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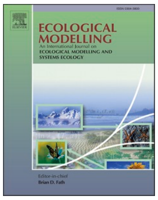

Proof-of-concept model for exploring the impacts of microplastics accumulation in the Maryland coastal bays ecosystem

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ABSTRACT

With increased global production of plastics since the 1950s, marine environments have experienced an increase in plastic pollution. This pollution has the potential to contaminate marine organisms with microplastics, which, in turn, may have deleterious effects on humans that consume seafood. Plastic pollution is often presented as a global issue; however, its sources are often based on local actions and potential health effects occur at an individual level. Environmental management to control this problem also can occur on a local scale. To draw attention to the issue and demonstrate the need to take management actions to reduce plastic inflow, we have developed a proof-of-concept model that connects inflow of plastic in a small-scale marine environment to a contaminants-based food web model. We use Ecotracer in the Ecopath with Ecosim modeling suite to estimate current organism concentrations of microplastics and then use model outputs to calculate human health effects. The model is used to project future microplastic concentrations in marine organisms and human health effects under different environmental plastic inflow rate scenarios. The model is parameterized to simulate the Maryland Coastal Bays ecosystem, which is adjacent to Ocean City, Maryland (USA) a region dependent on the tourism and seafood industries. We consider this a proof-of-concept model, because data for the system are limited. This approach helps to illustrate local consequences of a global problem. In addition, it provides a summary of pertinent regional data on the issues and helps identify gaps for future monitoring and research.

1. Introduction

Global plastic production has emerged with heightened importance since the 1950s with production increasing from 2 million tonnes (Mt) in 1950 to over 380 Mt, currently (Geyer et al., 2017). Uses range from single use food packaging to children's toys to synthetic textiles (Boucher and Billard, 2019). With this mass production of plastic, new pollutant issues arise, such as plastic contamination in marine environments. In 2010 alone, more than 8 million metric tons of plastic entered the ocean (National Oceanic and Atmospheric Administration, 2020a). As these plastics break down, they retain their polymer composition as microplastics, which are defined as plastic particles that are less than 5 mm in size (National Oceanic and Atmospheric Administration, 2020b). Microplastics are of increasing concern as they are unable to degrade quickly and completely in marine environments and are emerging pollutants of concern to both aquatic and terrestrial ecosystems (Alimba and Faggio, 2019; Gallo et al., 2018; Thompson, 2004). In turn, aquatic ecosystem organisms are at risk to being entangled in plastic debris, suffocating on smaller pieces, or accumulating such particles in their guts thereby reducing the availability for nourishment (Guzzetti et al., 2018; Santillo et al., 2017; Welden and Cowie, 2016). They also have the potential to absorb toxic compounds like polychlorinated biphenyls (PCBs), perfluoroalkyl substances (PFASs), polycyclic aromatic hydrocarbons (PAHs), antibiotics, and other persistent organic pollutants (POPs) (Andrady, 2011; Li et al., 2018; Llorca et al., 2018; Sørensen et al., 2020; Velzeboer et al., 2014). As such, microplastics have the potential to cause deleterious effects on the marine organisms that consume them, ultimately transferring microplastics and any associated contaminants to each trophic level and, in turn, to people who consume plastic-contaminated food.

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Though microplastic pollution is often reported as a global concern, its cause is often based in local and individual actions (e.g., litter on beaches and streets, through local water treatment facilities) (Vince and Hardesty, 2017). A recent report by the Joint Group of Experts on Scientific Aspects of Marine Protection indicates that "people's perceptions and behaviours contribute to the problem but are also crucial in any solutions suggested" (GESAMP, 2015); however, surveys indicate that microplastic pollution is not perceived as a major problem in the marine environment. Seafood consumption is a major risk pathway for human exposure to microplastics (Smith et al., 2018). In coastal communities, residents and tourists value local seafood that is safe from pollutants, thus connecting local actions that cause microplastic pollution to local outcomes for seafood safety may help in drawing attention to the issue and in implementing solutions (Jodice and Norman, 2020). To that end, we developed a model that connects environmental sources of microplastic pollution to seafood consumption through a regional food web model. Ocean City, Maryland (USA) invests heavily in and generates considerable tax revenue from tourism (Maryland Tourism Development Board and Maryland Department of Commerce, 2017). Ocean City is adjacent to the Maryland Coastal Bays, which serve as a source of local seafood and fishing opportunities for the region.

The Maryland Coastal Bays (MCBs) are an ecosystem susceptible to emerging environmental pressures like microplastics. The MCBs consist of five watersheds and encompass one of the most ecologically diverse estuaries on the eastern coast of the United States (Maryland Coastal Bays Program, 2020). The MCBs are home to several commercially important species as well as 108 rare, endangered, and threatened species, marking this region as a critical ecosystem (Maryland Coastal Bays Program, 2020). The MCBs ecosystem consists of primary producers like macroalgae, Submerged Aquatic Vegetation (SAV), and phytoplankton. Lower trophic level species include epibenthic invertebrates, *epi*/infauna, copepods, Blue Crab (*Callinectus sapidus*), and Atlantic Menhaden (*Brevoortia tyrannus*). Upper trophic level species include forage fish, benthic/demersal fish, planktivorous fish, Ctenophores, Bay Anchovy (*Anchoa mitchilli*), Summer Flounder (*Paralichthys dentatus*), Spot (*Leiostomus xanthurus*), Black Sea Bass (*Centropristis striata*), Weakfish (*Cynoscion regalis*), Terrapin, and piscivorous fish. The MCBs is also home to over 360 bird species. The high diversity in this region is related to the shallow water habitats that provide food as well as breeding and overwintering habitats for waterbirds (Maryland Department of Natural Resources, 2016). Colonial nesting waterbirds such as herons, egrets, gulls, skimmers, pelicans, and terns utilize the MCBs watershed for habitat. Snow geese, Canada geese, American Black Duck, Mallard and Bufflehead are just a few of the most abundant migratory waterbirds that use the MCBs as overwintering habitats (Maryland Department of Natural Resources, 2016). Local commercial and recreational fisheries are a large part of this ecosystem as well. The most abundant fisheries fleets for the MCBs include Blue Crab, Summer Flounder, Atlantic Menhaden, and Spot.

However, with the rise of economic development and human population growth, the MCBs show signs of stress with populations of aquatic wildlife already degraded (Maryland Coastal Bays Program, 2018). Also, due to its shallow depths and limited inlets to the ocean, the MCBs are capable of retaining microplastics and other aquatic contaminants due to poor estuarine flushing (Wazniak et al., 2005). Consequently, MCBs commercially important species, like Blue Crab and Summer Flounder, have the capability to consume increased concentrations of microplastics compared to species in open ocean environments (Wu et al., 2020) . Rare, endangered, and threatened species are greatly affected by microplastic accumulation and could in turn reduce the successes of recent recovery efforts (Plough et al., 2021; Valdivia et al., 2019). In some recovery plans for endangered species of the sea turtle – Kemp's Ridley (*Lepidochelys kempii*), loggerhead (*Caretta caretta*), green (*Chelonia mydas*), and leatherback (*Dermochelys coriacea*) – microplastics and other marine debris are one of the highest priority threats for their survival and recovery (Stephen Guertin, 2019). As there is no data on microplastic concentrations in the MCBs, and the concentrations of microplastics within each of the MCB organisms are not known at the present, an ecosystem model can help to address these unknowns and evaluate reasonable concentration predictions for the MCBs species. Fig. 1.

As the trophic pathways of the MCBs trophic groups are known, specific patterns of microplastic bioaccumulation can be estimated using an ecosystem-based modeling approach, such as Ecopath with Ecosim (EwE). EwE incorporates data points from multiple aspects of food web dynamics to provide a holistic view of an ecosystem (Christensen and Walters, 2004). EwE contains three main modules that provide mass balance analysis and dynamic modeling capabilities over time: Ecopath, Ecosim, and Ecospace. An additional module, Ecotracer, is capable of tracking contaminant concentrations in the environment and biota over time and has been used in several studies to trace mercury, ^{137}Cesium, PCBs, PAHs, and other radionuclides through marine ecosystems (Booth and Zeller, 2005; Booth et al., 2020; McGill et al., 2017; Larsen et al., 2016; Tierney et al., 2017). In this end, the Ecotracer software could be used to model the flow of contaminants, like microplastics, through the trophic levels and its accumulation within species.

Humans may be greatly affected by the microplastic accumulation in the aquatic species groups. Commercially important species, like Adult Blue Crab, Black Sea Bass, Summer Flounder, and Bluefish (*Pomatomus saltatrix*), are readily caught, prepared, sold, shipped, and consumed in this region. Atlantic Menhaden is also a commercially important species as it is used in the production of Omega 3 fish oil supplements sold nationwide. Microplastics, although commonly found in the digestive tracts of aquatic species, are capable of translocating into the gills, the tissues, and the circulatory system of these species (Smith et al., 2018). This allows these smaller plastics to enter the human food stream. Additionally, bivalves and small fish that are eaten whole are of great concern to the human diet as all of the accumulated microplastic could transfer to humans (Smith et al., 2018).

The objective of this study was to use the Ecotracer module of the EwE software to create a proof-of-concept model to simulate the flow of microplastic contamination through the MCB estuarine food web under varying conditions. We modeled the flow of plastics in the ecosystem

Fig. 1. Map of the Maryland Coastal Bays (MCBs). Retrieved from the Maryland Coastal Bays Program.

using a four-step process: (1) Parameterize the Ecotracer module, (2) Evaluate the model's applicability to the system, (3) Simulate current conditions (1990–2017), and (4) Simulate future potential conditions based on environmental plastic inflow rate scenarios. Simulations were run forward in time to determine the accumulation within species under different plastic inflow scenarios by modifying initial concentrations and environmental flow rates. Human Dietary Intake (HDI) of microplastic was also calculated based on microplastic accumulation within the aquatic species. The results of this study would better inform management on key species likely to be contaminated with microplastic debris in the MCBs, as well as possible pathways for microplastics to enter human food streams. As this is a proof-of-concept model, it is not designed for tactical management decision-making but rather as a strategic framework to inform environmental managers of the likely connections between plastic pollution in the coastal environment and of the potential impacts on both the food web and humans. This framework can be used to help managers decide on future research and monitoring to improve the model and better address the potential impacts of microplastic pollution in the system.

2. Materials and methods

2.1. Study system

The MCBs consist of five ecologically diverse estuaries, and represents the most species diverse region in Maryland, and supports several commercially important species (Maryland Coastal Bays Program, 2020). With two inlets for tidal exchange, flushing the MCBs is extremely slow thereby allowing nutrients and contaminants to accumulate in the MCBs rather than disperse to the Atlantic Ocean (Wazniak et al., 2005). The MCBs are susceptible to human population growth and economic expansion and show signs of stress with degraded aquatic populations.

2.2. Ecosystem modelling

The Ecopath with Ecosim (EwE) software has three main modules: Ecopath, Ecosim, and Ecospace. The Ecopath module provides a snapshot of an ecosystem that is in mass balance and can be used for trophic interaction analysis (Christensen and Walters, 2004). Its master equations relate the production of a species or group of species to its consumption, and can also include biomass accumulation, immigration, and emigration (Walters and Christensen, 2018). Ecosim is a time-dynamic simulation tool that can show ecosystem change, using time series of changes such as fisheries mortality or, importantly here, environmental contaminant changes (Christensen and Walters, 2004; Walters and Christensen, 2018). Ecospace is used to model spatial-temporal dynamics including groups' biomasses or contaminant concentrations on a defined grid map by applying Ecosim equations to individual grid cells (Christensen and Walters, 2004). It can be used to visualize the placement of local marine protected areas and the impact of this protection (Walters and Christensen, 2018) or to analyze the impact of fisheries management actions on a marine ecosystem over time (Couce Montero et al., 2021). The limitation to this module is that it requires a large data set that is not always available for a region. Because of data limitations, this module has not been applied for this proof-of-concept module.

Ecotracer is an additional module within EwE which models contaminant concentrations in the environment and biological groups (Christensen and Walters, 2004; Walters and Christensen, 2018). Ecotracer, using the time dynamics of Ecosim or Ecospace, highlights groups within the aquatic food web that are more affected by contaminant accumulation and details the pathway of contaminant transfer between the trophic levels (Christensen and Walters, 2004). While Ecosim biomass dynamic equations are solved over time, Ecotracer tracks the movement and accumulation of food web contaminants in parallel (Christensen and Walters, 2004). The Ecotracer module simulates the gains of contaminant into the biota from the environment via direct uptake, through uptake from food, and the concentration in immigrant biomass, against the losses of contaminant from the biota, through predation, non-predation mortality, emigration, metabolism, and contaminant decay (Christensen and Walters, 2004; Walters and Christensen, 2018).

More information on these modules, including their respective equations can be found in Supplementary Material.

2.3. Ecopath and Ecosim model

The Ecopath model used in this study was adapted from Rubalcava et al. (submitted). A brief summary of the model is presented here. The model was mass balanced by fulfilling two equations that relate production to consumption (Christensen and Walters, 2004; Christensen et al., 2005). It was then tuned to a calibration data set (time series of biomass indices on trophic groups). Forcing functions represent environmental factors that can affect interactions of trophic species in a food web (Christensen et al., 2005). In our model, fishing effort, primary production, and environmental time series data were used as drivers and forcing functions in the Ecosim modules. The calibration period for the model was 1990–2017 and the scenario period was 2018–2090. These time frames were also used for calibration and scenario analysis of the Ecotracer model.

The Ecopath model contains 21 aquatic species groups representing the MCB ecosystem in 1990, the first year of available data (Fig. 2). The input data used for the model came from local surveys and nearby estuaries with similar ecological characteristics. Specifically, the biomass inputs for the functional groups were estimated from the Maryland Department of Natural Resources (MD DNR) through their Coastal Bays Fisheries Investigation (CBFI) Trawl and Beach Seine Survey. Other input parameters including production/biomass (P/B) ratios, consumption/biomass (Q/B) ratios and total mortality (/year) were borrowed from a well-known nearby estuary, Chesapeake Bay (Christensen et al. 2009) or previous models built of the MCBs (Black, 2009).

Species were grouped into functional groups based on similar life history traits and on availability of data from the MD DNR trawl and seine survey. Specifically, the species in the Piscivorous fishes functional group included bluefish (*Pomatomus saltatrix*), crevalle jack (*Caranx hippos*), atlantic needlefish (*Strongylura marina*), scup (*Stenotomus chrysops*) and spotted hake (*Urophycis regia*). Forage fish transient functional group contained white mullet *(Mugil curema*), Northern kingfish (*Menticirrhus saxatilis*), Inshore lizardfish (*Synodus foetens*), Pinfish (*Lagodon rhomboides*), Northern puffer (Sphoeroides maculatus), Northern pipefish (*Syngnathus fuscus*), and the Northern searobin (*Prionotus carolinus*). The forage fish resident functional group includes mummichog (*Fundulus heteroclitus*), white perch (*Morone americana*), American eel (*Anguilla rostrata*), oyster toadfish (*Opsanus tau*), green goby (*Microgobius thalassinus*), and rainwater killifish (*Lucania parva*). Benthic/demersal fish group is comprised of winter flounder (*Pseudopleuronectes americanus*), Atlantic croaker (*Micropogonias undulatus*), Hogchoker (*Trinectes maculatus*), Smallmouth flounder (*Etropus microstomus*), and Black drum (*Pogonias cromis*). The planktivorous fish functional group includes Atlantic silverside (*Menidia menidia*), striped anchovy (*Anchoa hepsetus*), Alewife (*Alosa pseudoharengus*), Rough silverside (*Membras martinica*), blueback herring (*Alosa aestivalis*), Atlantic herring (*Clupea harengus*), butterfish (*Peprilus triacanthus*), and striped killifish (*Fundulus majalis*). Epibenthic invertebrates functional group comprises of grass shrimp (*Palaemonetes pugio*), sand shrimp (*Crangon septemspinosa*), brown shrimp (*Farfantepenaeus aztecus*), mud crab (*Paneopus* spp.), hermit crab (*Pagurus* spp.), spider crab (*Libinia emarginata*), lady crab (*Ovalipes ocellatus*), horseshoe crab (*Limulus polyphemus*), and mantis shrimp (*Squilla empusa*). Finally, the *epi*/infauna functional group contains Forbes sea star (*Asterias forbesi*) and hairy sea cucumbers (*Sclerodactyla briareus*). Species including Blue crab, black sea bass, Bay anchovy, spot, and summer flounder stood alone in the

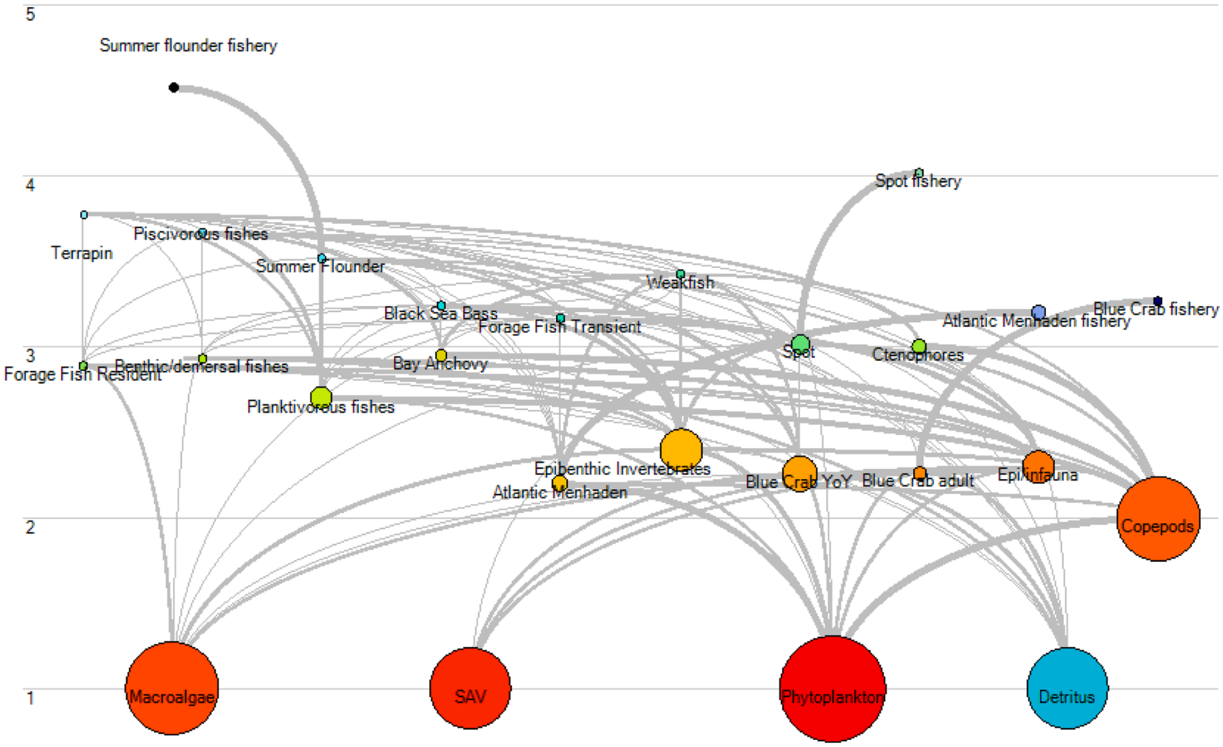

Fig. 2. Food web of the Maryland Coastal Bays (MCBs). The size of the circle represents biomass and the lines represent energy flow.

model because they are focal species for fisheries or a forage fish and enough data for input parameters for these species was available. Blue crab is broken down into multi-stanza groups because adequate data were available from the MD DNR trawl and seine surveys. Diet data for the Ecopath model is based on diet studies conducted in the region as well as literature. The commercial landings data for the four fleets (Blue Crab, summer flounder, spot and Atlantic menhaden) were obtained from MD DNR. They have available commercial fishery data from the early 1990s that was used as input data for the model.

The Ecopath model was established with a base year of 1990, so that the Ecosim module could be used and fitted to time series data, and vulnerability parameters estimated. Vulnerability was estimated using the auto-fitting procedure built into Ecosim (Christensen and Walters, 2004). As this is a proof-of-concept model for demonstration purposes, thorough investigation of model fit was limited to testing a few forcing functions with *a priori* expectations that they would influence fit. If this model were to be further developed for tactical management advice, a more thorough and systematic analysis of model fit would be warranted.

The 1990 Ecopath model was made time-dynamic in Ecosim by fitting the model to observed biomass time series data. The time series was obtained from the MD DNR through their trawl and seine survey that has been conducted since 1990 in the MCBs. Biomass was estimated for each functional group based on the catch-per-tow data from the survey from 1990 to 2017. To drive fishing related changes in the ecosystem, fishing effort was modeled by using rescaled catch data from MD DNR.

The primary production forcing function used in the Ecosim model was created from a Chlorophyll a index that was applied to the phytoplankton group. The Chlorophyll a time series was scaled to the 1990 value, the rescaled value was then used as a multiplier for the phytoplankton production. Chlorophyll a concentrations are measured (monthly or bimonthly) at 74 sites in the MCBs by the MD DNR Continuous Monitoring Program (CMP) (Eyes on the Bay, n.d.). The median value is calculated to create the Chlorophyll a index (EcoHealth Report Card, n.d.).

Environmental forcing functions were created using temperature and salinity data from the CMP. Median values were used for the forcing functions. Environmental responses for trophic groups were developed from literature values of preferred temperatures and salinities for the species - or the major species for aggregate groups.

The modeled biomass time series was fit to biomass time series indices using the “Fit to time series” tool. This procedure was set up to adjust groupwise vulnerability parameters in Ecosim. The vulnerability parameter modifies the consumption rate in the simulation (Christensen et al., 2005). Combinations of primary production and environmental forcing functions were tested to determine which external drivers had an appreciable influence on the production of the trophic groups – i.e., improved the fit to biomass indices. The final model included a primary production forcing function, a salinity forcing function applied to weakfish and blue crab (YoY and adult), and a temperature environmental forcing function applied to piscivorous fishes, weakfish, Atlantic menhaden and Blue crab (YoY and adult). Also, the sum of squared deviations (SS) for the best fitted time series was 167 with an Akaike information criteria (AIC) of −403.1. Further manual adjustment of the vulnerability parameter produced the final model used for the Ecotracer simulations.

2.4. Ecotracer modelling

2.4.1. Parameters

We used Ecotracer to model the trophic transfer of microplastics and their subsequent accumulation within each of the aquatic groups. In this study, we used the Ecotracer module with the time dynamics of Ecosim, rather than Ecospace due to data deficiency and this being a proof-of-concept model. Ecotracer requires four input parameters: (a) initial pool concentrations of some biotic trophic groups, including environmental concentration; (b) direct uptake parameters as rates per time per biomass per species; (c) concentrations per biomass in immigrating biomass; and (d) metabolism and decay rates of the contaminant for each biotic species. Overall, Ecotracer uses these parameters to track the flow of the contaminant through the biological organism groups and the environment.

2.4.2. Inputs

2.4.2.1. Biota inputs

2.4.2.1.1. Initial concentrations. Initial concentrations of microplastics for each trophic group were compiled from a variety of sources. Sources were either from the MCBs area, the broader Chesapeake Bay area, estuaries or similar systems, open ocean systems, or laboratory and synthetic systems. In order to quantify the quality of the input data, a ranking system was used with data from the MCBs scoring 1, the Chesapeake Bay area scoring 2, estuarine and similar systems scoring 3, open ocean systems scoring 4, and laboratory and synthetic systems scoring 5 (Table 1). The initial concentrations were adjusted to appropriate units by considering 65% of microplastic particles being fibers (length 500–1000 um) and 35% beads/spherules (length $<$ 500 um; average 350 um). Using this approach enabled us to have initial values for each trophic level, and to assess the quality of the input data, similar to using the pedigree index of Ecopath. Furthermore, we deemed that these values were suitable to test the ability of Ecotracer to trace microplastics in the underlying Ecopath model.

The basis for the increase of microplastics in the MCB are based on changes seen in the accumulation of microplastics in aquatic species from around the world. In one study, the consumption of plastics by North Sea fulmars (*Fulmaris glacialis*) had increased in 2010 from 1975 to 1990 by between two and three-fold (van Franeker and Law, 2015). We assume that the increase in accumulation in fulmars corresponds to an increased availability of microplastics in the environment. Additionally, a study on freshwater fish in Chicago found that microplastic concentration increased from between 1.5 particles/fish to 2.0 particles/fish in 1990 to between 3 particles/fish to 5 particles/fish in 2018 (Hou et al., 2021). This corresponds to an increase between two and three-fold as well. Finally, a systematic review of plastic ingestion in marine fish worldwide found that plastic ingestion rates increased by 2.4 ± 0.4% per year after 2010 (Savoca et al., 2021). This also correlates to both of the other study's rates.

Therefore, we hypothesize that the MCBs have had a tripling of microplastics over a thirty-year time period, as an upper approximation. Therefore, we reduced the current concentrations reported in the literature to 30% of their value to be indicative of the initial conditions in the MCB for 1990. We then ran simulations from 1990 forward in time with the tripling effect to reflect our estimate of the amount of microplastics in the MCB in 2017.

2.4.2.1.2. Direct absorption rates. From the literature review, direct absorption rate trends were recorded and entered into the model. Macroalgae, submerged aquatic vegetation (SAV), and phytoplankton all contributed to their microplastic concentrations via biofilm formation and entrapment of microplastics floating through the MCBs water or through plastic settling on the bottom of the MCBs. Macroalgae, SAV, and phytoplankton were assigned direct absorption rates of 1.440, 0.090, and 1.200, respectively (Booth et al., 2020; Walters and Christensen, 2018).

2.4.2.1.3. Proportion of contaminant excreted. The standard excretion rate used for most aquatic trophic groups was 0.35 to represent small molecule ($<$100 um) excretion ability and 0.50 to represent small molecule and medium molecule (100 um–500 um) excretion ability (Table 2) (Hoss and Settle, 1990; Sherr et al., 2017).

2.4.2.1.4. Other data points. Physical and metabolic decay rates were set to zero as microplastics do not readily decompose in aquatic organisms. Concentration in immigrating biomass and base volume

Table 1

Estimated initial and observed final trophic group microplastic concentrations and data sources. Pedigree of the ranking of trophic group microplastic data. Ranking key 1 = local MCBs data, 2 = Chesapeake Bay data, 3 = Estuary or similar system data, 4 = Open ocean data, 5 = Laboratory or synthetic system data.

Group name	Estimated initial concentration - 1990 (t/t)	Observed final concentration - 2017 (t/t)	Ranking of group microplastic data	Study
Trophic level 4				
Terrapin	1.00×10^{-7}	3.33×10^{-7}	4	(Healy et al., 2019); (Geggel, 2020)
Piscivorous fishes	1.27×10^{-10}	4.24×10^{-10}	4	(Bellas et al., 2016; Calderon et al., 2019; Neves et al., 2015; Pegado et al., 2018; Roch et al., 2019)
Summer flounder	2.68×10^{-9}	8.93×10^{-9}	3	(Bessa et al., 2018; McGoran et al., 2017)
Black sea bass	2.12×10^{-9}	7.06×10^{-9}	2	(Murphy et al., 2019)
Forage fish transient	7.92×10^{-10}	2.64×10^{-9}	3	Payton, 2017
Weakfish	7.10×10^{-11}	2.37×10^{-10}	3	(Ferreira et al., 2016)
Trophic level 3				
Spot	3.31×10^{-9}	1.10×10^{-8}	3	Payton, 2017
Forage fish resident	3.15×10^{-10}	1.05×10^{-9}	3	(Au, 2017; Stewart et al., 2018)
Ctenophores	1.65×10^{-10}	5.49×10^{-10}	5	(Chesapeake Bay Program, 2020; Sherr et al., 2017; Sun et al., 2016)
Benthic/demersal fishes	2.68×10^{-9}	8.93×10^{-9}	3	Payton, 2017
Planktivorous fishes	1.46×10^{-8}	4.85×10^{-8}	3,4	(De-la-Torre et al., 2019; Hammer et al., 2016; Ryan et al., 2019)
Bay anchovy	1.83×10^{-9}	6.10×10^{-9}	3	(Lefebvre et al., 2019; Renzi et al., 2019; Tanaka and Takada, 2016)
Trophic level 2				
Atlantic menhaden	2.06×10^{-7}	6.86×10^{-7}	3	Payton et al. 2020
Epibenthic invertebrates	6.56×10^{-9}	2.19×10^{-8}	3	(Devriese et al., 2015; Gray and Weinstein, 2017; Waite et al., 2018)
Blue crab YoY	2.97×10^{-8}	9.91×10^{-8}	3	(Renzi et al., 2020; Waddell et al., 2020)
Blue crab adult	1.43×10^{-8}	4.78×10^{-8}	3	(Renzi et al., 2020; Waddell et al., 2020)
Epi/infauna	1.70×10^{-8}	5.67×10^{-8}	2,3	(Fang et al., 2018; Graham and Thompson, 2009; Murphy et al., 2019; Williams, 2019)
Copepods	3.99×10^{-4}	1.33×10^{-3}	5	(Desforges et al., 2015; Omori, 1969)
Trophic level 1				
Macroalgae	8.11×10^{-6}	2.70×10^{-5}	1,3,5	(Morales-Núñez and Chigbu, 2019; Sundbæk et al., 2018)
SAV	5.83×10^{-6}	1.94×10^{-5}	2	(Murphy et al., 2019; Robinson et al., 2019)
Phytoplankton	3.88×10^{-6}	1.29×10^{-5}	4	(Cole et al., 2013; Rodriguez and Mullin, 1986)
Detritus	7.65×10^{-7}	2.55×10^{-6}	3	(Graham and Thompson, 2009)
Environment	3.33×10^{-7}	1.11×10^{-6}	1,2,3	(Maryland Department of the Environment, 2014; Mason et al., 2016; Yonkos et al., 2014)

Table 2
Contaminant proportion excretion for consumer groups in the model.

Group Name	Prop of contaminant excreted
Terrapin	0.50
Piscivorous fishes	0.80
Summer flounder	0.50
Black sea bass	0.50
Forage fish transient	0.50
Weakfish	0.50
Spot	0.50
Forage fish resident	0.50
Ctenophores	0.80
Benthic/demersal fishes	0.35
Planktivorous fishes	0.35
Bay anchovy	0.35
Atlantic menhaden	0.80
Epibenthic invertebrates	0.35
Blue crab YoY	0.35
Blue crab adult	0.35
Epi/infauna	0.35
Copepods	0.90
Macroalgae	0
SAV	0
Phytoplankton	0
Detritus	0
Environment	N/A

exchange loss were also set to zero.

2.4.2.2. Environmental input data

2.4.2.2.1. Initial concentration. The initial concentration was set to 3.33×10^{-7} t/km^2 from values found in Yonkos et al. (2014). The initial concentration used the same assumption as for aquatic species. The current literature value was reduced to 30% of its value to represent the 1990s value.

2.4.2.2.2. Base inflow rate. We used the amount of Wastewater Treatment Plant (WWTP) effluent released to the MCBs of ~40 million liters per day (Maryland Department of the Environment, 2014) combined with an estimate of an input of 1.51×10^9 microplastic particles/year (Mason et al., 2016) to derive the current Base Inflow Rate (BIR). We used WWTP data as billions of microplastic particles are released by WWTPs into waterways every day (Mason et al., 2016). We reduced the current BIR to 30% of its value to reflect the 1990s BIRs of microplastics.

2.4.2.2.3. Environmental decay rate. Environmental Decay Rate was set to 0.232 per year due to potential photodegradation of plastic compounds in the shallow waters of the MCBs (Zhu et al., 2020).

2.4.3. Forcing functions

In order to simulate changing environmental plastic inflow rates, we created environmental inflow forcing functions. The environmental inflow forcing functions change the environmental inflow rate to account for the tripling of microplastics in the environment every 30 years and to create new projected environmental plastic inflow scenarios.

2.5. Plastic inflow forecasting scenarios

Using the calibrated model, we investigated three environmental plastic inflow scenarios (Increasing Trend, Reduced Inflow, and Zero Inflow) to determine the microplastic accumulation response of each organismal group. The forecasting simulation period was from 2018 to 2090. The scenarios are summarized in Table 3. These scenarios include constant future fishing effort and constant primary production. There are no other environmental drivers that may affect the future ecosystem results.

Table 3
Definitions of the three environmental plastic inflow scenarios and their purposes.

Scenario name	Increasing inflow	Reduced inflow	Zero inflow
Definition	Inflow rate triples every thirty years	Inflow rate decreases linearly over time to 1990 inflow rate	Inflow rate decreases linearly over time to zero inflow rate
Purpose	Visualizes future increase in plastic pollution with no change in plastic inflow	Visualizes future decline in plastic pollution with some reduction in plastic inflow	Visualizes future decline in plastic pollution with extreme reduction in plastic inflow

2.6. Human health impact

Human Dietary Intake (HDI) of microplastic accumulation in aquatic species was modeled by equations adapted from Booth & Zeller (2005). It was calculated by multiplying the grams of seafood consumed per day (R) by the concentration of microplastic within the organism in ug/g (C).

$$HDI = \Sigma RC$$

The absolute concentration values were used from the simulated runs in this study. The FDA Advice About Eating Fish page was used to determine the dietary intake of each fish (Center for Food Safety and Applied Nutrition, 2020a). The recommended maximum servings of each fish species per week were used to calculate the grams of seafood consumed per day values.

3. Results

3.1. Calibration

Absolute microplastic concentration was shown to increase rapidly over time with the tripling trend with most species having an increase of 1–2 orders of magnitude. Root Mean Squared Logarithmic Error (RMSLE) was used to analyze the error of the system (Table 4), and the overall model has a RMSLE of 0.000278. Without the outlier species group, copepods, the RMSLE is 1.93×10^{-5}. This indicates that there are significant differences in some species between the reported literature values and model estimates, with the model concentrations generally being less than those calculated from literature values.

Like the starting concentrations, species in the lower trophic levels have greater concentrations of microplastics than species in upper trophic levels. All species increased in microplastic concentration except for weakfish, which experienced a biomass decrease in 2017, thereby decreasing the microplastic abundance accumulated as well. Commercially important species also saw high increases of microplastic concentration.

3.2. Data ranking results

We used a ranking score to analyze the quality of the data used in constructing our model. The overall score was 3.2. Species groups in Trophic Level 1 had an average rank of 3.0. Groups in Trophic Level 2 had an average rank of 3.3. Groups in Trophic Level 3 had an average rank of 3.4. Finally, species groups in Trophic Level 4 had an average rank of 3.2. With a rank between 3.0 and 3.4 for all Trophic Levels and the overall score, the data most corresponds to estuary or similar system data.

3.3. Environmental plastic inflow forecasting scenarios

The Increasing Inflow trend saw great increases in microplastics

Table 4
2017 Concentrations: literature calculated vs model estimate.

2017 Concentrations	Literature calculated value	Model estimate	Root mean squared logarithmic error
Terrapin	3.33×10^{-7}	1.02×10^{-8}	3.23×10^{-7}
Piscivorous fishes	4.24×10^{-10}	1.01×10^{-7}	1.01×10^{-7}
Summer flounder	8.93×10^{-9}	4.95×10^{-8}	4.06×10^{-8}
Black sea bass	7.06×10^{-9}	1.71×10^{-8}	1.00×10^{-8}
Forage fish transient	2.64×10^{-9}	8.48×10^{-8}	8.22×10^{-8}
Weakfish	2.37×10^{-10}	9.99×10^{-12}	2.27×10^{-10}
Spot	1.10×10^{-8}	9.15×10^{-6}	9.14×10^{-6}
Forage fish resident	1.05×10^{-9}	1.17×10^{-8}	1.06×10^{-8}
Ctenophores	5.49×10^{-10}	1.00×10^{-6}	10.00×10^{-7}
Benthic/demersal fishes	8.93×10^{-9}	2.40×10^{-8}	1.51×10^{-8}
Planktivorous fishes	4.85×10^{-8}	8.31×10^{-7}	7.82×10^{-7}
Bay anchovy	6.10×10^{-9}	7.07×10^{-8}	6.46×10^{-8}
Atlantic menhaden	6.86×10^{-7}	1.75×10^{-7}	5.11×10^{-7}
Epibenthic invertebrates	2.19×10^{-8}	2.34×10^{-6}	2.32×10^{-6}
Blue crab YoY	9.91×10^{-8}	1.80×10^{-7}	8.09×10^{-8}
Blue crab adult	4.78×10^{-8}	1.40×10^{-6}	1.35×10^{-6}
Epi/infauna	5.67×10^{-8}	8.21×10^{-7}	7.64×10^{-7}
Copepods	1.33×10^{-3}	6.81×10^{-7}	0.0013
Macroalgae	2.70×10^{-5}	1.52×10^{-5}	1.18×10^{-5}
SAV	1.94×10^{-5}	1.16×10^{-5}	7.80×10^{-6}
Phytoplankton	1.29×10^{-5}	3.66×10^{-6}	9.24×10^{-6}
Detritus	2.55×10^{-6}	3.81×10^{-6}	1.26×10^{-6}
Environment	1.11×10^{-6}	8.93×10^{-5}	8.82×10^{-5}

concentrations during the simulation period. Adult Blue Crab increased by over 1132%. Other commercially important species saw greatly increased concentrations: Piscivorous Fishes (362%), Summer Flounder (384%), Black Sea Bass (418%), and Atlantic Menhaden (209%). The highest trophic level and the lowest trophic level groups saw the greatest increase in microplastic concentration from 1990 to 2090.

When implementing the two plastic inflow scenarios, both reduction scenarios saw a decrease in microplastic concentrations (Table 5). The Reduced Inflow scenario saw a lesser decrease than the Zero Inflow scenario. In all species, both of the plastic inflow scenarios reduced the concentration of microplastics compared to the 2017 concentrations. The Reduced Inflow scenario decreased the microplastic accumulation in species by an average of 86%. The Zero Inflow scenario decreased the microplastic accumulation in species by an average of 96%. For both of these scenarios, the smallest decrease occurred in the Piscivorous Fishes group, and the greatest decrease was in the Phytoplankton group. The commercially important species saw improvements in their microplastic concentrations (Table 5 and Fig. 3). With the environmental plastic inflow scenarios, Adult Blue Crab reduced its 2090 projected concentration from 1.72×10^{-5} (Increasing Inflow) to 2.56×10^{-6} (Reduced Inflow) or 7.78×10^{-7} (Zero Inflow) (Fig. 4).

Table 5
Percent change of microplastic concentration with each environmental plastic inflow scenario for commercially important species from 2017 to 2090.

Trophic group	Increasing inflow increase (%)	Reduced inflow decrease (%)	Zero inflow decrease (%)
Piscivorous fishes	362	−85	−95
Summer flounder	384	−85	−96
Black sea bass	418	−85	−96
Atlantic menhaden	209	−86	−96
Blue crab adult	1132	−85	−95

The HDI of microplastics from the commercially important species in 2090 was modeled with and without a change in plastic inflow (Table 6 and Table 7). With no change in microplastic inflow or changes in dietary preferences and if the tripling trend continues, people in 2090 could be consuming microplastics concentrations between 1.08 ug/day in Atlantic Menhaden when consuming 2000 mg fish oil tablets, to 835.92 ug/day from the consumption of Adult Blue Crab. With the two reduction scenarios in place, these values decrease by over 95%. A human consuming Atlantic Menhaden fish oil tablets and Adult Blue Crab could instead consume 0.15 and 124.42 ug/day, respectively, from the 1.08 and 835.92 ug/day if there was no change in environmental plastic inflow.

4. Discussion

Many studies have assessed the accumulation of microplastics in aquatic organisms (i.e. Diepens and Koelmans, 2018; Ma and You, 2021). This study investigates the future impact of microplastic accumulation in aquatic species of different trophic levels with three environmental plastic inflow scenarios in the setting of the MCBs. As local data on microplastics needed to parameterize Ecotracer are sparse and not necessarily indicative of the actual conditions in the MCBs, this study should be considered a proof-of-concept model. That is, the model is useful for: (1) organizing data and knowledge about microplastics in the MCBs ecosystem; (2) providing information on potential human health effects; and (3) it can be used to draw attention to the issue and provide a framework for organizing new data and research on the system. However, additional work would be needed before the model is suitable for being used to provide environmental management decisions.

For this model to be used for management, some data deficiencies would need to be overcome. Our ranking score implies that there could be a substantial improvement when incorporating more local data. As there is very little aquatic microplastics data for the MCBs, our data also includes data from the Chesapeake Bay, estuarine and similar systems, the open ocean, and laboratory and synthetic systems. Most of the data came from estuarine and similar systems, thereby making the model not entirely representative of the MCBs, but as the data was from similar nearby systems, the results with MCB-specific data would likely produce results in similar ranges. This is why we consider that the model can be used for demonstration purposes, as it does not have the reliability and local data necessary to accurately inform managers and researchers of exact microplastic accumulation in the MCBs species present in this ecosystem. To improve upon this model, microplastic data for each trophic group within the MCBs ecosystem would be needed to explore potential plastics management plans. Subsamples of catch data through a trawl and beach seine surveys could be analyzed for plastics to fill this data gap and increase the accuracy of the model. Additional groups should be added to the model as well. As recreational fishing is a large part of the ecosystem, adding a recreational fishery time series dataset would improve the model's accuracy. Adding a local seabird trophic group with data from future trawl and beach seine surveys would also be a priority for future model improvement, as seabirds are an ecologically important part of the ecosystem. The results from this model could help

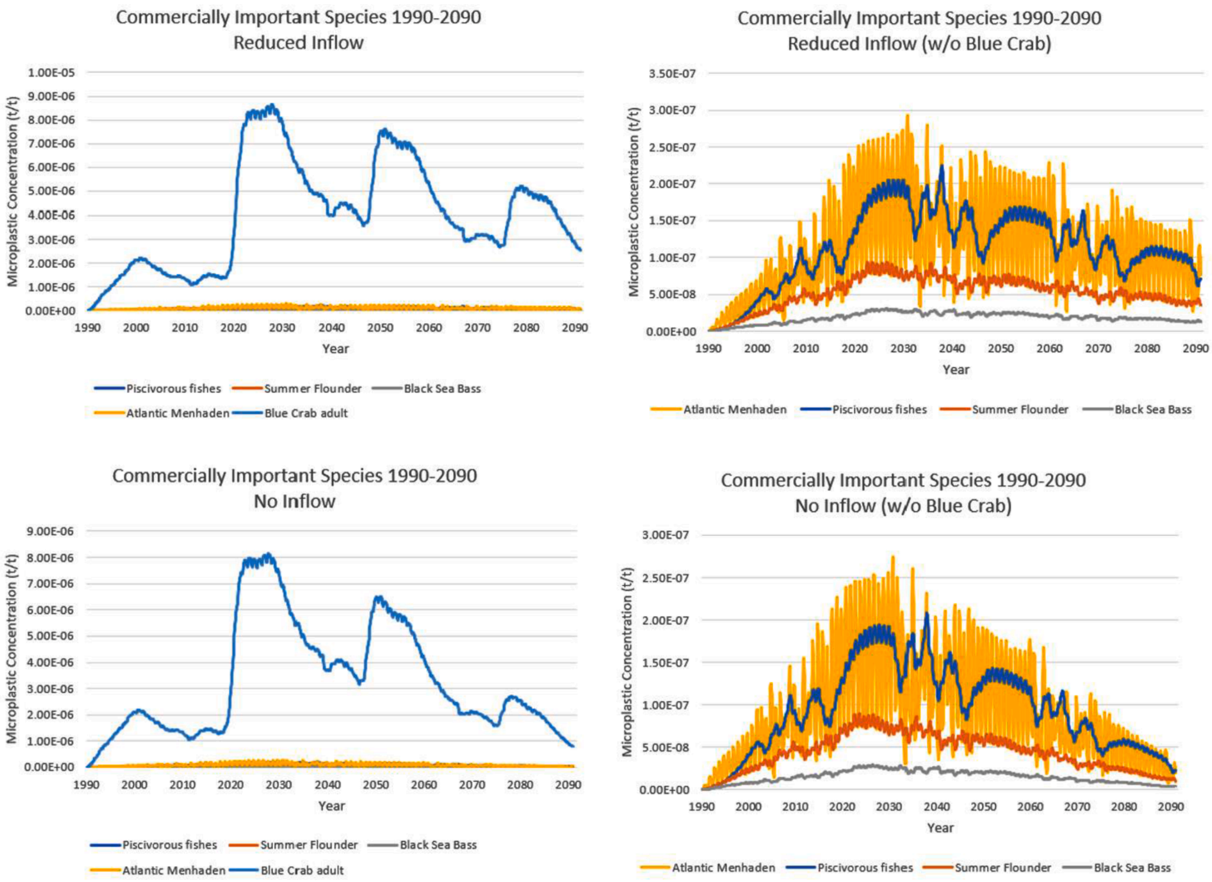

Fig. 3. Graphical display of the change in microplastic concentration of the commercially important species with the Reduced Inflow and Zero Inflow scenarios. From the left side graphs, Adult Blue Crab has a much greater concentration of microplastics thereby preventing the other commercially important species from being visualized properly. The right side graphs show the commercially important species without Adult Blue Crab for this reason.

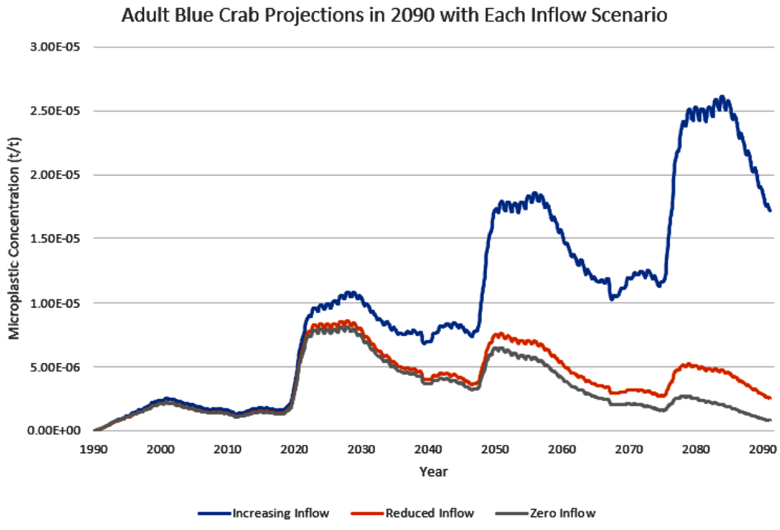

Fig. 4. Adult Blue Crab with all environmental plastic inflow scenarios.

identify future environmental plastic inflow rate targets for future management plans.

Additionally, uncertainty assessments that explore uncertainty in the model parameters and environmental plastic inflow concentration rates would enhance the model's credibility. Tools like the Monte Carlo routine, MultiSim, and Ecosampler in the EwE platform could be used to provide a more robust assessment. Ecosampler could capture parameter sensitivity of our Ecosim calibration and Ecotracer parameters in future versions of this MCBs model for management applications (Steenbeek et al., 2018).

Another tool that would enhance the model is using Ecospace in conjunction with Ecotracer. Ecospace would track changes in the concentrations of microplastics originating from a point source or as a result of changes in water currents or tidal flows. This may allow for a better

Table 6
The HDI calculations of the commercially important species.

Species name	Grams of seafood consumed per day (R)	Concentration of microplastics within the organism in 2090 (C)		Human dietary intake in 2090 per person (HDI)
Black sea bass	48.6 g	Increased inflow	0.09 ug/g	4.31 ug
		Reduced inflow	0.01 ug/g	0.63 ug
		Zero inflow	0.004 ug/g	0.18 ug
Summer flounder	48.6 g	Increased inflow	0.24 ug/g	11.66 ug
		Reduced inflow	0.04 ug/g	1.71 ug
		Zero inflow	0.01 ug/g	0.50 ug
Adult blue crab	48.6 g	Increased inflow	17.20 ug/g	835.92 ug
		Reduced inflow	2.56 ug/g	124.42 ug
		Zero inflow	0.78 ug/g	37.81 ug
Piscivorous fishes	16.2 g	Increased inflow	0.47 ug/g	7.53 ug
		Reduced inflow	0.07 ug/g	1.15 ug
		Zero inflow	0.02 ug/g	0.37 ug
Atlantic menhaden	2.0 g	Increased inflow	0.54 ug/g	1.08 ug
		Reduced inflow	0.08 ug/g	0.15 ug
		Zero inflow	0.02 ug/g	0.04 ug

Table 7
HHI in 2090 with reduced inflow and zero inflow scenarios.

Species	Increased inflow - 2090	Reduced inflow - 2090	Percent decrease	Zero inflow - 2090	Percent decrease
Black sea bass	4.31 ug/day	0.63 ug/day	85%	0.18 ug/day	96%
Summer flounder	11.66 ug/day	1.71 ug/day	85%	0.50 ug/day	96%
Adult blue crab	835.92 ug/day	124.42 ug/day	85%	37.81 ug/day	95%
Piscivorous fishes	7.53 ug/day	1.15 ug/day	85%	0.37 ug/day	95%
Atlantic menhaden	1.08 ug/day	0.15 ug/day	86%	0.04 ug/day	96%

understanding of the local dynamics of the microplastic accumulation in the modelled trophic groups. Doing so would require a sampling of microplastics as described above, but could help visualize the impact of the varying environmental plastic inflow rates on regions within the MCBs.

With these additions, in the future, this proof-of-concept model could be capable of simulating possible outcomes of environmental management decisions. It could identify species most affected by microplastic accumulation and explore the impact of proposed plastic management plans based on current and future trends.

In the present study, the plastic inflow rate was used as the parameter of change to determine the degree of microplastic accumulation change in aquatic species from 1990 to 2090 with each of our three environmental plastic inflow rates (Increased Inflow, Reduced Inflow, Zero Inflow). We also included a human health component to show the HDI of microplastics to detail how microplastics enter human food streams as well.

This study also detailed the abundance of microplastics in each of the species and the increase of microplastic concentration over time. Commercially important species in the MCBs saw tremendous increases in their concentrations which brings great implications for the seafood industry. Adult Blue Crab and Black Sea Bass saw the greatest increase of plastic concentration from 1990 to 2090; however all trophic levels are being greatly affected by microplastic pollution. Some bioaccumulation is also displayed as the higher trophic level organisms increased to a greater average percentage (303%) than the lower trophic level organisms (286%, excluding Adult Blue Crab).

Simulated environmental plastic inflow plans were shown to be effective in reducing the concentration of microplastics in each aquatic species in 2090. Primary producers saw the greatest decrease of microplastic concentrations with the Reduced Inflow and Zero Inflow scenarios. The Zero Inflow scenario was capable of reducing the 2090 plastic concentrations within the species to below the 2017 values to a greater degree than the Reduced Inflow scenario, as expected. For each species, microplastic concentrations were reduced by over 85% in the Reduced Inflow scenario and by over 95% in the Zero Inflow scenario.

Microplastics are also of great concern to human health, as plastics leach into aquatic species tissues and bloodstream (Smith et al., 2018). Previous studies have detected microplastics in human feces, showing that humans are indeed consuming microplastics in their daily diets (Schwabl et al., 2019). This limited proof-of-concept model shows that if plastic inflow rates triple every 30 years, Adult Blue Crab and Summer Flounder will see increased microplastic concentrations of 1132% and 384%, respectively, from 1990 to 2090, with dramatic increases in Human Dietary Intake of microplastics. This brings great risk to humans as the definitive effects of microplastics on human health are not definitively known, although it is known that most plastics have estrogenic activity, which have adverse effects on fetal and juvenile mammals (Yang et al., 2011).

This emphasizes the likely need for environmental plastic inflow rates to be reduced and microplastic management plans heightened, especially for the highest microplastic polluters. Such endeavors entail designing Wastewater Treatment Plant and washing machine filters capable of trapping microplastics and microplastic fibers before they reach waterways. Plastic pollution regulation can also be heightened to reduce such waste. As many countries and regions have started efforts to ban single use plastics or grocery store plastic bags, greater impact can result from greater legislation. The Microbead-Free Waters Act of 2015, prohibiting microbeads in Personal Care Products is one such effort that resulted in trillions of beads no longer reaching the waters (Center for Food Safety and Applied Nutrition, 2020b). This also involves plastic reduction and collection plans for when the microplastics reach the waterways. Scientific advancement of remediation procedures, in terms of biological, chemical, and physical degradation and removal, are of great importance as the rise of microplastic pollution will continue to increase without microplastic management plans.

This proof-of-concept model demonstrates the need for further investigation of microplastic accumulation in the MCBs aquatic organisms. Some studies have looked into the effects of microplastics on fish health, however few have determined how often ingested microplastics contain absorbed toxic compounds and heavy metals (Diepens and Koelmans, 2018; Rodrigues et al., 2019). This in turn increases comorbidity, juvenile defects, and starvation rates amongst aquatic species. More detailed study on the abundance and effects of microplastic accumulation in aquatic species is required for a more accurate understanding of this ever-increasing problem.

5. Conclusions

Microplastics are an increasingly important issue to address as accumulation is a risk factor for all aquatic species. These microplastics particles have the potential to contaminate marine organisms which can provide deleterious effects on both the organism and the humans that consume the seafood.

Plastic management plans are needed to help mitigate this issue as less plastic in the oceans, bays, and waterways will prevent severe accumulation in aquatic species, and ultimately humans as well. Ecosystem models, such as the study's proof-of-concept model presented herein, can be used to demonstrate and understand the trophic pathways that lead to microplastic accumulation in aquatic ecosystems and, ultimately, human consumption. With some additional research and monitoring data, this model can be used to inform management by demonstrating potential scenarios for microplastic accumulation in the aquatic species of the MCBs, as well as in the humans who consume commercially important species taken from the waters of the MCBs ecosystem. As this model was developed using modeling software that has widespread use around the world, this modeling approach can be adapted to other regions for this purpose.

Anthropogenic activity has resulted in considerable microplastic pollution of our world's ocean. Perceptions about the risk and the broad, global nature of the problem may result in limited or no action to resolve the issue. More local scale modeling, such as what we have demonstrated here, which connects the local sources of the pollution to local impacts, may be a useful way to organize information to develop local solutions.

Author statement

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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.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.ecolmodel.2021.109849.

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