Supplemental Materials

Sediment modeling approach

Benthic sediment samples have been collected in Chesapeake Bay since the 1850s, with the earliest data patchily distributed in space and time. In the mid-1970s, a systematic survey of the benthic sediments in the Bay was undertaken by Maryland Geological Survey (MGS: Kerhin et al. 1988, 1998) and Virginia Institute of Marine Science (VIMS: Byrne et al. 1982). To date, this remains the only comprehensive treatment of the Bay's sediments. Proportion of silt/clay (i.e., sediment <63 μm), geographic location, and depth from these two sources were extracted from the usSEABED database, a compilation of publicly available sediment data (Buczkowski et al. 2020). Depth of collection was missing from all stations in Virginia and about 11% of stations in Maryland; therefore, depths for all stations were extracted from a 1/3 arc-second digital elevation model (DEM) of Chesapeake Bay (National Centers for Environmental Information 2017) and stations beyond the extent of the DEM were removed from further analysis. Proportion of silt/clay was averaged across subsamples and replicate samples when available (~ 75% of stations); sites where estimates were highly variable (range ≥ 0.2) were removed.

All analyses were run in R version 4.2.2 (R Core Team 2023) using RStudio version 2022.12.0 (RStudio Team 2020). A statistical model for proportion of silt/clay was developed using the generalized additive models for location, scale, and shape (GAMLSS) framework. This approach extends the generalized additive modeling (GAM) framework (Wood 2017) to encompass a wider range of distribution families and allow for distribution parameters beyond μ (i.e., σ, usually scale; ν, usually skewness, and τ, usually kurtosis) to be modeled (Rigby & Stasinopoulos 2005, Stasinopoulos et al. 2017). The package *gamlss* (version 5.4-12: Stasinopoulos & Rigby 2023) provides several distribution families on (0, 1), including inflated distributions (i.e., those that encompass 0 and/or 1). To allow for interactions between latitude, longitude, and depth, a tensor product smooth was implemented by using *gamlss.add* (version 5.1-6: Stasinopoulos & Rigby 2023), which interfaces with *mgcv* (version 1.8.42: Wood 2023).

As the proportion of silt/clay included both 0s and 1s, the model took the general form of $Y_s \sim \text{BEINF}(\mu, \sigma, \nu, \tau)$, where the observed proportion of silt/clay (Y_s) was modeled using the zero- and one-inflated beta distribution and the μ is the mean of the BE(μ, σ) component of the distribution. The mean of the BEINF distribution is $(\mu + \tau)(1 + \nu + \tau)^{-1}$, where $\nu = p_0/(1 - p_0 - p_1)$ and $\tau = p_1/(1 - p_0 - p_1)$ and p_0 and p_1 are the probabilities that y_s will be exactly 0 and 1, respectively. Model development, including the choice of basis dimensions, was guided by AIC, diagnostic plots, and patterning of residuals. The final model was used to predict the proportion of silt/clay throughout the ChesMMAP sampling frame.

Supplementary tables

Table S1: Degrees of freedom (df), likelihood (-2log(L)), Δ AIC, and Δ BIC for the ecological niche models that successfully converged; distributions are sorted by increasing AIC. All models took the form of: count ~ s(water temperature) + s(salinity) + s(dissolved oxygen) + s(depth) + s(silt/clay) + offset(log(area swept)). Note that the following distributions failed to converge in 1,000 iterations: ZAPIG, ZIPIG, ZAZIPF, ZALG, NBF, ZINBI, ZINBF, DPO, ZIP2, ZAP; the ZABNB and ZASICHEL distributions were unable to run. More information on the distribution families available in the gamlss package can be found in Rigby et al. (2020).

Distribution	df	-2log(Lik)	Δ AIC	Δ BIC
BNB	34.6	10,907.3	0.0	0.0
ZIBNB	35.6	10,907.3	2.0	8.2
ZISICHEL	37.2	10,931.4	29.4	45.3
GPO	37.8	10,948.2	47.4	67.3
YULE	32.9	10,969.4	58.7	48.2
SICHEL	36.1	10,981.8	77.4	86.5
SI	36.1	10,981.9	77.5	86.4
PIG	33.9	11,012.3	103.5	99.0
WARING	30.0	11,023.3	106.8	78.6
DEL	40.8	11,042.8	147.9	186.0
NBI	33.4	11,082.9	173.3	166.0
ZANBI	37.8	11,229.2	328.3	347.9
NBII	28.6	11,533.4	614.0	576.8
GEOMo	45.4	13,081.6	2,195.8	2,261.9
GEOM	32.5	13,656.3	2,744.8	2,731.9
ZIP	47.0	33,645.2	22,762.7	22,838.8
PO	35.7	48,646.6	37,741.5	37,748.1

Table S2: Degrees of freedom (df), likelihood (-2log(L)), Δ AIC, and Δ BIC for the species distribution models that successfully converged; distributions are sorted by increasing AIC. All models took the form of: count ~ te(longtitude, latitude, by = month) + offset(log(area swept)). Note that the following distributions failed to converge: ZAPIG, ZIPIG, ZAZIPF, ZALG, ZANBI, NBF, ZINBI, ZINBF, ZAP; the DPO, ZABNB, and ZASICHEL distributions were unable to run. More information on the distribution families available in the gamlss package can be found in Rigby et al. (2020).

Distribution	df	-2log(Lik)	Δ AIC	Δ BIC
BNB	50.1	10,692.6	0.0	0.0
ZISICHEL	51.3	10,703.7	13.5	20.9
SICHEL	53.6	10,722.4	36.7	57.8
SI	53.6	10,722.4	36.7	58.0
PIG	53.0	10,729.1	42.3	60.2
ZIBNB	50.6	10,737.5	46.0	49.2
WARING	55.6	10,735.2	53.6	87.3
GPO	50.0	10,777.2	84.4	83.7
YULE	61.0	10,787.8	117.0	183.9
DEL	53.9	10,802.4	117.4	140.8
NBI	43.4	10,870.1	164.1	122.6
NBII	45.6	11,319.9	618.2	590.1
GEOMo	68.4	12,526.2	1,870.1	1,982.2
GEOM	43.2	12,871.8	2,165.5	2,123.1
ZIP	74.0	37,531.8	26,886.9	27,033.6
ZIP2	74.0	37,536.9	26,892.0	27,038.7
PO	39.3	51,196.6	40,482.4	40,415.9

Table S3: Degrees of freedom (df), likelihood (-2log(L)), Δ AIC, and Δ BIC for the models of relative abundance that successfully converged; distributions are sorted by increasing AIC. All models took the form of: count ~ year + month + region + pb(depth) + offset(log(area swept)), with year, month, and region coded as factors and a p-spline smooth on depth. Note that the following distributions failed to converge: ZIPIG, ZINBI, ZINBF, ZIP2, ZIP; the ZABNB distribution was unable to run. More information on the distribution families available in the gamlss package can be found in Rigby et al. (2020).

Distribution	df	-2log(Lik)	Δ AIC	Δ BIC
ZISICHEL	32.1	10,895.5	0.0	2.2
BNB	30.6	10,905.7	7.2	0.0
ZIBNB	31.6	10,905.7	9.2	8.2
WARING	30.0	10,912.1	12.4	1.6
SICHEL	31.6	10,910.1	13.7	13.1
SI	31.6	10,910.1	13.7	13.1
PIG	30.5	10,913.7	15.0	7.5
GPO	30.1	10,984.9	85.4	75.3
YULE	28.1	10,992.0	88.6	66.5
DEL	33.5	11,019.7	126.9	137.6
ZALG	32.9	11,252.5	358.6	365.7
ZANBI	33.9	11,252.7	360.8	373.9
NBI	43.2	11,248.7	375.5	446.1
NBII	29.5	11,402.7	502.1	488.6
ZAZIPF	29.6	11,636.1	735.5	722.2
ZAPIG	43.0	11,616.1	742.4	811.7
DPO	41.3	13,554.0	2,676.9	2,735.7
GEOMo	39.8	13,572.3	2,692.2	2,741.7
GEOM	29.5	13,630.8	2,730.1	2,716.1
NBF	45.7	16,075.4	5,207.2	5,293.2
PO	35.1	47,316.5	36,427.1	36,448.0

Supplementary figures

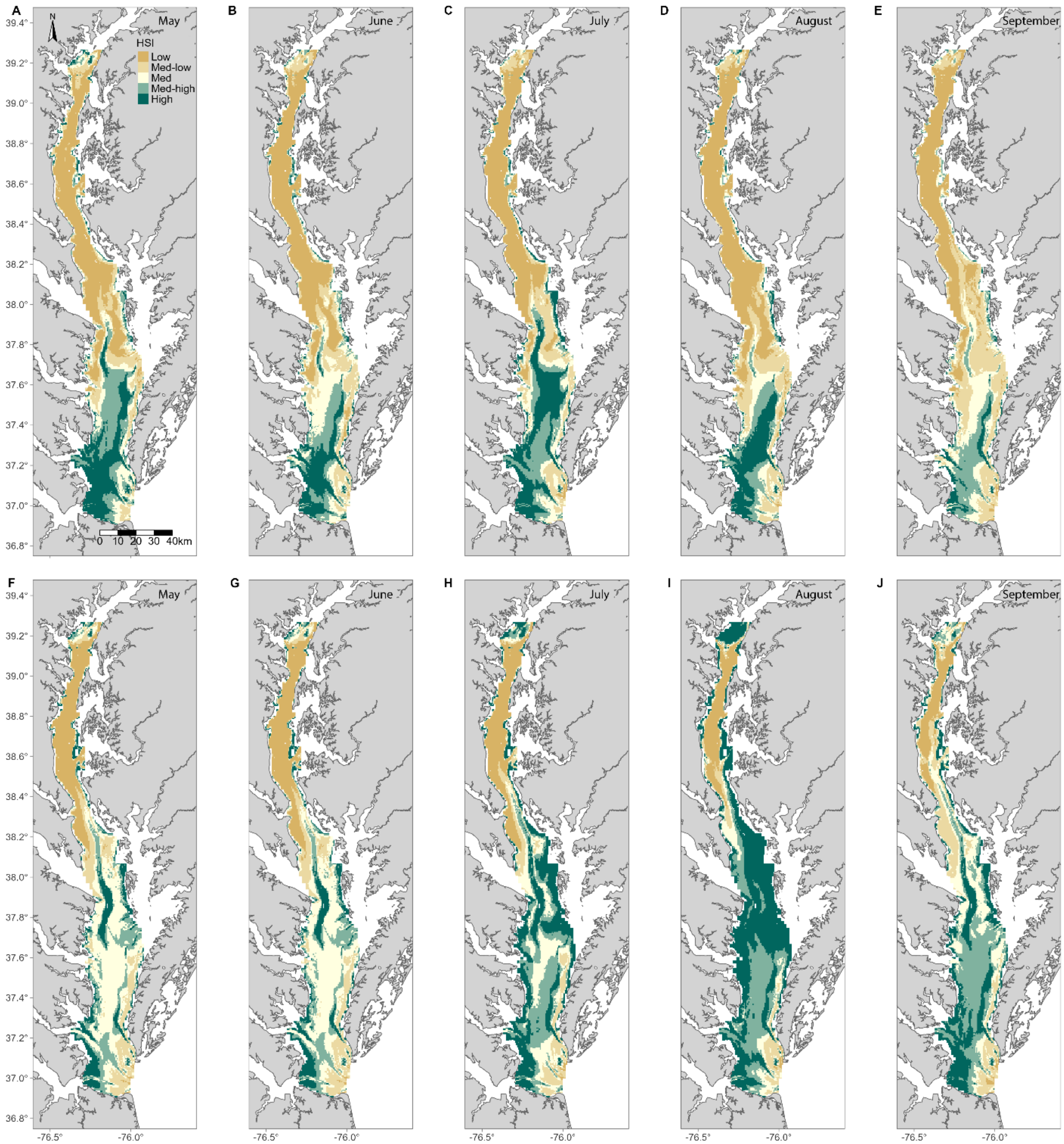

Figure S1: Spatial distribution of habitat suitability for years with the lowest (A-E, May - September 2004) and highest (F-J, May - September 2012) total annual habitat suitability. Habitat suitability was developed by pairing the selected ecological niche model with a coupled hydrodynamic-biogeochemical model (ROMS-ECB: St-Laurent & Friedrichs 2024), which provided daily, hindcast estimates of bottom temperature, bottom salinity, bottom dissolved oxygen, and depth; static estimates of Proportion of silt/clay was based on a spatial GAM. Values represent the average habitat suitability for each month, May to September, for each cell; quintiles were calculated based on data from all years (2002-2018).

References

Buczkowski BJ, Reid JA, Jenkins CJ (2020) Sediments and the sea floor of the continental shelves and coastal waters of the United States—About the usSEABED integrated sea-floor-characterization database, built with the dbSEABED processing system. U.S. Geological Survey, Reston, VA, USA.

Byrne RJ, Hobbs CH III, Carron MJ (1982) Baseline sediment studies to determine distribution, physical properties, sedimentation budgets, and rates in the Virginia portion of the Chesapeake Bay: Final report. Virginia Institute of Marine Science, William & Mary, Gloucester Point, VA, USA.

Kerhin RT, Halka JP, Wells DV, Hennessee EL, Blakeslee PJ, Zoltan N, Cuthbertson RH (1998) Chesapeake Bay Earth Science Study (CBESS): Physical properties of surficial sediments; Chesapeake Bay; Maryland (Tabular Data). Maryland Geological Survey, Baltimore, MD, USA.

Kerhin RT, Halka JP, Wells DV, Hennessee EL, Blakeslee PJ, Zoltan N, Cuthbertson RH (1988) The surficial sediments of Chesapeake Bay, Maryland: Physical characteristics and sediment budget. Maryland Geological Survey, Baltimore, MD, USA.

National Centers for Environmental Information (2017) NOAA NOS Estuarine Bathymetry - Chesapeake Bay (M130).

R Core Team (2023) R: A Language and Environment for Statistical Computing. https://www.R-project.org/

Rigby RA, Stasinopoulos DM (2005) Generalized additive models for location, scale and shape. J R Stat Soc Ser C Appl Stat 54:507–554.

Rigby RA, Stasinopoulos MD, Heller GZ, De Bastiani F (2020) Distributions for Modeling Location, Scale, and Shape: Using GAMLSS in R. Chapman and Hall/CRC, Boca Raton, Florida.

RStudio Team (2020) RStudio: Integrated Development for R. http://www.rstudio.com/

Stasinopoulos MD, Rigby RA (2023) Package “gamlss”. Version 5.4-12. https://cran.r-project.org/web/packages/gamlss/index.html

Stasinopoulos MD, Rigby RA, Heller GZ, Voudouris V, De Bastiani F (2017) Flexible regression and smoothing: using GAMLSS in R. Chapman & Hall/CRC, Boca Raton, Florida.

St-Laurent P, Friedrichs MAM (2024) On the sensitivity of coastal hypoxia to its external physical forcings. J Adv Model Earth Syst 16:e2023MS003845.

Wood SN (2017) Generalized Additive Models: An Introduction with R, Second Edition, 2nd ed. Chapman and Hall/CRC, Boca Raton.

Wood SN (2023) Package “mgcv”. Version 1.8-42. https://cran.r-project.org/web/packages/mgcv/index.html