced operation in 1969, utilizes a once-through cooling system where water is withdrawn from the Forked River and discharged into a canal that flows into Oyster Creek (for details, see Online Resource 3). During normal plant operations, approximately 662 million gallons of water per day (MGD) are withdrawn from Forked River for cooling the main condenser at the facility (CWIS) and an additional 749 MGD are withdrawn from Forked River for diluting the thermal effects of the condenser cooling water (DWIS) (State of New Jersey 2010). Under an Administrative Consent Order (State of New Jersey 2010) agreed upon between the state of New Jersey and the operators of OCNGS, power generation at the facility will cease no later than December 31, 2019.

Ecosystem Model

We developed a trophic model for the Barnegat Bay using the Ecopath with Ecosim 6.4.3 (EwE) software package (Christensen and Pauly 1992; Christensen and Walters 2004). EwE is a well-known program for addressing questions of aquatic ecosystem changes with over 400 trophic mass balance models built for a variety of ecosystems, ranging in size from oceanic basins to small estuaries (Colléter et al. 2015), including other estuaries within the mid-Atlantic region of the USA (Christensen et al. 2009; Frisk et al. 2011). Ecopath is a trophic mass balance analysis program that parameterizes an initial model using two master equations, one to describe the production term for each group:

Production = catch + predation + net migration + biomass accumulation + other mortality and one equation for the energy balance for each group: Consumption = production + respiration + unassimilated food

This base model provides the foundation for the simulation component of EwE, Ecosim, where a series of coupled differential equations are used to simulate biomass dynamics through time, fitting the model to time series reference data and forcing functions entered by the user (Christensen and Walters 2004).

Ecopath requires four groups of basic input parameters to be entered into the model for each of the species (or groups) of interest: diet composition, biomass accumulation, net migration, and catch (for fished species). Three of the following four additional input parameters must also be entered: biomass (in weight per area), production/biomass (P/B, year^{-1}), consumption/biomass (Q/B, year^{-1}), and ecotrophic efficiency, which is the fraction of the production consumed or harvested within the system. The model uses the input data along with algorithms and a routine for matrix inversion to estimate any missing basic parameters so that mass balance is achieved (Christensen et al. 2008). Once the Ecopath model has been balanced the mass-balanced linear equations are then re-expressed as coupled differential equations so that they can be used by the Ecosim module to simulate what happens to the species groups over time (Christensen and Walters 2004). Changes to the groups' biomass or other parameters are based on their response to forcing factors (i.e., environmental drivers, alterations in fishing effort) included by the user. Model runs are compared with time series data, and the closest fit, which minimizes the difference between internally calculated sum of squares values, is chosen to represent the system (see Mackinson et al. 2009 for details on the procedure). Time series data for model calibration are thus essential for developing an Ecosim model (Christensen et al. 2009). Therefore, time series data depicting trends in relative and absolute biomass, fishing effort by gear type, fishing and total mortality rates, and catches for as long a period as possible should be viewed as additional data requirements.

Barnegat Bay Ecopath Model

Our model of the Barnegat Bay ecosystem is comprised of 27 biomass groups, including 12 fish species, five benthic invertebrate groups, two gelatinous zooplankton species, three planktonic groups, two benthic vegetation groups, two shorebird groups, and a detrital pool. A complete description of the sources used to determine the parameter values for each of the biomass groups is available in Online Resource 1, with a summary provided here. Additionally, the model and all supporting data have been uploaded to EcoBase, an open-access repository of EwE models (http://sirs.agrocampus-ouest.fr/EcoBase/).

The Ecopath model was developed in 1981, the earliest year for which reliable catch data for many of the fish species is available and shortly after, a large research initiative in the central portion of Barnegat Bay was completed (Sugihara et al. 1979). For most of the species/groups, P/B and Q/B were taken from published studies of the same species/groups from nearby estuaries. These parameters are fairly consistent across similar ecosystems, though P/B can vary with fishing mortality (Christensen et al. 2008). Standing biomass estimates specific to Barnegat Bay were only available for bay anchovy (*Anchoa mitchilli*, Vougliotis et al. 1987), hard clams (Celestino 2002), and submerged aquatic vegetation (Lathrop et al. 2001). Sea nettle (*Chrysaora quinquecirrha*) biomass for 1981 was estimated by reducing a current biomass estimate by 75 % to reflect the apparent scarcity of sea nettles in the bay at that time (T. Young, pers. comm.). Atlantic croaker (*Micropogonias undulatus*), a common component of contemporary field surveys, was recorded only sporadically in samples collected during the mid and late 1970s (McClain et al. 1976). In order to include this species in the model, its biomass was estimated by the software to balance the requirements of its predators and fishery at their earliest recorded values for Barnegat Bay. The biomasses of the remaining groups were modified from literature values or estimated by the software assuming literature-derived ecotrophic efficiencies (see Online Resource 1 for derivations). The diet data for most of the fish groups are based on a diet study conducted in the Barnegat Bay by Festa et al. (1978), with the diets of the remaining groups taken from literature values or other models (see Online Resource 2 for the initial diet matrix). For predatory fish, when stomach contents were listed as "unidentified fish" or as a species not included in the model, that percentage of the diet was redistributed among the other diet categories in proportion to their prevalence by weight in the identified portion of the diet. As described above, Atlantic croaker was scarce in the Barnegat Bay at the time of the diet study and was not listed as a prey item for any of the piscivorous fish in the model. We know from studies in other nearby systems that when croaker are present, they are a common food source for weakfish (*Cynoscion regalis*), striped bass (*Morone saxatilis*), and bluefish (*Pomatomus saltatrix*) (Nemerson and Able 2004; Frisk et al. 2006; Christensen et al. 2009). Limited predation on Atlantic croaker was therefore added to the initial diet matrix of the model as it is not possible to add them as a prey item during the simulation procedure (Pinnegar et al. 2014). The levels of predation on croaker are based on the consumption rates found in EwE models of the Delaware Bay (Frisk et al. 2006) and Chesapeake Bay (Christensen et al. 2009). Thus, Atlantic croaker biomass in the early years of the model is likely overestimated. We also included harvest data in the model, which is incorporated as the landings (t/km^2/year) for the year in which the model is initiated. The Barnegat Bay model includes gear-specific landings for the blue crab fishery provided by the NJ Bureau of Marine Fisheries and species-specific landings for other fish and invertebrates. The species-specific landings combine the National Oceanic and Atmospheric Administration's recreational landings as recorded in the Marine Recreational Fishing Survey and Marine Recreational Information Program (NOAA 2015a) and commercial landings as recorded by the Fisheries Statistics Division (NOAA 2015b). This large amount of data was reduced through a series of gear and location filters to approximate landings for Barnegat Bay as they are not collected at the estuary level in New Jersey (see Online Resource 1 for the process). To assess the impacts of the OCNGS on the biota of Barnegat Bay we, treated the power plant as a "fishery" to account for the mortality due to the use of bay water for cooling the power plant (Amergen 2008). The power plant is a human-derived source of direct mortality for which we have an estimated annual biomass removal for specific biomass groups and as such can be considered to operate in a similar fashion as a traditional fishery. However, because the mortality caused by OCNGS is not removed from the system as a landing, we modeled it as discards that flow into a detrital pool. The landing values included in the model are in Table 1, with details on their derivations found in Online Resource 3.

The initial values for the input parameters were assessed using the PREBAL routine (Link 2010) to identify issues of model structure and data quality prior to balancing. The diagnostics evaluate the parameter's consistency with general ecological and fishery principals to ensure both theoretical and practical rigor. Each input parameter for each biomass group was also assigned a degree of uncertainty based on the provenance of the data. Taxa-specific data collected within Barnegat Bay is given

Table 1 Basic input parameters for the Barnegat Bay ecosystem model. Catch includes fishery landings and OCNGS discards. Color scale represents the level of confidence in data inputs for biomass, P/B, Q/B, and EE. Estimated from a variety of sources as described in Online Resource 1

Scale
- Sampling based high precision
- Sampling based low precision
- Approximate or indirect method
- Best Professional Judgement
- From other model
- Estimated by Ecopath

Group name	Trophic Level	Biomass (t/km^2)	P/B ($year^{-1}$)	Q/B ($year^{-1}$)	Ecotrophic Efficiency	Catch (t/km^2)
Piscivorous seabirds	4.21	0.250	0.163	120	0.0	
Non-piscivorous seabirds	2.73	0.121	0.511	120	0.0	
Weakfish	3.89	3.969	0.26	3	0.95	0.0383
Striped bass	4.19	1.383	0.4	2.4	0.9	0.00001
Summer flounder	3.95	2.300	0.52	2.6	0.95	0.8067
Bluefish	3.85	2.733	0.52	3.1	0.95	0.750021
Winter flounder	3.09	4.661	0.52	3.4	0.95	0.93205
Atlantic silversides	3.15	4.461	0.8	4	0.95	0.0248
Atlantic croaker	3.22	0.179	0.916	4.2	0.9	0.01311
Spot	3.17	0.561	0.9	6.2	0.9	0.00398
Atlantic menhaden	2.77	12.427	0.5	31.42	0.95	0.058616
River herring	3.39	1.180	0.75	8.4	0.95	0.004322
Mummichog	2.78	3.465	1.2	3.65	0.95	0.000001
Bay anchovy	3.41	4.86	3	9.7	0.839	0.0112
Benthic infauna/epifauna	2.10	77.425	2	10	0.9	
Amphipods	2	3.323	3.8	19	0.9	
Blue crab	2.93	6.257	1.21	4	0.95	1.4406
Hard clams	2	26.18	0.5	5.1	0.629	
Oyster	2	0.001	0.63	2	0	
Copepods	2.72	12.485	25	83.33	0.95	
Microzooplankton	2	6.694	140	350	0.95	
Sea nettles	4.15	0.345	13	20	0	
Ctenophores	3.47	5.29	16.2	35	0.042	
Benthic algae	1	3.533	80		0.899	
Phytoplantkon	1	21.273	160		0.95	
SAV	1	5.82	5.11		0.317	
Detritus	1	1			0.132	

the highest pedigree (lowest uncertainty), followed by species-specific sampling from other systems, literature-derived values, best professional judgment, and finally parameters estimated by Ecopath. We then balanced the model by changing values for those parameters with the highest degree of uncertainty based on the data pedigree.

Barnegat Bay Ecosim Model

Baseline Model

With balancing complete, we then incorporated time series data to model ecosystem dynamics for the period 1981–

2013. Fishery-dependent time series data were used to force changes in the Ecosim module (see Online Resource 4 for a complete listing and their derivations). Because time series data must be continuous to be used to drive the model, we used catch time series data for commercial and recreational finfish landings from nine stocks (NOAA 2015a; NOAA 2015b). Another common source of data for ecosystem models is formal stock assessments, which utilize similar time series data for single-species management. Currently, there are no stock assessments specific to Barnegat Bay. While there is no formal stock assessment for blue crab, the NJ Bureau of Marine Fisheries does collect commercial blue crab landing data by gear and location. This data was used to create gear-specific time series, which consisted of the ratio of the landings in a given year to the initial year's landings, and used to force the model. It should be noted that the NJ blue crab landing data collection in Barnegat Bay began in 1995, so data from 1981 to 1994 are estimated from NMFS statewide landings based on a regression of the Barnegat Bay data against statewide landings over the same period. The final source of Barnegat Bay-specific fishery-dependent time series data comes from OCNGS. Because of the nature of OCNGS operations, the cooling and dilution intake structures function nearly continuously, with the only shutdowns associated with temporary, short-term maintenance. As such, the plant water withdrawal has been fairly consistent over the time frame in question, and therefore, the impacts of the plant have been modeled as a steady effort.

A total of 38 fishery-independent time series were used to assess the model fit. Again, there are limited repeated assessments of biota specific to Barnegat Bay; however, to assess the model fit, it is not necessary to have records for each year in the time series. Thus, we used a combination of fishery-independent surveys spanning a variety of time frames to determine how well our model reflects changes in the ecosystem (see Online Resource 4 for a complete listing and their derivations). Available data included a Rutgers University Marine Field Station long-term otter trawl survey (1995–2013; Vasslides et al. 2011), hard clam surveys conducted by the NJ Department of Environmental Protection (NJDEP) in 1986/1987, 2001, and 2011 (Celestino 2002; Celestino 2013), and short-term (2011–2013) surveys for benthic infauna (Taghon et al. unpublished data), copepods, and microzooplankton (Howson et al. unpublished data). The only consistent time series directly available for primary producers is for submerged aquatic vegetation (SAV). SAV coverage for the bay is available for 1980, 1987, 1999, 2003, and 2009 based on aerial photograph analysis in Lathrop et al. (2001) and Lathrop and Haag (2011). The acreage of seagrass in each year serves as a datapoint of relative abundance, though this method can mask declines in overall biomass due to changes in density or condition. A shorter time series (2008–2013) of relative abundance of phytoplankton bay-wide was estimated from chlorophyll *a* readings taken via aircraft remote sensing. An a priori determination was made that some of the sampling methods could not be relied upon to provide a reliable time series of relative abundance for select species (e.g. *Fundulus heteroclitus* in bottom trawls), and these time series were not used in the model fitting.

An additional source of fish time series data incorporated into the model is an index of biomass generated from the nearshore trawl surveys conducted each fall by the NJDEP. While sampling for this survey occurs along the New Jersey coast adjacent to Barnegat Bay, it provides an estimate of relative biomass in each year for those species that leave the estuary each fall for offshore or southern waters.

The vulnerability values for certain groups were also modified from the default value. Vulnerability is a term in the consumption equation for Ecosim that enables the modeler to specify how trophic flows of biomass are controlled (Walters et al. 2000). The model system may be more predator-controlled (top-down) or prey-controlled (bottom-up). The vulnerability term of the consumption equation for a given predator-prey interaction determines the level of predation mortality for the prey that results from a large increase in predator biomass (Walters and Juanes 1993) and is based in foraging arena theory (Ahrens et al. 2012). Vulnerability values range from 1 to infinity, with a default value of $v = 2$. A low vulnerability value means that a large increase in predator biomass causes a small change in predation mortality for a given prey group. Conversely, a high vulnerability value means that a large increase in predator biomass causes a similarly large change in predation mortality for a given prey group. A high vulnerability value results in model behavior that more closely follows the Lotka-Volterra form. Vulnerability values were estimated for only those groups with a time series of at least 3 years through the automated "fit to time series" algorithm, which seeks to minimize the sum of squares difference between the observed and modeled results. The "Search groups with time series" option was utilized, and a single vulnerability was assigned for each predator-prey interaction within a predator group. The vulnerability values for sea nettles and Atlantic croaker were both adjusted to reflect the known increases in biomass of those groups within the modeled time period. The vulnerabilities for 14 predator groups were adjusted, with the remaining vulnerability values set at the default value, $v = 2$. In practice, adjustments to the vulnerability parameter improve the model fit to data and help explain some of the variability in the data.

The Monte Carlo approach was used to test for sensitivity of Ecosim's outputs to Ecopath input parameters. Mean, lower limit, and upper limit of the distribution used to draw random values for key input parameters (B, P/B, and ecotrophic efficiency) for each group in the model were determined based on the model pedigree. The software made 100 random draws from range of possible input values, determined whether the set of parameters resulted in a balanced model, then ran the Ecosim simulation based on the new randomly selected parameters. The output from the Monte Carlo simulations was plotted (biomass over time for each group) and visually inspected to determine if temporal patterns in group biomasses were consistent or divergent. Consistent patterns suggest that although some underlying uncertainty in the input parameters for the model exists, the conclusions about factors influencing those patterns are robust.

Confidence intervals were developed for the percent change in biomass for each group under the baseline and test scenario. The percent change in biomass for each group was calculated for each of the 100 Monte Carlo trials and then ordered. The 5th and 95th ranked trails were then selected to provide the upper and lower 90 % confidence intervals. The overlap, or lack thereof, of the confidence intervals for each group between the baseline and test scenarios were then evaluated to determine if the test scenario lead to significant changes.

Oyster Creek Nuclear Generating Station closure scenario

After the baseline Ecosim scenario was fit to the available time series data, the model can be extended to make predictions about the future state of the ecosystem under different management strategies. To assess potential ecosystem changes associated with the cessation of power generation at OCNGS by 2020, we developed two scenarios. Under the baseline scenario, all of the time series forcing data for 2013 were extended until 2030, including the OCNGS "fishing" effort. Under the OCNGS closure scenario, all of the time series forcing data from 2013 are extended until 2030, except the plant's fishing effort, which is reduced to 4 % of the full operating capacity from 2020 to 2030.

Ecosystem Metrics

The trophic structure of the ecosystem was described using a graphical representation, which documents the flow of energy between individual groups. Within Ecopath, producer groups are assigned a trophic level of 1 while consumers are given a trophic level of 1 + (the weighted average of their prey's trophic level) (Christensen et al. 2008). The direct and indirect effects that a small change in biomass of one group (or fishery effort) will have on the biomass of the other groups can be evaluated through the mixed trophic impact (MTI) analysis, which is based on the approach developed by Ulanowicz and Puccia (1990). We evaluated the MTI of OCNGS at model initialization and again in 2019, the year prior to OCNGS decommissioning.

Results

Barnegat Bay Ecopath Model

The static model shown in Fig. 2 represents a balanced model of the trophic connections within Barnegat Bay in 1981 with the groups arranged by trophic level. Changes to the initial input parameters in order to balance the model were primarily limited to adjustments to the diet matrix, particularly for non-fish groups, which tended to be from published studies from different locations, and to weakfish and striped bass, to account for ontogenic shifts in diet preferences (see Online Resource 2). The need to adjust input values was further moderated by the fact that biomass for many of the groups was estimated internally within EwE, which allowed for a greater degree of flexibility. The final parameter values and their pedigrees are given in Table 1.

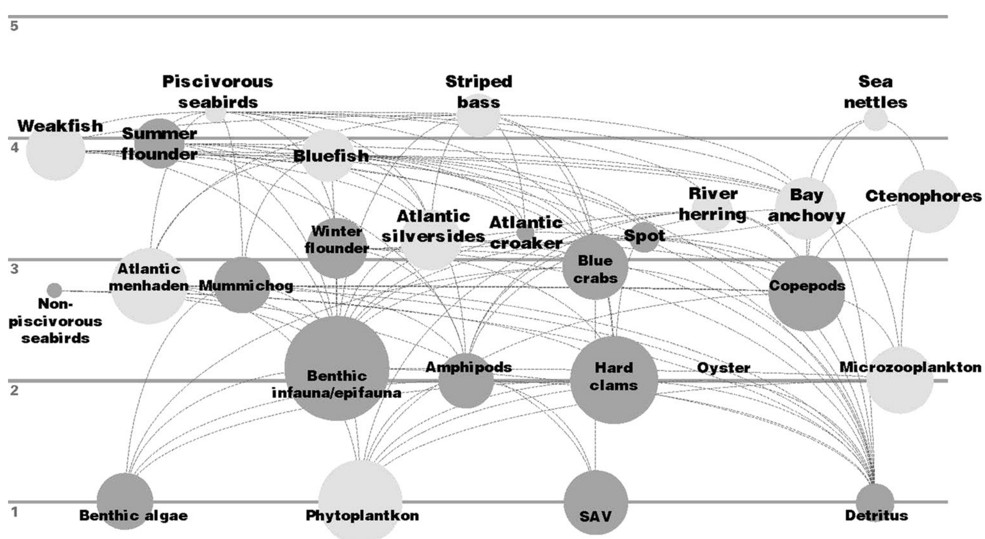


Fig. 2 Barnegat Bay ecosystem model in 1981. *Numbered horizontal lines* indicate trophic level. The *size of the circle* indicates relative biomass, while the *lines* indicate energy flow from one group to another

The MTI analysis (Fig. 3) suggests that the direct and indirect impacts of OCNGS are negligible when compared to the effects associated with inter-species trophic interactions. While OCNGS had both positive (spot (*Leiostomus xanthurus*) = 0.015397) and negative (weakfish = −0.01772, Atlantic croaker = −0.07719) impacts in the initial model year, they were an order of magnitude smaller than the impact of the strongest effects calculated for the other groups. In 2019, the year prior to the simulated closure, the relative size of the OCNGS effects remains small (0.013881 to −0.02098). However, OCNGS now has a net positive effect on Atlantic croaker (0.003549).

Barnegat Bay Ecosim Model

When the time series data are incorporated into the model and the vulnerability values are adjusted to fit the time series, the overall fit of the model prediction to the available data is reasonable, and the model behaves within reasonable bounds. The model fitting procedure improved the sum of squares scores from 817.4 to 720.2. There is variability in how well the predicted biomass trends match the available time series data among the groups (Fig. 4). For winter flounder, summer flounder, Atlantic croaker, and blue crab, the overall trends in biomass are captured by the model, but annual fluctuations are not well represented. In contrast, the decline in hard clams that occurred during the early part of the time period is not captured in the model.

When we ran 100 Monte Carlo simulations utilizing the pedigree values set during the Ecopath model construction, the current model was the best fit. For the remainder of the trials, the biomass trends were similar, though the relative abundance varied between simulations.

Oyster Creek Nuclear Generating Station Closure Scenario

The total system biomass summed for 2020–2030 under the baseline scenario was 2637.04 t/km^2, compared to 2637.45 t/km^2 for the same time frame under the OCNGS closure scenario. While the change in overall biomass was small, the effect on the biomass of individual groups varied, though never by more than 3 % (Fig. 5). Of the groups directly impacted by OCNGS impingement and entrainment, Atlantic croaker has the greatest response associated with the plant closure, decreasing in biomass by nearly 2.5 % compared to the baseline simulation. Weakfish and blue crab both see a greater than 1.5 % increase in biomass under this scenario. Changes in

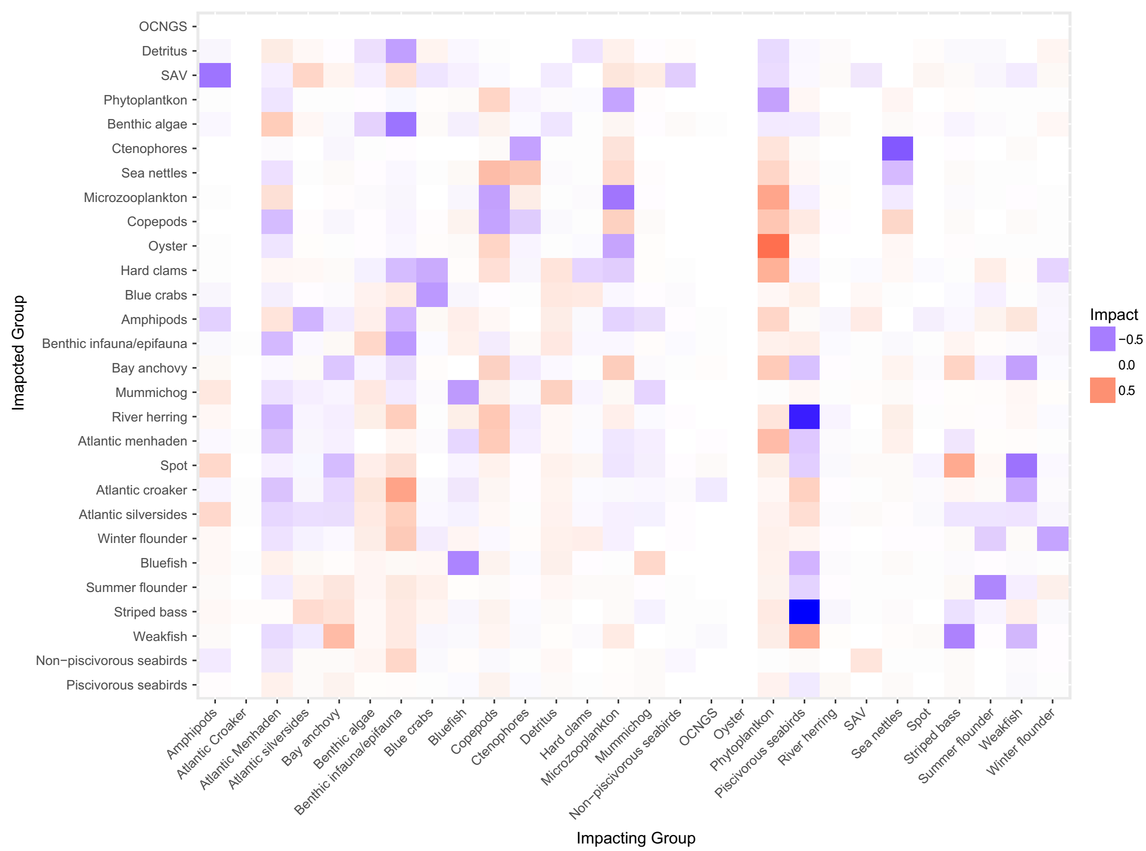


Fig. 3 Mixed trophic impact (MTI) analysis showing direct and indirect impacts. *Red blocks* show a positive impact, *blue blocks* a negative impact. The values are not considered absolute but are comparable between groups

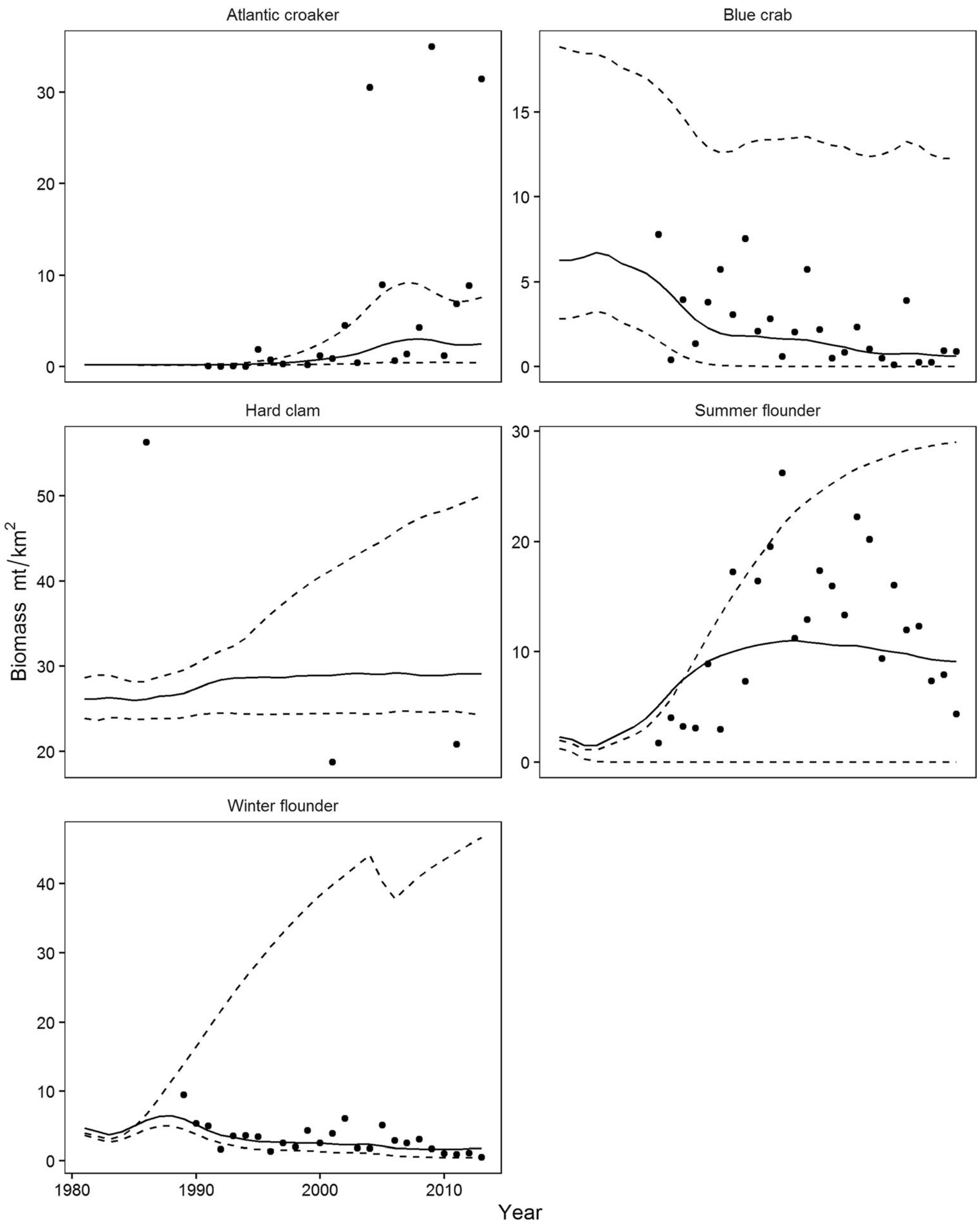


Fig. 4 Relative abundance (*filled circles*), fitted-model predicted biomass (*solid lines*), and model predicted maximum and minimum biomass (*dashed lines*) for 5 of the 27 biomass groups in Barnegat Bay Ecosim model: Atlantic croaker, blue crab, hard clam, summer flounder, and winter flounder. The groups' individual contributions to the total sum of squares were 67.34, 24.74, 0.886, 8.575, and 7.296, respectively

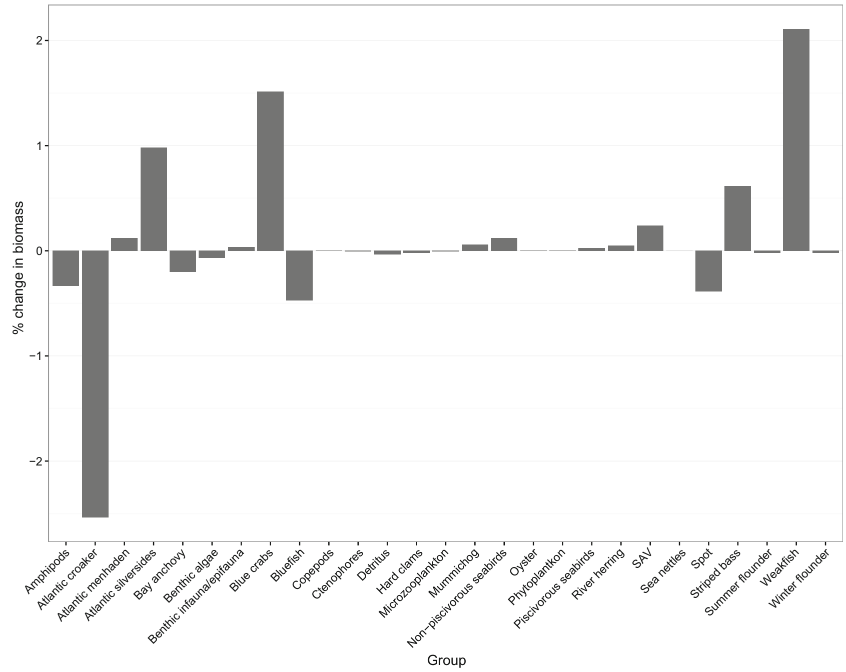
biomass to groups not directly impacted by OCNGS were smaller in magnitude, with only striped bass having a change greater than 0.5 %. Evaluation of the Monte Carlo trials suggests that closure of the OCNGS does not lead to a change in biomass for any group significantly different than that seen under the baseline scenario.

Discussion

As power generating plants around the world age and are decommissioned or replaced with improved environmentally protective technologies, there will potentially be impacts to the aquatic ecosystems that provide cooling water for their operation and receive process water. Here, we developed an ecosystem model that describes potential changes in an estuarine community following the decommissioning of a nuclear generating station with a once-through cooling system. While we are not the first to include the effects of a power generating station within an EwE model (Lobry et al. 2008), we are the first to use the Ecosim module to predict how altering a power generating plant's water use will impact the ecosystem as a whole.

Our results indicate that indirect effects mediated through trophic interactions may be more substantive, and of opposite direction, than what would be expected from a single-species approach. Atlantic croaker in our system is a prime example. Based solely on the impingement and entrainment impact studies conducted by the plant, one would expect Atlantic croaker to benefit from

Fig. 5 Percent change in biomass between the OCNGS closure simulation and the baseline simulation in 2030



the reduced mortality associated with the plant's decommissioning. However, weakfish, which is one of the most important predators of Atlantic croaker, is predicted to increase in biomass as a result of reduced mortality from the OCNGS. Our model predicts that the net effect on Atlantic croaker biomass in Barnegat Bay will be a slight decline compared to a no-change scenario due to increased predation mortality.

Comparison of the results of the dynamic simulations with the static mass balance model highlights the value of simulation. The results of the scenario modeling are different from what would be expected given the MTI analysis, particularly for the initial year of the model. The negative impact of OCNGS on Atlantic croaker in the initial model year should translate into additional croaker biomass if the OCNGS effort is reduced, which contradicts the results of the Ecosim scenario. However, the MTI analysis for the year immediately prior to the OCNGS decommissioning suggests a positive impact on croaker associated with the plant operations, which is consistent with the results of the Ecosim scenario. Thus, at some point during the modeled time frame, the dominant impact of OCNGS on croaker switched from direct mortality to indirect effects associated with their predators. As noted by Christensen et al. (2008), MTI analysis is not amenable to making predictions of what will happen in the future given changes in interaction terms specifically because changes in abundance may lead to changes in diet composition and that is not accommodated within this routine. This switching behavior reinforces the desirability of using the Ecosim module to assess the potential indirect effects of non-trophic-related activities compared with assumptions of a steady-state system.

The trophic level at which the effects of the power generating station are most visible in our model is higher than those of other models. Lobry et al.'s (2008) results based on MTI analysis suggest that the primary effects of a nuclear generating station in the Gironde estuary of France were on intermediate trophic level (TL) species (TL range 2.03–3.25). In our study, the species impacted by OCNGS ranged in trophic level from 2.93 for blue crab to 3.89 for weakfish. Our higher trophic level impacts are driven by a combination of direct power plant mortality on early life history stages of predators as well as indirect effects through a reduction in biomass of their prey. In comparison, the main upper trophic level species in the Gironde model enter the estuary as juveniles or adults and likely do not experience the same level of power plant-related mortality (Lobry et al. 2003). Thus, impacts of power generating stations on aquatic biota may be system specific and related to the presence of vulnerable early life stages of predator and prey fishes.

The limited availability of data specific to Barnegat Bay led to compromises in the overall structure of the model. For instance, all of the biomass groups within the model are represented by a single age stanza. For many of the species/groups, this is unimportant as their role in the food web does not depend on life history, i.e., phytoplankton, zooplankton, benthic invertebrates, and SAV. However, for species for which we wish to investigate management actions or where there may be ontogenic shifts in diet preferences, age-structured stanzas provide increased resolution into the interactions in question. As pointed out above, mortality associated with impingement and entrainment at OCNGS occurs primarily to early life history stages of the taxa within the system, and separating that from juvenile and adult mortality would reduce uncertainty within the model. Of course, this increased level of resolution requires ever increasing amounts of data to populate the input parameters. The current single stanza model appears to capture the overall trends in biomass (where available) reasonably well and is thus useful for investigating questions of ecosystem functioning and exploring scenario development.

In addition to the direct impacts to fish communities associated with losses due to impingement and entrainment, power generating stations can impact aquatic resources through the release of heated cooling water into the environment (Homer 1976; Jones et al. 1996; Teixeira et al. 2009). In temperate climates, this heated water can be an attractant to fish during the winter months and can raise ambient temperatures above thermal thresholds during summer months. The EwE software package includes the ability to assign an optimal temperature and temperature range for each biomass group that influences their feeding rate. It follows that reduced feeding rates would lead to decreased fitness and reduced biomass. We did not evaluate the thermal effects of the OCNGS decommissioning on the aquatic resources of Barnegat Bay as the warm water plume associated with the plant is limited in its spatial extent to immediately adjacent to the mouth of Oyster Creek (Z. Defne, pers. comm.), though any future spatially explicit model of the bay may wish to include it.

It should be noted that the outcomes of management scenarios are only as reliable as the data used to construct them. The OCNGS fishery data had to be extensively manipulated (Online Resource 3) to expand the reported mortality from numbers of individuals to weights, particularly for entrainment losses. The methodology used to determine impingement and entrainment losses and mortality in the Amergen (2008) report were slightly modified from those of earlier studies at OCNGS (EA Engineering, Science, and Technology Inc. 1986), which were the subject of a critical external peer review (Summers et al. 1989). In addition, there was a change in intake protection structures, and thus mortality rates, between the start of our model and the 2008 mortality study. Thus, the OCNGS removals used here are a likely conservative estimate.

One of the main benefits of this type of holistic model is the ability to develop and evaluate a number of potential management scenarios from an ecosystem-wide perspective. This approach can lead to some surprising findings, as was seen in the OCNGS decommissioning scenario. Understanding how changes in anthropogenic activities interact with natural process to alter multiple components within an ecosystem will allow resource managers to better assess the impacts of proposed undertakings and hopefully lead to more resilient and sustainable systems.

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