Final Report: Oyster Advisory Commission Consensus Recommendations on Oyster Management

A REPORT TO THE GOVERNOR AND THE MARYLAND GENERAL ASSEMBLY

DECEMBER 1, 2021

As required by Natural Resources Article §4–215 and §4-204

Maryland Department of Natural Resources Fishing and Boating Services
and the Oyster Advisory Commission in consultation with
The University of Maryland Center for Environmental Science

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Section 1. Report from the Oyster Advisory Commission

Consensus Process: Package of Recommendations

The Oyster Advisory Commission (OAC) provided the Maryland Department of Natural Resources with an approved package of recommendations. This package was voted on by the commission on November 8, 2021 and received 80% agreement among the commissioners. All voting members were in attendance on November 8, 2021.

OAC Recommendations

This document contains the consensus recommendations of the Oyster Advisory Commission. These recommendations are based on options that were rated with an agreement level of 75% or higher and the text has been approved by commissioners at the November 8, 2021 OAC meeting. OAC members have considered more than 100 options in developing this list of consensus recommendations.

Legislation passed by the General Assembly in 2019 tasked the Oyster Advisory Commission with developing a set of consensus management actions for enhancing and implementing the fisheries management plan for oysters and to achieve the targets identified in the oyster stock assessment with the goal of increasing oyster abundance. Despite considerable effort and complications from the pandemic, the OAC has been able to reach consensus on a management action that would have positive impacts on oyster abundance and habitat, as called for in the legislation. While the consensus recommended should result in improvement, OAC commissioners will continue deliberations to develop further actions that will result in benefits at a desirable scale.

Shell and Substrate Resource Recommendations. There is an important need for clean shell and substrate that will support enhancement of all sectors of the oyster resource, including the public fishery, aquaculture, and public and private restoration efforts.

➢ DNR should evaluate and develop cost effective strategies for identifying and obtaining sources of shells and substrate.

➢ DNR should review the current state laws and regulations to evaluate and develop potential strategies, including providing economic incentives, to retain shell in the state of Maryland and reuse it.

➢ DNR should support a Maryland-wide substrate action subcommittee of the OAC to evaluate strategies, costs, and benefits for substrate enhancement.

➢ DNR should work collaboratively with the OAC to commission an academic peer-reviewed study to evaluate the ability of bar cleaning in low/underperforming harvest areas to promote improved spat sets.

Monitoring and Marking Recommendations. Enforcement and monitoring play an important role in ensuring the protection of the oyster resource and the timely tracking of its status. The recommendations are:

➢ DNR should work to improve the Fall Dredge Survey (e.g., new locations, fall dredge survey before start of fishery, cooperative survey with industry, etc.).

➢ DNR should develop tools to mark navigation hazards and oyster management boundaries.

Management Action Recommendations. This recommendation is the management recommendation evaluated by the model, as called for in the legislation, that earned the consensus of the group. The OAC recommends that the following actions be taken to rebuild oyster populations, enhance harvest revenue, increase habitat, and reduce nitrogen and phosphorus in Maryland's Chesapeake Bay.

➢ Over the next 25 years, a combination of replenishment, restoration and aquaculture activities should be collectively planned and undertaken in Eastern Bay, with an equal amount of funding for spat planting in sanctuaries ($1M annually adjusted for inflation) and for spat and shell planting on fishery bars ($1M annually adjusted for inflation) in addition to current replenishment and restoration activities. The effectiveness of this option should be evaluated every 5 years.

➢ The OAC supports keeping the oyster fishery open.

➢ The OAC supports replenishment plantings on oyster fishery bottom.

Business Practices, Investment Allocation, & Marketing Recommendations. OAC members recommend the following:

➢ Improve organization and cooperation among groups and integrate projects across the 3 sectors (fishery, aquaculture, restoration).

➢ Improve processor capabilities and techniques (e.g., more shucking houses, develop frozen product).

➢ Use bars north of the Bay Bridge as “investments” against disease outbreaks in lower Bay.

➢ Use nutrient credit opportunities to help finance restoration on sanctuaries and replenishment on public fishery bottom in Maryland’s Chesapeake Bay.

Education and Training Recommendations. There is an important need to educate and train citizens about stewardship of the oyster fishery and resources to maintain it for current and future generations.

➢ Special effort should be placed on outreach and education in minority communities to enhance awareness of the oyster resource and associated career opportunities and environmental benefits.

Improved Science Recommendations. OAC members identified several knowledge gaps, which if filled, would enhance management of the oyster resource.

➢ Conduct a comprehensive survey of the Maryland Bay bottom with a focus on describing the current amount, quality, and location of oyster habitat.

➢ Develop the ability to make stock assessment projections of abundance and harvest.

➢ Determine ways to reduce sedimentation.

➢ Conduct studies to estimate the loss rates of shell (both newly planted and existing bottom) and artificial substrate.

➢ OAC should be a mechanism for reviewing studies and stock assessments, as requested by commissioners.

Membership

Under the consensus building process defined in statute (§4–204), 60% of the OAC members must be oyster industry orientated (e.g., public fishery and aquaculture) and 40% non-industry orientated (e.g., environmental groups and academia). Member organizations are codified in statute, and the list of individual commissioners selected by their organization are:

Type	Commissioner	Organization
Voting Members	Keith Bradley (proxy John Edwards)	Wicomico County Oyster Committee
	Robert T Brown	Maryland Watermen's Association
	Mark Bryer	The Nature Conservancy
	Keith Busick	Baltimore County Oyster Committee
	Allison Colden (proxy Doug Myers)	Chesapeake Bay Foundation
	Jack Cover	National Aquarium
	Simon Dean (proxy Rachel Dean)	Calvert County Oyster Committee
	Ron Fithian	Kent County Oyster Committee
	Matt Fowler (proxy Bill Kiliniski)	Charles County Oyster Committee
	Reggie. Harrell	Aquaculture Coordinating Council
	Jeff Harrison	Talbot County Oyster Committee
	Brian Hite (proxy Nick Lane)	St Mary's County Oyster Committee
	Jesse Iliff	Arundel Rivers Federation
	Scott Knoche (proxy Brittany Wolfe-Bryant)	Morgan State University PEARL
	Vincent Leggett (proxy Tyrone Meredith)	Blacks of the Chesapeake
	Tom Miller	University of Md Center for Environmental Science
	Jim Mullin	Maryland Oystermen Association
	Matt Pluta (proxy Elle Bassett)	ShoreRivers
	Jason Ruth	Harris Seafood Company (Seafood Dealer)

	Johnny Shockley	Blue Oyster Environmental
	David Sikorski	Maryland Coastal Conservation Association
	Ann Swanson (proxy Mark Hoffman)	Chesapeake Bay Commission
	Daniel Webster	Somerset County Oyster Committee
	Bob Whaples	Dorchester County Oyster Committee
	Troy Wilkins	Queen Anne's County Oyster Committee
	Rob Witt (proxy Rob Howes)	Anne Arundel County Oyster Committee
	Vacant (Opted Not to Participate)	BaySavers
	Vacant (Recused Themselves)	Oyster Recovery Partnership
Non-Voting Members	Marlon Amprey	Maryland House of Delegates
	Sean Corson	National Oceanic and Atmospheric Administration
	Sarah Elfreth	Maryland Senate
	Steve Hershey	Maryland Senate
	Christopher Judy	Maryland Department of Natural Resources
	Johnny Mautz	Maryland House of Delegates
	Angie Sowers	U.S. Army Corps of Engineers

Section 2. Report from the Maryland Department of Natural Resources

Oyster Advisory Commission

The Oyster Advisory Commission (OAC) has the duty of advising the Maryland Department of Natural Resources (DNR) on matters related to oysters in Maryland's portion of the Chesapeake and Coastal bays. This is accomplished by:

- Providing DNR with advice on matters related to oysters in the Chesapeake Bay;
- Reviewing the best possible science;
- Recommending changes to the framework and strategies for rebuilding and managing the oyster population in the Chesapeake Bay under the Chesapeake Bay Oyster Management Plan;
- Reviewing the latest findings relevant to the Environmental Impact Statement evaluating oyster restoration alternatives for the Chesapeake Bay;
- Reviewing any other scientific, economic, or cultural information relevant to oysters in the Chesapeake Bay; and
- Developing a package of consensus recommendations, in coordination with the department, for enhancing and implementing the fishery management plan for oysters as required per statute.[1]

The OAC was also charged with developing a package of consensus recommendations through a facilitated consensus solutions process based on a 75% majority agreement level for each recommendation. Their consensus recommendations are outlined in Section 1 of this report.

Senate Bill 808 of 2020 (and Maryland Code, Natural Resources § 4-215) prescribed the process by which the consensus must be reached. To meet those statutory obligations, DNR coordinated with the University of Maryland Center for Environmental Science (UMCES), independent facilitators, and members of the OAC.

The process was informed by a collaboratively developed, science-based modeling tool (the model) which is described in greater detail by UMCES in Section 3 of this report.

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[1] *This duty was added to the OAC's list of responsibilities in 2020 as a result of the passage of Senate Bill 808 of 2020.*

The model was used to quantify the long-term impacts of management actions and possible combinations of management actions on:

- Oyster abundance;
- Oyster habitat;
- Oyster harvest;
- Oyster harvest revenue; and
- Nitrogen removal.

DNR conducting an oyster survey to evaluate the state's shellfish resources.

The statute also requires that Maryland's oyster fishery management plan must meet the following objectives:

- Maintain a harvest in the fishery while ending the overfishing of oysters in all areas and regions of the Chesapeake Bay and its tributaries, according to biological reference points established by the most recent oyster stock assessment;
- Achieve fishing mortality rates at target levels;
- Increase oyster abundance;
- Increase oyster habitat;
- Facilitate the long-term sustainable harvest of oysters, including the public fishery.

Consensus Process Overview

The OAC held monthly meetings from February 2020 to November 2021 plus additional meetings in between the monthly meetings. Due to the COVID-19 pandemic, most monthly meetings were held virtually so that the OAC could continue their work. This was especially important given the deadline by which the OAC had to reach consensus.

Technology, internet access, and hardware were a challenge for some commissioners, especially those in more remote or rural areas of the state. To address this, facilitators offered to loan iPads to commissioners who needed them. Once the stay-at-home order was lifted, meetings were held in a hybrid format at the request of some commissioners. This allowed commissioners the option to attend in-person or virtually depending on their organization's COVID-19 protocols and policies or the individual commission member's level of comfort. While this did allow the commission to complete their work on time, it limited the ability for commissioners to have personal interaction and have direct or informal conversations about areas of agreement and areas of disagreement - all of which are essential components of a consensus process. As a result, DNR has agreed to continue engaging members of the OAC in the consensus process in the future.

In accordance with the Open Meetings Act, all meetings were open to the public and allowed for public comment. All meetings also adhered to U.S. Centers for Disease Control and Prevention and Maryland Department of Health guidance.

Commission members discuss and rate options at a hybrid meeting in Kent Island.

All meeting agendas, materials presented to the commission, and summaries of the meetings can be found on the OAC website (dnr.maryland.gov/fisheries/pages/mgmt-committees/oac-index.aspx).

The public was included in the process and their feedback was reported back to the commission.

Vision Statement

To guide the work of the OAC within the consensus process, the commissioners developed a working vision statement:

> *Our goal is to increase oyster abundance/population and habitat in Maryland's Chesapeake Bay. We will rely on science and stakeholder knowledge to work comprehensively towards:*
> - *Shared stewardship, supporting oysters in harvest areas, aquaculture, and in sanctuaries;*
> - *A healthy ecosystem, and*
> - *A sustainable fishery and aquaculture industries that contribute to the economic health of the state.*

Oyster Model Overview

To assist the consensus process and to ensure the process fulfilled statutory obligations, the UMCES modeling team developed a scientific model to evaluate potential management and restoration options for oysters in Maryland's Chesapeake Bay. The model was developed collaboratively with the OAC.

The model tracked the number of oysters and amount of available hard bottom oyster habitat on 1,082 oyster bars. Oysters were separated into three size classes: spat (less than one year old), small (greater than one year old and less than three inches in shell height), and market (equal to and greater than three inches in shell height). The model was "conditioned" using data on the harvest on each bar and the most recent stock assessment estimates of abundance by size category during 1999-2021. The model included harvest, disease and other mortality, reproduction, growth, creation of new shell, and loss of shell and artificial substrate. Conditioning the model ensures that the parameter estimates used in the analysis (and their uncertainty) are consistent with the historical data. The model also included plantings of oysters and shell. Due to time and data constraints, aquaculture was not included in the model.

The conditioned model was used to project the outcomes of potential management and restoration options for 25 years into the future to describe both short-term and long-term expected performance. Performance was measured using projected oyster abundance, amount of oyster habitat, harvest, value of harvest, amount of nitrogen removed by oyster bars, amount of nitrogen removed by harvest, the fraction of time harvest rates were above their targets and upper limits, and the fraction of time abundance was below its lower limit.

Management Options Examined

OAC examined many oyster management options to determine if these options could support their vision statement. Management options examined included both options that could be modeled using the model described above and options that could not be modeled (see Appendix 1 for list of options examined). Seventy-four modeled options were examined and 30 non-modeled options were examined.

Examples of modeled options included:

- Planting oysters (hatchery spat-on-shell, wild natural seed, and aquaculture oysters) on both fishery and sanctuary bottom
- Planting shell on fishery and sanctuary bottom
- Planting alternative substrates on sanctuary bottom
- Rotational harvest
- Changing harvest limits
- Opening and closing fishery bottom
- Large-scale restoration
- Dredging shell and replanting it

Examples of non-modeled options included:

- Shell and substrate resources
- Enforcement
- Monitoring oyster populations and harvest
- Alternative types of fishery management
- Sanctuaries
- Business practices, investments, and marketing of harvested oysters
- Improvements to scientific data knowledge

OAC commissioners examined each option and rated it as acceptable, having minor reservations, having major reservations, and not acceptable. The first two ratings indicate agreement and the last two ratings indicate disagreement with the option. Percent agreement to implement an option in the future was calculated using the *voting members* ratings. Those options that had a high percent agreement were evaluated for inclusion in the package of recommendations (see Section 1). Only those options that had at least a 75% agreement threshold and approved text describing the option were included in the package of recommendations.

Some options received a 0% agreement and were not included in the package of recommendations; however, receiving 0% agreement sends a strong and important message to DNR. These 0% options were:

- Modeled Option #5: Status quo management of the oyster resource except that all plantings (shell, spat on shell, wild seed, and artificial substrate) are stopped.
- Modeled Option #7: Status quo management of the oyster resource and converting all low harvest (less than 200 bushels harvested from 1999-2020) into sanctuary bottom.
- Modeled Option #25: Converting all oyster bottom into sanctuaries and ceasing both restoration and replenishment plantings.
- Modeled Option #72: A combination of constraining the fishing rates to the stock assessment’s target biological reference fishing rate and conducting a modified past (prior to 2006) DNR Seed and Shell Program whereas 1 million bushels of shell is planted annually.

Timeline for Implementation

Natural Resources Article §4–215 and §4-204 requires DNR to develop an implementation schedule for each recommendation. While some recommendations can be implemented immediately, others may require further discussion with the OAC or may require resources not available at this time.

Shell and Substrate Recommendations.

➢ DNR should evaluate and develop cost effective strategies for identifying and obtaining sources of shells and substrate.

DNR can begin implementing this immediately.

➢ DNR should review the current state laws and regulations to evaluate and develop potential strategies, including providing economic incentives, to retain shell in the state of Maryland and reuse it.

DNR can begin implementing this immediately.

➢ DNR should support a Maryland-wide substrate action subcommittee of the OAC to evaluate strategies, costs, and benefits for substrate enhancement.

DNR can begin implementing this immediately.

➢ DNR should work collaboratively with the OAC to commission an academic peer-reviewed study to evaluate the ability of bar cleaning in low/underperforming harvest areas to promote improved spat sets.

DNR will begin collaborating with the OAC and seeking potential funding sources in 2022.

Monitoring and Marking Recommendations. The department can implement these two recommendations immediately. Ongoing work has already been conducted to develop a mobile application that uses interactive maps to aid an individual who is on the waters of the state in determining their location, in real time, relative to: aquaculture leases; demonstration leases; fixed fishing devices - registered pound net sites; natural clam or oyster bars; oyster sanctuaries; Public Shellfish Fishery Areas (PSFA); SAV Protection Zones; Yates Bars; and any other data areas that the department deems relevant.[2]

Management Action Recommendations.

➢ Over the next 25 years, a combination of replenishment, restoration and aquaculture activities should be collectively planned and undertaken in Eastern Bay, with an equal amount of funding for spat planting in sanctuaries ($1M annually adjusted for inflation) and for spat and shell planting on fishery bars ($1M annually adjusted for inflation) in addition to current replenishment and restoration activities. The effectiveness of this option should be evaluated every 5 years.

DNR supports this recommendation though funding will need to be identified.

➢ The OAC supports keeping the oyster fishery open.

This is consistent with the current Oyster Management Plan (OMP) and will be incorporated into the updated OMP.

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[2] https://dnr.maryland.gov/fisheries/pages/ishellfish/main.aspx

➢ The OAC supports replenishment plantings on oyster fishery bottom.

DNR is currently implementing this and will continue to do so in the future.

Business Practices, Investment Allocation, & Marketing Recommendations.

➢ Improve organization and cooperation among groups and integrate projects across the 3 sectors (fishery, aquaculture, restoration).

DNR supports this recommendation; the Eastern Bay recommendation is a good example of how the three sectors can work together at an unprecedented level.

➢ Improve processor capabilities and techniques (e.g., more shucking houses, develop frozen product).

DNR can begin implementing this recommendation immediately; DNR will work with the Maryland Department of Commerce, the Maryland Department of Agriculture, and economic development organizations to achieve this.

➢ Use bars north of the Bay Bridge as "investments" against disease outbreaks in lower Bay.

DNR can implement this recommendation immediately; DNR is already planting spat/seed in the upper bay. DNR will continue to work with the OAC and other stakeholders and partners to implement this recommendation.

➢ Use nutrient credit opportunities to help finance restoration on sanctuaries and replenishment on public fishery bottom in Maryland's Chesapeake Bay.

DNR will continue to work with the Chesapeake Bay Program and U.S. Environmental Protection Agency on the approval of public fishery harvest as a Best Management Practice (BMP), and determine any opportunities once the parameters of the program are established.

Education and Training Recommendations.

➢ Special effort should be placed on outreach and education in minority communities to enhance awareness of the oyster resource and associated career opportunities and environmental benefits.

DNR concurs with this recommendation and will continue working with a variety of stakeholders, agencies, community leaders, and partners to enhance our efforts.

Improved Science Recommendations. DNR will begin exploring potential funding sources to implement these recommendations. DNR will also develop a briefing for the OAC regarding reducing sedimentation. DNR will continue to convene the OAC to review these materials, studies, and stock assessments.

Future Actions

DNR fully supports the OAC recommendation to continue advising our department on actions that can provide positive benefits for the oyster resource.

The department plans to convene the next meeting of the OAC in January 2022 with the goal of continuing to build consensus and finding more common ground on the common goal of improving the oyster resource.

Section 3. Report from the University of Maryland Center for Environmental Science

Description of Model Development and Analyses for the Maryland Oyster Consensus Process

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Chapter 1. Description of the Maryland Oyster Consensus Model

Marvin Mace III and Michael Wilberg

Introduction

The purpose of the Oyster Consensus model is to simulate outcomes of potential management and restoration options for oysters in the Chesapeake Bay Maryland, U.S.A. This model is part of a stakeholder driven effort to develop a package of consensus recommendations for enhancing and implementing the fishery management plan for oysters in Maryland. Our objectives were to conduct a collaborative management strategy evaluation with stakeholders to guide management of oysters in Maryland. This process was required under the bill passed by the Maryland General Assembly in 2020 entitled Natural Resources - Fishery Management Plans - Oysters (Per Natural Resources Article § 4-215(e)(5)(iii)1, Annotated Code of Maryland, SB 808, Chapter 598 and HB 911, Chapter 597, MSAR 12769).

Methods

Operating Model

The operating model describes the oyster population and fishery dynamics. The model tracks oyster abundance in three different stages: spat (< 1 year old), small (≥ 1 year old and < 76 mm in length), and market (>1 year old and ≥ 76 mm in length). The model operates from 1999-2019 and then for 25 years after 2019, with the initial values in 1999 calculated from the most recent estimates of abundance in the 2020 Maryland Oyster Stock Assessment Update (Maryland Department of Natural Resources 2020). During each year there are two time periods: (1) the portion of the year when oyster harvest is not allowed (April-Sept.), and (2) oyster fishing season, which occurs during October through March the following year. The only process affecting abundance of oysters during the fishing season is fishing mortality (i.e., no growth, recruitment, or natural mortality occurs), while recruitment, growth, and natural mortality all occur each year outside of the fishing season.

Spatial Domain

The spatial domain for the operating model is all natural oyster bars located in the Chesapeake Bay, Maryland (excluding the mainstem of the Potomac River, which is managed by the Potomac River Fisheries Commission). There have been several attempts to map all oyster habitat in Chesapeake Bay, Maryland starting with the Yates Survey conducted during 1906-1912. The Maryland Bay Bottom Survey was conducted during 1975-1983 and generated maps that updated the Yates survey (Smith et al. 2001). We used a combination of surveys to estimate the starting values for the volume of habitat on each oyster bar (see Chapter 5).

In addition to individual oyster bars, we also aggregated estimates at a regional scale, similar to the Maryland Oyster Stock Assessment, where oyster bars are nested within regions. Aggregation at the regional level was done primarily because the model included regional variation in natural mortality, recruitment, and fishing mortality. Regional summaries were also necessary to compare estimates with the stock assessment estimates and to provide spatial outputs of performance measures.

Fishing Season (October-March)

Abundance, N (Table 1), in year $y + 1$, season $t = 1$, on bar b was calculated as

$$N_{y+1,t=1,b,s} = \{N_{y,t=2,b,s=sp},\ if\ s = sp\ N_{y,t=2,b,s=sm} e^{(-sel_{sm} F_{y,b})},\ if\ s = sm\ N_{y,t=2,b,s=mk} e^{(-F_{y,b})},\ if\ s = mk\ .$$

Fishing mortality F in year y, season $t = 2$, on bar b for stage s was modeled as a function of density-dependent fishing intensity f in year y on bar b, selectivity *sel* for stage s, and a random deviation that varied by region r and year y,

$$F_{y,b} = f_{p,b} sel_s \varepsilon_{y,r}. \qquad (2)$$

Fishing intensity was a function of density that provided a continuous approximation of harvesting all oysters above a minimum threshold,

$$f_{p,b} = \frac{\xi_{p,g,4}(1-e^{\xi_{p,g,1} D_{y,t,b,s}})}{1+e^{-\xi_{p,g,2}(D_{y,t,b,s}-\xi_{p,g,3})}} \qquad (3)$$

where $\xi_{p,g,n}$ are period and gear specific parameters that determine the relationship between density of market oysters and the fully-selected fishing mortality rate and

$$D_{y,t=1,b,s=mk} = \frac{N_{y,t=1,b,s=mk}}{0.2A_{b,total}} \qquad (4)$$

where $A_{b,total}$ is the total area of oyster bar b and we assumed that oysters were aggregated on 20% of the oyster bar on average. To constrain the $f_{p,g}$ function to reasonable values for fishing mortality, the $\xi_{p,g,1}$ and $\xi_{p.g,3}$ parameters were written in terms of $\xi_{p,g,2}$,

$$\xi_{p,g,1} =- 4.5365 + 1.2178 f_{p,g,2}, \qquad (5)$$

$$f_{p,g,3} = 1.9862(f_{p,g,2})^2 - 6.1153 f_{p,g,2} + 5.3886, \qquad (6)$$

and $f_{p,g,4}$ was set to 3, which restricts fishing mortality to a maximum exploitation rate of about 0.95. The parameter values for eq. 5 and 6 were chosen by first developing a series of relationships of fishing mortality rates as a function of critical density, where it was modeled that all oysters above a critical threshold were harvested. Critical thresholds of between 1 and 20 oysters per m^2 were considered. Parameter values for eq. 5 and eq. 6 were estimated by finding parameter values that resulted in approximate matches of the functions using linear models.

For each bar, only one gear type was allowed in the model so that harvest by that gear type represented all harvest from a given bar. The gear type for each bar was determined by the gear type with the most harvest from each bar and if there was not reported harvest from a bar, then gear type was determined by gear-specific harvest from the closest bar and regulations on allowed gears. Five gear types were included: (1) hand tong, (2) power dredge, (3) sail dredge, and (4) patent tong, and (5) diver. To account for changes in regulations/conditions that affect fishing mortality as a function of density over time, we specified separate time periods (p)

$$p = \{1,\ if\ 1999 \leq y \leq 2010\ or\ y = 2020\ 2,\ if\ 2011 \leq y \leq 2018\ 3,\ if\ y = 2019. \qquad (7)$$

The first period corresponds to years with relatively low harvest, the second represents a time with increased harvest, and the third corresponds to a change in regulations beginning in the 2019-2020 season that reduced the daily bushel limits for each gear type, restricted harvesting to four days a week, and allowed no harvest above the Bay Bridge. The year 2020 was included in period 1 due to effects of Covid-19 that restricted demand for oysters. Stage specific selectivity was specified as

$$sel_s = \{0,\ if\ s = sp\ 0.01,\ if\ s = sm\ 1,\ if\ s = mk\ . \qquad (8)$$

The value of 0.01 for small oysters was selected because it resulted in the proportion of small oysters in the harvest of 0.05, which is similar to the proportion of small oysters observed during sampling of harvest in 2018 (Maryland Department of Natural Resources 2018).

The number of oysters harvested C in year y on bar b was calculated as

$$C_{y,b} = \sum_s N_{y,t=2,b,s}\left(1 - e^{-F_{y,b,s}}\right) \qquad (9)$$

and was converted into bushels using $B_{y,b} = C_{y,b}/c_B$ where c_B is a constant that converts abundance to bushels (36 L). The constant c_B was set equal to 226 oysters per bushel based on data from the 2018 Maryland Oyster Stock Assessment (Mace et al. 2021).

Outside of Fishing Season (April-September)

Recruitment, natural mortality, and growth were modeled to occur outside of the fishing season, the same as the Maryland Oyster Stock Assessment (citation). Oyster management activities, such as planting substrate of oysters, and other habitat related processes were also modeled as occurring during April-September. Recruitment is thought to largely occur during July-September, most natural mortality is thought to occur during late-spring to early fall, and most growth should occur during the periods with higher temperatures and food availability (Mace et al. 2021). The majority of shell and spat planting activities occur during April-September (MD DNR unpublished data).

The total number of recruits (i.e., $N_{s=sp}$) for year y, season $t = 1$, on bar b was a function of the density $\widetilde{D}$ of recruits per L of habitat in year y, season $t = 1$, on bar b, the volume V of habitat category h in year y, season $t = 2$, on bar b, the number of spat planted N_P in year y, season $t = 1$, on bar b, and the survival S_P of planted spat from the time of planting to September 30,

$$N_{y,t=2,b,s=sp} = P_{y,t=1,b} S_P + c_R \widetilde{D}_{y,t=1,b,s=sp} V_{y,t=1,b,h=fresh} + \sum_{h \neq fresh} V_{y,t=1,b,h} \widetilde{D}_{y,t=1,b,s=sp}. \quad (10)$$

An increase in recruitment for $V_{h=fresh}$ by a constant $c_R = 4.3$ was included to account for the higher relative recruitment of oysters on recently planted (i.e., fresh) shell compared to older shell (MD DNR unpublished data). The survival S_p of planted spat from the time of planting to October 1 was set at 0.22.

The density $\widetilde{D}$ of recruits per liter of habitat in year y, season $t = 1$, on bar b was modeled using a form of the Beverton-Holt type spawner-recruit curve (Quinn and Deriso 1999),

$$\widetilde{D}_{y,t=2,b,s=sp} = \left(\frac{\widetilde{D}_{y,t=2,b,eggs}}{e^{\alpha_r} - \frac{\beta}{\alpha_r} \widetilde{D}_{y,t=2,b,eggs} + \frac{\beta}{\alpha_r} \widetilde{D}_{y,t=2,b,eggs} e^{\alpha_r}} \right) e^{\zeta_{y,r}} \quad (11)$$

where α_r represents the region-specific density independent processes affecting larval mortality, β is a constant that represents the density-dependent processes affecting larval mortality, and $\zeta_{y,r}$ are year and region-specific recruitment deviations that were modeled as a log-normal random variable, $\zeta_{y,r} \sim N(0, \sigma_R)$, where σ_R is the log-scale standard deviation of recruitment among years and regions, and $\widetilde{D}_{y,t=2,b,eggs}$ is the density of eggs per liter of habitat in year y on bar b that was calculated as

$$\widetilde{D}_{y,t=2,b,eggs} = \frac{\sum_{b'} T_{b',b} E_{y,b'}}{\sum_{h} V_{y,t=1,b,h}} \quad (12)$$

where $T_{b',b}$ is the probability of larvae produced at bar b' to be transported to bar b, $E_{y,b'}$ is the total number of eggs produced on bar b' in year y, and $V_{y,t=2,b,h}$ is the total volume of habitat category h in year y, season $t = 1$, on bar b. We attempted to include region-specific density-dependent values for the β parameter in eq. 11, but when included, the estimates were close to 0 and the model was numerically unstable. Also, we expect that density dependence would primarily be driven by competition for space, which should be a similar process across all of Maryland. Therefore, we chose to just specify one overall β value for all regions. Estimates of the proportion of larvae that were produced on bar b' and transported to bar b were produced by a larval transport model (see Chapter 2).

The total number of eggs E produced in year y on bar b was a product of abundance N in year y on bar b for stage s, the average fecundity, x, of female oysters in s, the proportion female oysters, r, in stage s, and the proportion of mature oysters m in stage s summed over stages,

$$E_{y,t=2,b} = \sum_{s} N_{y,t=2,b,s}\, x_s\, r_s\, m_s\,. \qquad (13)$$

All small and market oysters were assumed to be mature, and spat were assumed to be immature,

$$m_s = \begin{cases} 0, & if\ s = sp \\ 1, & if\ s = sm \\ 1, & if\ s = mk \end{cases}. \qquad (14)$$

Female fecundity (i.e., number of eggs produced by a female) for an oyster in stage s was specified as (Choi et al. 1993)

$$x_s = \begin{cases} 0, & if\ s = sp \\ 14,000,000, & if\ s = sm \\ 32,000,000, & if\ s = mk \end{cases}. \qquad (15)$$

Oysters are partial sequential hermaphrodites where the proportion of females increases with size. The ratio of male to female oysters at stage s was calculated as

$$r_s = \begin{cases} 0, & if\ s = sp \\ 0.3, & if\ s = sm \\ 0.6, & if\ s = mk \end{cases}. \qquad (16)$$

The abundance N of small oysters in year y, at the beginning of fall (season $t = 2$), on bar b was calculated as

$$N_{y,t=2,b,sm} = S_{sp} N_{y,t=1,b,s=sp} + N_{y,t=2,b,s=sm}(1 - G_r)e^{M_{y,r,s=sm}} + S_w W_{y,b} \qquad (17)$$

where $M_{y,r,s}$ is the natural mortality rate for year y in region r for oysters in stage s, G_r is the probability of transition from the small to market stage in region r, $W_{y,b}$ is the number of wild seed oysters planted in year y on bar b, and S_w is the survival of wild seed oysters from the time of planting until October 1. The value of S_{sp} was specified as 0.5 (Wilberg et al. 2011; Damiano and Wilberg 2019; Mace et al. 2021). Data for wild seed plantings were originally in bushels planted and to convert to individuals we assumed that there were 1,267 individuals per bushel.

The abundance N of market oysters in year y, season $t = 2$, on bar b was calculated as

$$N_{y,t=2,b} = N_{y,t=1,b,s=sm} G_r e^{M_{y,r,s=sm}} + N_{y,t=1,b,s=mk} e^{M_{y,r,s=mk}} \qquad (18)$$

Natural mortality rates were assumed to be the same for small and market oysters (Mace et al. 2021). Estimated proportions of individuals that grew from small to market oysters each year were taken from the most recent updated stock assessment (Maryland Department of Natural Resources 2020).

Habitat

The total volume V of habitat in year y in season t on bar b was calculated as the sum of habitat volume in all habitat categories h in year y season t on bar b,

$$V_{y,t,b} = \sum_h V_{y,t,b,h}. \qquad (19)$$

There were four categories of habitat on each oyster bar: (1) live oysters, (2) old shell - this includes oysters that were not removed by fishing activity and died naturally and also planted shell that degrades over time, (3) fresh shell, and (4) alternate substrate.

Habitat volume V for live oysters ($h = live$) in year $y + 1$ on bar b in season t was calculated as

$$V_{y,t,b,h=live} = \sum_{s \neq sp} \frac{N_{y,t,b,s}}{\lambda_s} \qquad (20)$$

where λ is a constant that converts abundance of oysters in stage s to volume. The value of λ for small oysters was 600 and for market oysters was 350 per Maryland bushel (Maryland DNR unpublished data). Spat did not contribute to habitat. Maryland bushels were converted to Liters using 46 L/Maryland bushel.

Habitat volume V for old shell ($h = old$) in year $y + 1$ in season $t = 1$ on bar b was calculated as

$$V_{y+1,t=1,b,h=old} = (1 - \delta_{shell})V_{y,t=2,b,h=old} + (e^{-\eta})\nu V_{y,t=2,b,h=fresh} \qquad (21)$$

where $\delta_{r,shell}$ is the annual rate of habitat decay for shell (2.1% per yer), $V_{y,t=2,b,h=old}$ is the volume of old shell on bar b in year y in season $t = 2$, η is the instantaneous rate of loss of planted shell, ν is the proportion of fresh shell converted to old shell each year (70%), and $V_{y,t=2,b,h=fresh}$ is the volume of fresh shell in year y on bar b. The value of η was specified as 0.3 based on Smith et al. (2005).

Habitat volume V for old shell in year y in season $t = 2$ on bar b was calculated as the sum of old shell in the previous season and the number of small and market oysters that died from natural mortality,

$$V_{y,t=2,b,h=old} = V_{y,t=1,b,h=old} + \sum_{s \neq sp} N_{y,t=1,b,s}(1 - e^{M_{y,r,s}}).$$

Habitat volume V for fresh shell ($h = fresh$) in year $y + 1$ in season $t = 1$ on bar b was calculated as the sum of fresh shell that remained from the previous year and newly planted shell,

$$V_{y+1,t=1,b,h=fresh} = e^{-\eta}(1 - \nu)V_{y,t=2,b,h=fresh} + P_{y+1,b,h=fresh} \qquad (22)$$

where $P_{y,b,m=fresh}$ is the volume of shell planted in year y on bar b.

Habitat volume for fresh shell in year y in season $t = 2$ on bar b was equal to the volume of habitat in season $t = 1$ (i.e., $V_{y,t=2,b,h=fresh} = V_{y,t=1,b,h=fresh}$).

Habitat volume V for alternate substrate ($h = alt$) in year $y + 1$ in season $t = 1$ on bar b was calculated as

$$V_{y+1,t=1,b,h=alt} = (1 - \delta_{alt})V_{y,t=2,b,h=alt} + P_{y+1,b,m=alt} \qquad (23)$$

where δ_{alt} is the proportion of alternate substrate lost each year due to degradation, $V_{y,b,h=alt}$ is the volume of alternate substrate in year y on bar b, and $P_{y+1,b,m=alt}$ is the volume of alternate substrate planted in year $y + 1$ on bar b. Habitat volume for alternate substrate in year $y + 1$ in season $t = 2$ on bar b was equal to the volume of habitat in season $t = 1$ (i.e., $V_{y+1,t=2,b,h=alt} = V_{y+1,t=1,b,h=alt}$). The proportion of alternate substrate lost each year due to degradation was set at 0.01 per year.

Initial habitat in year $y = 0$ in season $t = 1$ on each bar b was estimated as the sum of habitat categories $h = live$ and $h = old$ for the initial year,

$$V_{0,t=1,b} = V_{0,t=1,b,h=old} + \sum_{s \neq sp} g_s N_{0,t=1,b,s} \qquad (24)$$

where the initial volume of habitat category $h = old$ on bar b was estimated as

$$V_{0,t=1,b,h=old} = \varepsilon_{V_b} V_{b,h=old} \qquad (25)$$

where $V_{b,h=old}$ is an initial estimate of habitat volume based on habitat surveys, etc., and ε_{V_b} is a bar-specific deviation in initial habitat modeled as a lognormal random variable, $\varepsilon_{V_b} \sim N(0, \sigma_{V_b})$, where σ_{V_b} is the log-scale standard deviation for initial habitat deviations among all bars.

Initial Abundance

Initial abundance N in 1999 ($y = 0$) on bar b for stage s was specified based on abundance estimates for region r in which bar b is located. Abundance estimates for region r are based on stage-specific abundance estimates for 1999 from the 2020 Maryland Oyster Stock Assessment Update (Maryland Department of Natural Resources 2020). Stage-specific abundance estimates for region r in 1999 were first apportioned to all bars in region r based on the proportional volume of habitat, $V_{0,b,h=old}$, for each bar,

$$N_{0,b,s} = N_{0,r,s} \frac{V_{0,b,h=old}}{\sum_{b \in r} V_{0,b,h=old}} \qquad (26)$$

where $N_{0,r,s}$ are stage-specific abundance estimates from the Maryland Oyster Stock Assessment.

Conditioning the Operating Model

To ensure that parameter values of the operating model were consistent with the harvest data, planting data, and abundance estimates from the Maryland Oyster Stock Assessment, we fitted the model to data on bar-specific harvest during 1999-2020 and regional abundance estimates during 1999-2020. Bar-specific harvest data were obtained from Maryland Department of Natural Resources. For 1999-2010 and 2019-2020 we used harvest data from seafood dealer buy tickets (hereafter buy tickets) and for 2010-2018 we used individual harvester reports (hereafter harvest reports). We used the harvest reports for 2010-2018 even though data from buy tickets were also available for that time period. We did this because the harvest reports are filled out by individual harvesters while buy tickets are filled out by seafood dealers and so we assumed that the harvest location information in the harvester reports are more accurate than location information in the buy tickets. Stage-specific abundance estimates for each region were available from the 2021 update of the Maryland Oyster Stock Assessment.

Log-normal likelihood functions, with additive constants ignored, were used for abundance and harvest

$$L_X = \sum \frac{1}{2}\left(\frac{ln(X+c)-ln(\hat{X}+c)}{\sigma_X}\right)^2 \qquad (27)$$

where X is spat, small, or market abundance or catch for region r, c is a small constant to increase numerical stability, and σ_X is the log-scale standard deviation for X. The log-scale standard deviation for X was 0.1 for the stock assessment estimates of abundance by stage and was 0.2 for bar-specific harvest.

Other parameters that were estimated by including a penalty in the objective function were region specific deviations ε_r for the a_r, year and region specific recruitment deviations $\varepsilon_{y,r}$; year and region specific deviations in natural mortality; $\xi_{p,g,2}$ for the relationship between fishing mortality and oyster density; the deviation in initial habitat for each bar ε_{V_b}; and year and region specific deviation in fishing mortality $\varepsilon_{y,r}$.

For the region-specific deviations in the a parameter of the egg-recruit relationship the following penalty was applied

$$P_1 = 0.5\sum(\varepsilon_r)^2/0.05, \qquad (28)$$

which assumed a log-scale standard deviation of 0.224. A log-normal penalty was applied to the year- and region-specific deviations in recruitment, natural mortality, and fishing mortality,

$$P_X = \frac{1}{2}\sum_r \sum_y \frac{(X_{y,r} - \overline{X}_r)^2}{\sigma_X} \qquad (29)$$

where $X_{y,r}$ is the year- and region-specific log-scale deviation for X, $\overline{X}_r$ is the mean of $X_{y,r}$ over all years, and σ_X is the log scale standard deviation of X among years. For the year- and region-specific recruitment deviations, $\overline{X}_r$ was set to zero. For natural mortality, $\overline{X}_r$ was the average of the region-specific estimates over all years.

A log-normal penalty was applied to the deviation in initial habitat for each bar ε_{V_b},

$$P_2 = \frac{1}{2}\sum_b \left(\frac{\varepsilon_{V_b}}{\sigma}\right)^2 \qquad (30)$$

A lognormal penalty was applied to the $\xi_{p,g,2}$ parameter for the density dependent fishing mortality

$$P_3 = \frac{1}{2}\sum_p \sum_g (-\ 1.117\ -\ \xi_{p,g,2})^2 / 0.04$$

The objective function was minimized to obtain parameter estimates. The objective function was a combination of likelihoods and penalties

$$L\ = P_1 + P_2 + P_3 + \sum_X L_X + \sum_X P_X \qquad (31)$$

Forecasts of Option Performance

A set of specified management strategies, hereafter referred to as an option, together with values for each of the parameters described above in Conditioning the Operating Model were used to project the performance of options for 25 years. For each option, 200 simulations were run to summarize the variation in performance metrics given the uncertainty in parameter values and future stochastic variability in the relationship of fishing mortality with oyster density, natural mortality, and recruitment. The forecasting model used the same dynamics equations as described for the estimation portion of the operation model.

Management Options

Options consisted of sets of planned planting activities (shell, artificial substrate, spat on shell, and wild seed), sanctuary and open fishing areas, other potential regulations (e.g., returning to the 2018 regulations), rotational harvest areas, moving wild seed, and dredging buried shell. The amount and location (i.e., oyster bar) of shell, alternate substrate, hatchery spat on shell, and wild seed plantings were specified for each option. The gear allowed for oyster harvest on each bar was specified. The locations of oyster sanctuaries, areas where oyster harvest is not allowed, could be specified. Rotational harvest (opening bars for harvest on a specific schedule) could be specified. Dredging of buried shell was also specified for certain options along with the subsequent locations for planting the dredged shell. The specified locations and amounts of management activities were included to describe the actions that would be taken in each of the 25 years of the forecasts. Maps of activities for each option are provided in Appendix A.

Details of Options

Option 1: Status Quo

The status quo option is set up to resemble the oyster management in Maryland during 2010-2020. All planting activity (i.e., shell, hatchery spat, wild seed, and alternate substrate) in this option is based on planting data from 2010-2020. The gear allowed on each bar, including bars that allow no gear (i.e., sanctuaries), is based on regulations during the 2019-2020 fishing season. The pattern of how fishing responds to oyster abundance is based on 2019. For the status quo there are no bars open to rotational harvest and there is no shell dredging on any bars.

Option 2: Seed and Shell 2M bu/yr

The second option is designed to resemble the seed and shell program as it was conducted during 1991-2006. The amount of seed planted each year and the locations of plantings are based on historical data from 1991-2006. Seed bars were modified to remove those north of the Choptank River based on feedback from the OAC. The gear allowed on each bar, including bars that allow no gear (i.e., sanctuaries), is the same as the status quo. There are no bars open to rotational harvest and there is no shell dredging on any bars.

Option 3: Complete Restoration

This option is the same as the status quo except that restoration of the St. Mary's and Manokin Rivers is completed as described in the restoration blueprints.

Option 4: SQ with 2018 Regs

This option is the same as the status quo except for the use of fishing regulations prior to the 2018-2019 season when bushel limits were modified and harvesting oysters was prohibited on Wednesdays.

Option 5: SQ regs, no planting

This option is the same as the status quo except that all plantings (shell, spat on shell, wild seed, and artificial substrate) are stopped. This was done to examine the effect of planting activities similar to those planting activities done during 2010-2020 on oyster populations in Maryland.

Option 6: Power dredging UB

This option is the same as the status quo except that power dredging is allowed on all oyster bars north of the Bay Bridge except those bars that were sanctuaries in 2018.

Option 7: Low harvest bars -> sanctuaries

This option is the same as the status quo except that all oyster bars with < 200 bushels of reported harvest during 1999-2020 were placed into sanctuaries.

Option 8: Open non-rest. sanc.

This option is the same as the status quo except that all oyster bars except for those bars in sanctuaries in large scale restoration tributaries (i.e., Harris Creek, Tred Avon, Little Choptank, Manokin, St. Mary's) are opened to hand tonging.

Option 9: Spat in UB sanc.

This option is the same as the status quo except that all oyster bars above the Bay Bridge receive a one-time planting of hatchery spat. The planting is done on three bars each year spending $500,000 per year until all bars are planted once.

Option 10: Man O War Shoals 50% in Harvest

This option is the same as the status quo except that the plan for dredging shell from Man O War shoals is implemented as described in the permit application. There are 3 scenarios in the permit application for dividing the dredged shell among restoration and fishery areas. This option places 50% of dredge shell in restoration areas and 50% in public fishery areas. Dredging takes place every 3 years and 2 million bushels of shell is dredged each dredging year and then all 2 million bushels placed on oyster bars the same year.

Option 11: Man O War Shoals 10% in Harvest

This option is the same as the status quo except that the plan for dredging shell from Man O War shoals is implemented as described in the permit application. There are 3 scenarios in the permit application for dividing the dredged shell among restoration and fishery areas. This option places 90% of dredge shell in restoration areas and 10% in harvest areas. Dredging takes place every 3 years and 2 million bushels of shell is dredged each dredging year and then all 2 million bushels placed on oyster bars the same year.

Option 12: Man O War Shoals 75% in Harvest

This option is the same as the status quo except that the plan for dredging shell from Man O War shoals is implemented as described in the permit application. There are 3 scenarios in the permit application for dividing the dredged shell among restoration and fishery areas. This option places 25% of dredge shell in restoration areas and 75% in harvest areas. Dredging takes place every 3 years and 2 million bushels of shell is dredged each dredging year and then all 2 million bushels placed on oyster bars the same year.

Option 13: Rotational harvest UB

This option is the same as the status quo except that there are 4 bars in the middle Chester River that are open to rotational harvest. Each bar is open to harvest every four years with only one bar open to harvest in a given year. Each bar is planted with 10 million hatchery spat the year after it is closed to harvesting.

Option 14: New restoration areas 1

This option is the same as the status quo except that there is major restoration work in 5 additional tributaries. For each tributary, 8% of historic bottom is used as a proxy for how much area to restore. Hatchery spat is planted at a target density of 988 individuals per square meter and alternate substrate is planted at a target of 12 inches. The restoration sites in this option include areas in the Nanticoke River, Eastern Bay, South River, Hooper Strait (Tangier Sound), and Chester River.

Option 15: New restoration areas 2

This option is the same as the status quo except that there is major restoration work in 5 additional tributaries. For each tributary, 8% of historic bottom is used as a proxy for how much area to restore. Hatchery spat is planted at a target density of 988 individuals per square meter and alternate substrate is planted at a target of 12 inches. The restoration sites in this option include areas in the Nanticoke River, Point Lookout, Upper Patuxent, Upper Choptank, and Hooper's Strait.

Option 16: New restoration areas 3

This option is the same as the status quo except that there is major restoration work in 5 additional tributaries. For each tributary, 8% of historic bottom is used as a proxy for how much area to restore. Hatchery spat is planted at a target density of 988 individuals per square meter and alternate substrate is planted at a target of 12 inches. The restoration sites in this option include poor performing sanctuaries in Herring Bay, Lower Chester, Calvert Shore, Miles River, and Wye River.

Option 17: Sanc. plantings option A

This option is the same as the status quo except that restoration activity (i.e., hatchery spat and alternate substrate planting) is increased in all sanctuaries that are not part of the large-scale restoration tributaries. The target density for hatchery spat is 2 million per acre and total amount spent each year on hatchery spat is the cost equivalent of 500,000 bushels of shell. No alternate substrate is planted in this option.

Option 18: Sanc. plantings option B

This option is the same as the status quo except that restoration activity (i.e., hatchery spat and alternate substrate planting) is increased in all sanctuaries that are not part of the large-scale restoration tributaries. The target density for hatchery spat is 2 million per acre and total amount spent each year on hatchery spat is the cost equivalent of 1 million bushels of shell. No alternate substrate is planted in this option.

Option 19: Sanc. plantings option C

This option is the same as the status quo except that restoration activity (i.e., hatchery spat and alternate substrate planting) is increased in all sanctuaries that are not part of the large-scale restoration tributaries. The target density for hatchery spat is 2 million per acre. For this option, each sanctuary gets planted with spat on shell every four years. This results in about 996 acres planted annually. No alternate substrate is planted in this option.

Option 20: Sanc. plantings option D

This option is the same as the status quo except that restoration activity (i.e., hatchery spat and alternate substrate planting) is increased in all sanctuaries that are not part of the large-scale restoration tributaries. The target density for hatchery spat is 2 million per acre and target height for artificial substrate is 6 inches. For this option, the amount spent each year is the cost equivalent of 500,000 bushels of shell, which is split evenly between hatchery spat and alternate substrate.

Option 21: Sanc. plantings option E

This option is the same as the status quo except that restoration activity (i.e., hatchery spat and alternate substrate planting) is increased in all sanctuaries that are not part of the large-scale restoration tributaries. The target density for hatchery spat is 2 million per acre and target height for artificial substrate is 6 inches. For this option, the amount spent each year is the cost equivalent of 1 million bushels of shell, which is split evenly between hatchery spat and alternate substrate.

Option 22: Sanc. plantings option F

This option is the same as the status quo except that restoration activity (i.e., hatchery spat and alternate substrate planting) is increased in all sanctuaries that are not part of the large-scale restoration tributaries. For this option, alternate substrate is placed in medium-high salinity sanctuaries at a target height of 6 inches. The amount spent each year is the cost equivalent of 500,000 bushels of shell. No hatchery spat is planted in this option.

Option 23: Sanc. plantings option G

This option is the same as the status quo except that restoration activity (i.e., hatchery spat and alternate substrate planting) is increased in all sanctuaries that are not part of the large-scale restoration tributaries. For this option, alternate substrate is placed in medium-high salinity sanctuaries at a target height of 6 inches. The amount spent each year is the cost equivalent of 1 million bushels of shell. No hatchery spat is planted in this option.

Option 24: 30% bottom in sanc.

This option is the same as the status quo except that the total amount of area in sanctuaries is increased from 24% to 30%. The additional 6% was not selected from the fishery "best bars" but was high quality bottom. A total of 19,270 acres was placed into sanctuaries.

Option 25: No fishing (no plantings)

In this option all public fishery areas are changed to sanctuaries, and no planting is done.

Option 26: Everything open to fishing

This option is the same as the status quo except that all oyster bars are open to fishing. The gear assigned to each bar was based on the gear with the greatest reported harvest or the gear assigned to the nearest bar if no harvest was reported. Areas with artificial substrate present were assigned diver as the harvest gear.

Option 27: 4-yr rotational harvest by region

All oyster bars not in sanctuaries in the large-scale restoration tributaries (i.e., Harris Creek, Tred Avon, Little Choptank, Manokin, St. Mary's) are open to harvest on a rotational schedule with 25% of bars open each year. In this option, the Maryland portion of the bay is divided into 4 different regions, which all are composed of multiple NOAA Codes. Within each region, all bars within a NOAA Code are open to harvest every four years.

Option 28: 4-yr rotational harvest in NOAA codes

All oyster bars not in sanctuaries in the large-scale restoration tributaries (i.e., Harris Creek, Tred Avon, Little Choptank, Manokin, St. Mary's) are open to harvest on a rotational schedule. In this option, 25% of bars within each NOAA Code are opened to harvest every four years on a rotational schedule. The bars are chosen randomly based on the reported harvest during 2010-2018 monthly harvester reports.

Option 29: Opt. 27 + shell and spat

All oyster bars not in sanctuaries in the large-scale restoration tributaries (i.e., Harris Creek, Tred Avon, Little Choptank, Manokin, St. Mary's) are open to harvest on a rotational schedule with 25% of bars open each year and bars are replanted with shell and hatchery spat after they are closed to harvesting. In this option, the Maryland portion of the bay is divided into 4 different regions, which all are composed of multiple NOAA Codes. Within each region, all bars within a NOAA Code are open to harvest every four years. Replanting occurs after a bar is closed and each year there is 250,000 bushels of shell and 400 million hatchery spat planted on bars that recently closed to harvest.

Option 30: Opt. 28 + shell and spat

This option is the same as the status quo except that all oyster bars not in sanctuaries in the large scale restoration tributaries (i.e., Harris Creek, Tred Avon, Little Choptank, Manokin, St. Mary's) are open to harvest on a rotational schedule. In this option, 25% of bars within each NOAA Code are opened to harvest every four years on a rotational schedule. The bars are chosen randomly based on the reported harvest during 2010-2018 monthly harvester reports. Replanting occurs after a bar is closed and each year there is 250,000 bushels of shell and 400 million hatchery spat planted on bars that recently closed to harvest.

Option 31: Constrain to target fishing rates

This option is the same as the status quo except that harvest in each NOAA Code is limited to approximately the target fishing rates from the Maryland Oyster Stock Assessment.

Option 32: Constrain to 75% target fishing rates

This option is the same as the status quo except that harvest in each NOAA Code is limited to approximately 75% of the target fishing rates from the Maryland Oyster Stock Assessment.

Option 33: Seed and Shell 1M bu/yr

This option is the same as Option 2, except that the amount of shell planted is 1 million bushels per year.

Option 34: Seed and Shell 500k bu/yr

This option is the same as Option 2, except that the amount of shell planted is 500,000 bushels per year

Option 35: 14.a - 14 except using shell as substrate

This option is the same as option 14 except shell is used for restoration activities instead of artificial substrate

Option 36: 15.a - 15 except using shell as substrate

This option is the same as option 15 except shell is used for restoration activities instead of artificial substrate

Option 37: 16.a - 16 except using shell as substrate

This option is the same as option 16 except shell is used for restoration activities instead of artificial substrate

Option 38: Lit. Chop. rotation with $600,000 spat on shell/yr

This option is the same as the status quo except that there is a rotational harvest schedule for oyster bars in the tributaries (prongs) of the Little Choptank sanctuary where no restoration work had been done. There are a total of 7 bars used in the rotational harvest with all bars open for harvest every 2 years and planted with the equivalent of $600,000 worth of hatchery spat after they are closed to harvest. The bars are divided up so that 3 bars are open all together in one year and the other 4 bars are open to harvest the following year.

Option 39: Lit. Chop. rotation with $600,000 shell/yr

This option is the same as the status quo except that there is a rotational harvest schedule for oyster bars in the tributaries (prongs) of the Little Choptank sanctuary where no restoration work had been done. There are a total of 7 bars used in the rotational harvest with all bars open for harvest every 2 years and planted with the equivalent of $600,000 worth of shell after they are closed to harvest. The bars are divided up so that 3 bars are open all together in one year and the other 4 bars are open to harvest the following year.

Option 40: Lit. Chop. rotation with $150,000 spat on shell/yr

This option is the same as the status quo except that there is a rotational harvest schedule for oyster bars in the tributaries (prongs) of the Little Choptank sanctuary where no restoration work had been done. There are a total of 7 bars used in the rotational harvest with all bars open for harvest every 2 years and planted with the equivalent of $150,000 worth of hatchery spat after they are closed to harvest. The bars are divided up so that 3 bars are open all together in one year and the other 4 bars are open to harvest the following year.

Option 41: Lit. Chop. rotation with $150,000 shell/yr

This option is the same as the status quo except that there is a rotational harvest schedule for oyster bars in the tributaries (prongs) of the Little Choptank sanctuary where no restoration work had been done. There are a total of 7 bars used in the rotational harvest with all bars open for harvest every 2 years and planted with the equivalent of $150,000 worth of shell after they are closed to harvest. The bars are divided up so that 3 bars are open all together in one year and the other 4 bars are open to harvest the following year.

Option 42: East. Bay $1M for rest. (spat), $500K fishery (shell and spat)

This option is the same as the status quo except that there is additional shell and hatchery seed plantings on sanctuary and fishery bars in Eastern Bay. For this option there was $1,000,000 spent each year on planting hatchery spat in sanctuaries with 250 million hatchery spat planted annually at 6 million per acre. For this option, there was $500,000 spent each year on planting shell and hatchery spat in public fishery areas. There was $200,000 spent on planting 50 million hatchery spat at 1 million per acre and $300,000 spent on planting 30 acres with shell at 2000 bushels per acre.

Option 43: East. Bay $1M for rest. (spat), $1M fishery (shell and spat)

This option is the same as the status quo except that there is additional shell and hatchery seed plantings on sanctuary and fishery bars in Eastern Bay. For this option there was $1,000,000 spent each year on planting hatchery spat in sanctuaries with 250 million hatchery spat planted annually at 6 million per acre. For this option, there was $1,000,000 spent each year on planting shell and hatchery spat in public fishery areas. There was $400,000 spent on planting 100 million hatchery spat at 1 million per acre and $600,000 spent on planting 60 acres with shell at 2000 bushels per acre.

Option 44: Combo 19 + 3

This option is a combination of options 19 and 3.

Option 45: Combo 14 + 3

This option is a combination of options 14 and 3.

Option 46: Combo 19 + 3 + 31

This option is a combination of options 19, 3, and 31.

Option 47: Combo 14 + 3 + 31

This option is a combination of options 14, 3, and 31.

Option 48: Combo 21 + 3

This option is a combination of options 21 and 3.

Option 49: Combo 21 + 3 + 31

This option is a combination of options 21, 3, and 31.

Option 50: 2.a Seed and Shell (no seed)

This option is the same as option 2, but no natural seed is removed or planted.

Option 51: 33.a Seed and shell $1M (no seed)

This option is the same as option 33, but no natural seed is removed or planted.

Option 52: 34.a Seed and shell $500k (no seed)

This option is the same as option 34, but no natural seed is removed or planted.

Option 53: Combo 3 + 7

This option is a combination of options 3 and 7.

Option 54: Rotational harvest Up. Bay sanc. (no planting)

This option is the same as the status quo, except all sanctuaries (Upper Chester River, Chester ORA, Lower Chester River, Man-O-War Shoals, and Magothy) above the bay bridge are removed and converted to public fishery areas with a rotational harvest schedule. Each bar is open every 4 years, with different bars open different years so there are always some bars open to harvest in a given year.

Option 55: Rotational harvest Up. Bay Sanc. (w/ spat)

This option is the same as the status quo, except all sanctuaries (Upper Chester River, Chester ORA, Lower Chester River, Man-O-War Shoals, and Magothy) above the Bay Bridge are removed and converted to public fishery areas with a rotational harvest schedule. Each bar is open every 4 years, with different bars open different years so there are always some bars open to harvest in a given year. In this option, each bar is planted with hatchery spat the year after it is open to fishing. Hatchery spat are planted at a density of 1 million per acre and only up to 50 million are planted on each bar.

Option 56: Remove low productivity sanctuaries (cat. C&D)

This option is the same as the status quo except that low performing sanctuaries (categories C & D) are removed and converted to public fishery areas. Data on the rank of each sanctuary from the MD DNR Oyster Management Review 2016-2020 (Maryland Department of Natural Resources 2021) was used to select poor performing sanctuaries that were converted to public fishery areas.

Option 57: Remove low productivity sanctuaries (replace with other bottom)

This option is the same as the status quo except that low performing sanctuaries (categories C & D) are removed and converted to public fishery areas. Sanctuary area was then increased back to 20%. The new sanctuary area was not selected from the fishery "best bars" but was high quality bottom. Data on the rank of each sanctuary from the MD DNR Oyster Management Review 2016-2020 (Maryland Department of Natural Resources 2021) was used to select poor performing sanctuaries that were converted to public fishery areas.

Option 58: Low productivity sanctuaries become rotational areas (cat. C&D)

This option is the same as the status quo except that low performing sanctuaries (categories C & D) are removed and converted to public fishery areas on a rotational harvest schedule. Data on the rank of each sanctuary from the MD DNR Oyster Management Review 2016-2020 (Maryland Department of Natural Resources 2021) was used to select poor performing sanctuaries that were converted to public fishery areas. Each bar in the rotational harvest schedule was open once every five years and the year a given bar was open was chosen so that there were bars open for harvest each year. There were no plantings after a bar had been opened to harvest.

Option 59: Upper Patuxent Sanctuary to 4 yr rotational harvest (no planting)

This option is the same as the status quo except that sanctuary areas in the upper Patuxent River were converted to public fishery areas on a rotational harvest schedule. Each bar is open every 4 years, with different bars open different years so there are always some bars open to harvest in a given year. There were no plantings after a bar had been opened to harvest.

Option 60: Upper Patuxent Sanctuary to 4 yr rotational harvest (spat)

This option is the same as the status quo except that sanctuary areas in the upper Patuxent River were converted to public fishery areas on a rotational harvest schedule. Each bar is open every 4 years, with different bars open different years so there are always some bars open to harvest in a given year. After being open to harvest, bars were planted with hatchery spat at a density of 1 million individuals per acre.

Option 61: All 51 sanctuaries open to public fishery

This option is the same as the status quo except that all sanctuaries are converted to public fishery areas (same as option 26).

Option 62: All 51 sanctuaries open to public fishery as rotational areas

This option is the same as the status quo except that all sanctuaries are converted to public fishery areas on a rotational harvest schedule. Each bar is open every 4 years, with different bars open different years so there are always some bars open to harvest in a given year. There were no plantings after a bar had been opened to harvest.

Option 63: Combo 2+3+4+13+14 (some options modified)

This option is a combination of options 2, 3, 4, 13, and 14 with some modifications. Option 3 is included with the addition of the completion of the St. Mary's and Manokin Rivers using only shell and hatchery seed. Gear allowed on each bar, including bars that allow no gear (i.e., sanctuaries) is based on 2019-2020 fishing season except for the Upper Bay. Option 14 is included with restoration in Eastern Bay, South River, Severn, Upper Patuxent River, Herring Bay, with no alternative substrate used in restoration activities. Option 4 was included with 2018 fishing regulations: 5 days a week fishing and pre-2019 bushel limits for all gears. The author of this option intended for shell to be recovered from low performing oyster bars, but it was not possible to implement in the model. Therefore, the option assumes enough shell is available for the management. Hatchery spat on shell and wild Seed from Virginia are planted in public fishery areas. All sanctuaries all bars north of the Bay Bridge are converted to public fishery areas, and all bars in the upper bay are placed in a rotation harvest with 25% of bars open every four years. Each bar is planted with hatchery seed at a density of 1 million per acre with a maximum of 50 million individuals planted on a bar in a given year.

Option 64: Combo 2+3+14+54+59 (w/ modifications

This option is a combination of options 2, 3, 14, 15, 54, and 59 with some modifications. This option includes completion of the St. Mary's and Manokin Rivers using only shell and hatchery seed. Complete large-scale restoration in the following current sanctuaries: Severn, South, Herring Bay, Up. Choptank & ORA, Breton Bay, Miles, Calvert Shore. Remove Up Patuxent sanctuary and do rotational harvest with out-of-state seed and SOS replenishment plantings. Remove all sanctuaries above Bay Bridge and do rotational harvest with replenishment on a 4 yr cycle. Remove Wicomico River West sanctuaries and conduct rotational harvest with out-of-state seed and spat on shell replenishment plantings on a 4 yr cycle. Conduct the old shell program (no seed) on fishery bars in med-high salinity areas of Dorchester, St Marys, Calvert, Somsert, Wicomico, Talbot. Conduct the old seed program (out-of-state seed and spat on shell) in low-med areas of Kent, Baltimore, Charles, Anne Arundel, and Queen Annes fishery bars. Uses pre-2019 fishing regulations.

Option 66: 2 with seed from VA

This option is the same as option 2 except that all wild seed planted is from out of state.

Option 67: Sanctuary seed areas

This option is the same as the status quo except that some oyster bars in sanctuaries, in the Honga, Naticoke, and Manokin Rivers, are used as seed bars for planting of wild seed on other bars throughout Maryland. A total of seven bars are used as seed bars. On these bars, wild seed is removed every seven years and prior to the year of removal, 40,000 bushels of shell are planted on each bar. The seed removed from these bars are planted in Eastern Bay, the mainstem, the lower and mid Choptank River, Tred Avon River, Miles River, the lower Patuxent River, the South River, and the Wicomico River. All wild seed is planted in public fishery areas.

Option 68: SOAR plant aquaculture adults in sanctuaries

This option is the same as the status quo except that oysters are purchased from aquaculture operations and planted in sanctuaries. For this option, there are 2 million small oysters (> 1 year old and less than 3 inches long) planted each year. The plantings are divided evenly among 10 sanctuary bars each year.

Option 69: Combo 10 + 33

This option is a combination of options 10 and 33.

Option 70: There was no model option #70

Option 71: Combo 16 + 33

This option is a combination of options 16 and 33.

Option 72: Combo 31 + 33

This option is a combination of options 31 and 33.

Option 73: Combo 32 + 33

This option is a combination of options 32 and 33.

Option 74: 10 but use 7 Foot Knoll (500k bu/yr)

This option is the same as the status quo except that Seven Foot Knoll is dredged every 2 years. Each time dredging takes place there is 500,000 bushels of shell removed. Fifty percent of the dredged shell is planted in public fishery areas and 50% is planted in sanctuaries.

Parameter Values

Parameter values for each simulation were drawn from a multivariate normal distribution defined by the estimated parameters and their asymptotic variance-covariance matrix. Additionally, values of year-specific deviations were needed for recruitment, natural mortality, and fishing mortality. The deviations in recruitment among regions Y for each simulation year sy were drawn from a multivariate normal distribution

$$Y_{sy} \sim MVN(\mu, \Sigma) \qquad (32)$$

where μ is a vector of length j, where j is the number of regions, and each element μ_r is the mean of recruitment deviations for region r during 1999-2020 from the estimation model (Conditioning the Operating Model),

$$\mu_i = \frac{\sum_{y=0}^{n} \hat{\varepsilon}_{y,r}}{n} \qquad (33)$$

where n is the number of years during 1999-2020. The variance-covariance matrix Σ has j rows and j columns and was the variance-covariance matrix of recruitment deviations during 1999-2020 among regions. Deviations among regions for natural mortality and fishing mortality were also drawn from a multivariate normal distribution as described above. This approach to forecasting assumes that the spatial covariance patterns will be the same during the next 25 years as they were during 1999-2020.

Performance Measures

Performance measures are used to compare how well options are expected to achieve oyster management and stakeholder goals. The primary performance measures used were oyster abundance, surface habitat (shell and artificial substrate), fishery harvest, fishery revenue, nitrogen removal, and performance versus the reference points from the most recent update of the Maryland Oyster Stock Assessment. Performance measures were summarized over specific periods (e.g., average over first five or last ten years of projections or proportion of the time above or below a management reference point) to capture performance of an option. The primary goal of the performance measures is to allow comparison among options. The uncertainty in expected performance of any given option is quite high for specific measures like how many oysters will there be in ten years or what will the harvest be in 15 years.

Oyster Abundance

Two performance measures were calculated to represent change in oyster abundance. First, adult abundance in year y was calculated as the sum of small and market abundance in season $t = 1$

$$N_{y,t=1,adult} = \sum_{b} \sum_{s \neq sp} N_{y,t=1,b,s} \qquad (34)$$

and the abundance of market oysters in year y in season $t = 1$ was also used as a metric for oyster abundance

$$N_{y,t=1,s=mk} = \sum_b N_{y,t=1,b,s=mk} \qquad (35)$$

These metrics for oyster abundance were used because market oysters are the focus of the commercial oyster fishery in Maryland and adult oysters, small and markets stages, are the individuals capable of reproduction.

Surface Habitat

The total volume of oyster habitat in year y for season $t = 1$ was calculated as the sum of the volume of all habitat types on all bars

$$V_{y,t=1} = \sum_b \sum_h V_{y,t=1,b,h}. \qquad (36)$$

Fishery Harvest and Revenue

Total harvest in year y was calculated as the sum of harvest from all bars in year y

$$C_y = \sum_b C_{y,b}, \qquad (37)$$

and total revenue in year y was calculated as the product of total harvest and the price for a bushel of oysters $Rev_y = C_y price$. The price for a bushel of oysters was set at \$45.58, which was the average price per bushel in October-February 2019 (most recent pre_Covid months).

Nitrogen Removal

The amount of nitrogen removed from the water column each year due to denitrification was the sum of nitrogen removed in summer and fall seasons

$$Nitro_y = \frac{14.1}{1000} (Nitro_{y,t=1} + Nitro_{y,t=2})4416 \qquad (38)$$

where $14.1/1000$ in the kg/mole and 4416 is the number of hours in summer and fall[3]. Nitrogen removal in the summer (in moles per hr) is calculated as a function of abundance $N_{y,b,s}$, and average dry weight of oysters in stage s,

$$Nitro_{y,t=1} = \sum_b \sum_s 0.6401 c_{d,s} N_{y,t=1,b,s} + 193.79. \qquad (39)$$

Nitrogen removal in the fall (in moles per hr) is calculated as

[3] The model results shown in the OAC meetings did not properly account for the number of hours in the seasons in which we modeled nitrogen removal as occurring. This was corrected for the numbers in this report.

$$Nitro_{y,t=2} = \sum_b \sum_s 03653 c_{d,s} N_{y,t=1,b,s} + 72.192. \qquad (40)$$

These relationships between density and nitrogen removal were from Kellogg et al. (2021).

The dry weight of oysters was calculated as

$$c_{d,s} = c^{2.29} \cdot 3.6 \times 10^{-5} \qquad (41)$$

where the median shell height in mm for each stage (c) was,

$$c = \{30,\ if\ s = sp\ 60,\ if\ s = sm\ 85,\ if\ s = mk\ . \qquad (42)$$

The amount of nitrogen removed each year due to harvest is a function of the number of small and market oysters harvested

$$Nitro_{y,catch} = \sum_b c_{sm} C_{y,t=1,b,s=sm} + c_{mk} C_{y,t=1,b,s=mk} \qquad (43)$$

where $c_{sm} = 0.07$ and $c_{mk} = 0.12$ convert number of oysters to kilograms of nitrogen. The value of nitrogen removal was also calculated using a price per pound of $1036 (see Chapter 3).

Abundance and Fishing Mortality Reference Points

The abundance and target and limit harvest rate reference points from the 2020 Maryland Oyster Stock Assessment (Maryland Department of Natural Resources 2020) were compared to the abundance and harvest rate values for each year in the forward simulations to determine the proportion of years within a simulation when the fishing mortality reference point was above the target or limit reference point and when the abundance reference point was below the limit reference point. Calculation of the harvest rates followed the same approach to account for planted oysters as was done in the stock assessment (Maryland Department of Natural Resources 2018).

Results

All options described above were run and specific results for each option can be found in Appendix A (Fig. A1 to Fig. A288 and Table A.1). For each option, the value of every performance measure was calculated relative to the status quo in the short term during 2023-2027 (Fig. 1 to Fig. 6) and the long term during 2035-2055 (Fig. 7 to Fig. 12). In each figure, individual performance measures are listed from top to bottom and if the associated bar is to the left and blue, then the value of the performance measure in that option is worse than the status quo. If the associated bar is the to the right and red, then the value of the performance measure for that option is better than the status quo.

The bill entitled Natural Resources - Fishery Management Plans - Oysters (Per Natural Resources Article § 4-215(e)(5)(iii)1, Annotated Code of Maryland, SB 808, Chapter 598 and HB 911, Chapter 597, MSAR 12769) specified that any management actions put forth by the Oyster Advisory Committee should result in an increase oyster abundance and oyster habitat. Therefore, for each option, the abundance of adult (small and market) oysters and total volume of habitat was compared between 2019 and 2046 to determine if there was an expected increase or decrease. The amount of harvest was also compared between 2019 and 2044 to determine if there was an expected increase or decrease.

The options that had a >50% probability of an increase in adult abundance, total habitat volume, and harvest relative to 2019 were 63 and 64 (Table 2). There were no options that had a >50% probability of an increase in two of the three comparisons (adult abundance, total shell volume, or harvest). Options that had an increase only in adult abundance were 18, 19, 21, 22, 23, 43, 44, 46, 47, 48, 49, 66 and only in harvest was 67. There were no options that resulted in only an increase in total habitat volume.

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Table 1. Definition of variables used in operating model.

Variable	Description	Value
	Indicator variables/subscripts	
y	year	1999-2020
t	season	1 = October-March 2 = April-September
b	oyster bar	1-1182
s	stage	sp = spat sm = small mk = market
r	region	1-36
p	time period	1 = 1999-2010, 2020 2 = 2011-2018 3 = 2019
g	harvest gear	1 = hand tong, 2 = power dredge, 3 = sail dredge, 4 = patent tong, 5 = diver
h	habitat type	1 = live oysters, 2 = old shell, 3 = fresh shell, 4 = alternate substrate
	Estimated parameters	
$\zeta_{y,r}$	year and region-specific deviations in recruitment	estimated
$\varepsilon_{y,r}$	year and region-specific deviations in fishing mortality	estimated
M	natural mortality	estimated
ε_{v_b}	deviations in initial habitat on each oyster bar	estimated
ξ_2	parameter for density-dependent fishing intensity function	estimated
α	density independent egg-recruit parameter	estimated

β	density dependent egg-recruit parameter	estimated
	Calculated/Specified quantities	
N	abundance	calculated
F	fishing mortality rate	calculated
f	fishing intensity	calculated
D	density per m^2	calculated
$\widetilde{D}$	density per liter of habitat	calculated
ξ_1	Parameter of fishing intensity-density relationship	calculated
ξ_3	Parameter of fishing intensity-density relationship	calculated
ξ_4	Parameter of fishing intensity-density relationship	calculated
sel	fishery selectivity	$\{0,\ if\ s\ =\ sp\ 0.01,\ if\ s\ =$
C	fishery catch	calculated
V	habitat volume	calculated
P	hatchery spat	calculated
S_p	survival of hatchery spat from planting until October 1	0.22
c_R	proportional increase for recruitment on fresh shell	4.3
$T_{b',b}$		calculated
E	number of eggs produced by female oysters	calculated
x	female fecundity (i.e., number of eggs by one female)	$\{0,\ if\ s\ =\ sp\ 14,000,000,$
r	ratio of male to female individuals	$\{0,\ if\ s\ =\ sp\ 0.3,\ if\ s\ =\ s$
m	proportion of mature individuals	$\{0,\ if\ s\ =\ sp\ 1,\ if\ s\ =\ sm$

S_{sp}	Survival of spat from planting to October 1	0.5
G	probability of transition from small to market stage	from 2020 Maryland Oyster Stock Assessment
W	wild seed planted	calculated
S_{W}	survival of wild seed from planting to October 1	1.0
λ	conversion from oyster abundance to volume	$\{600, \ if\ s = sm\ 350, \ if\ s$
δ_{shell}	annual rate of habitat decay for shell	0.021
η	instantaneous rate of loss for planted shell	0.3
ν	proportion of fresh shell converted to old shell annually	0.70
P	planted substrate	calculated
δ_{alt}	annual rate of habitat decay for alternate substrate	0.01

Table 2. Did total (over the whole area modeled) adult abundance, surface shell, and harvest increase from 2019 to 2046?

Option	Abundance	Surface Shell	Harvest
1	No	No	No
2	No	No	No
3	No	No	No
4	No	No	No
5	No	No	No
6	No	No	No
7	No	No	No
8	No	No	No
9	No	No	No
10	No	No	No
11	No	No	No
12	No	No	No
13	No	No	No
14	No	No	No
15	No	No	No
16	No	No	No
17	No	No	No
18	Yes	No	No
19	Yes	No	No
20	No	No	No
21	Yes	No	No
22	Yes	No	No
23	Yes	No	No
24	No	No	No
25	No	No	No
26	No	No	No
27	No	No	No
28	No	No	No
29	No	No	No
30	No	No	No
31	No	No	No
32	No	No	No
33	No	No	No
34	No	No	No
35	No	No	No
36	No	No	No
37	No	No	No

38	No	No	No
39	No	No	No
40	No	No	No
41	No	No	No
42	No	No	No
43	Yes	No	No
44	Yes	No	No
45	No	No	No
46	Yes	No	No
47	Yes	No	No
48	Yes	No	No
49	Yes	No	No
50	No	No	No
51	No	No	No
52	No	No	No
53	No	No	No
54	No	No	No
55	No	No	No
56	No	No	No
57	No	No	No
58	No	No	No
59	No	No	No
60	No	No	No
61	No	No	No
62	No	No	No
63	Yes	Yes	Yes
64	Yes	Yes	Yes
66	Yes	No	No
67	No	No	Yes
68	No	No	No
69	No	No	No
71	No	No	No
72	No	No	No
73	No	No	No
74	No	No	No

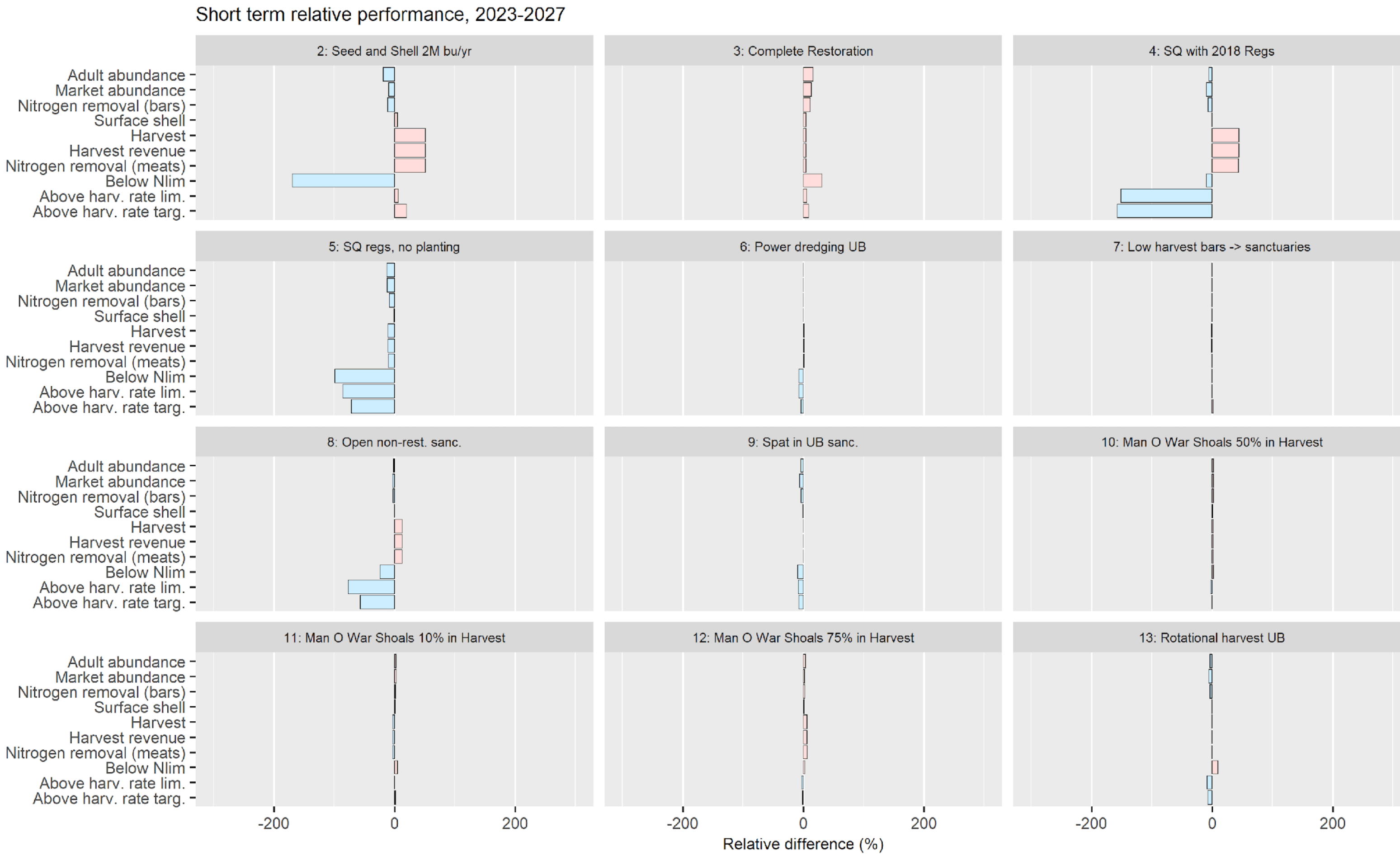

Fig. 1. Relative difference in median short-term performance of options 2 - 13 compared to the status quo during 2023-2027.

Red bars indicate improvements from the status quo and blue bars indicate worse outcomes than the status quo.

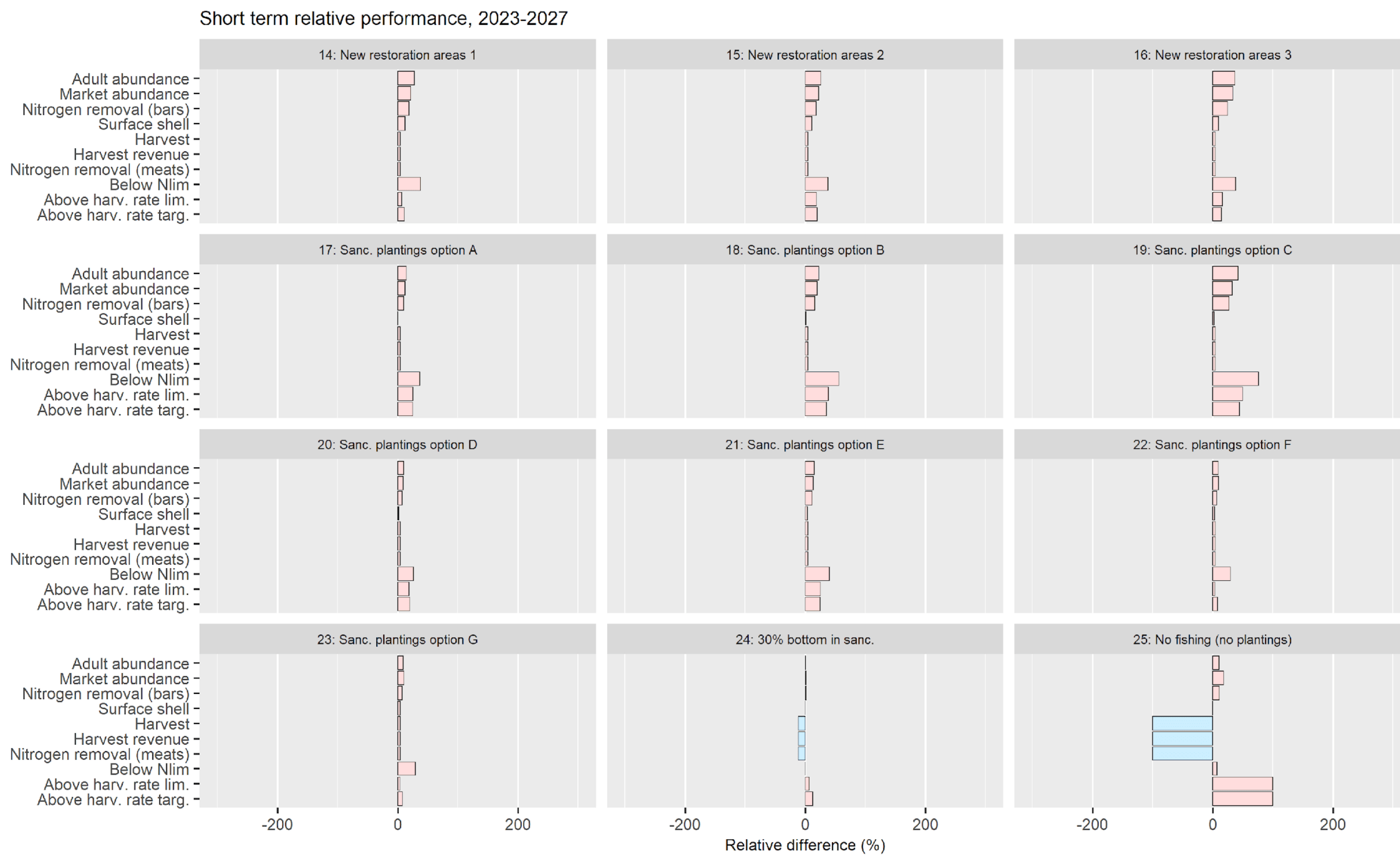

Fig. 2. Relative difference in median short-term performance of options 14 - 25 compared to the status quo during 2023-2027.

Red bars indicate improvements from the status quo and blue bars indicate worse outcomes than the status quo.

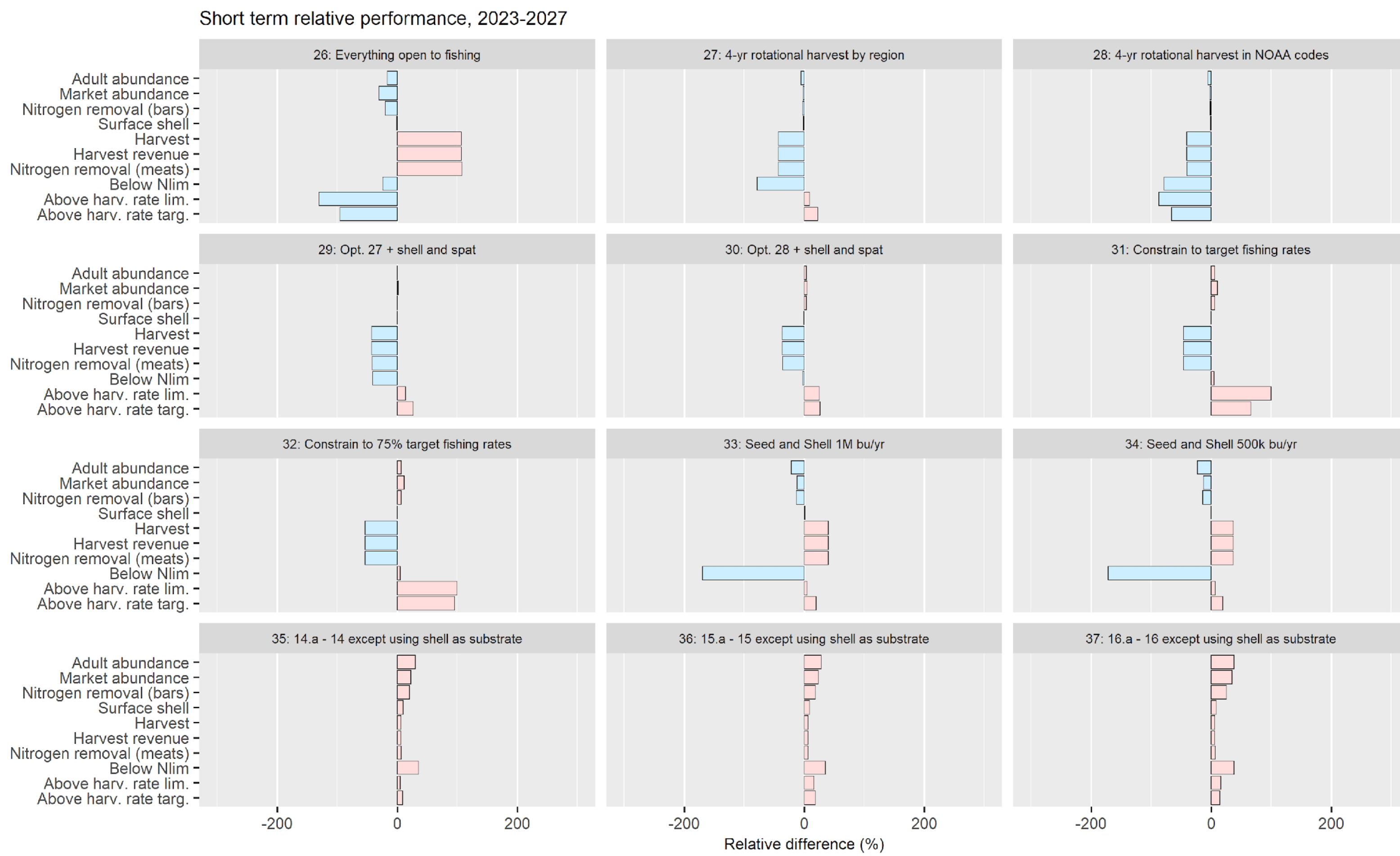

Fig. 3. Relative difference in median short-term performance of options 26 - 37 compared to the status quo during 2023-2027.

Red bars indicate improvements from the status quo and blue bars indicate worse outcomes than the status quo.

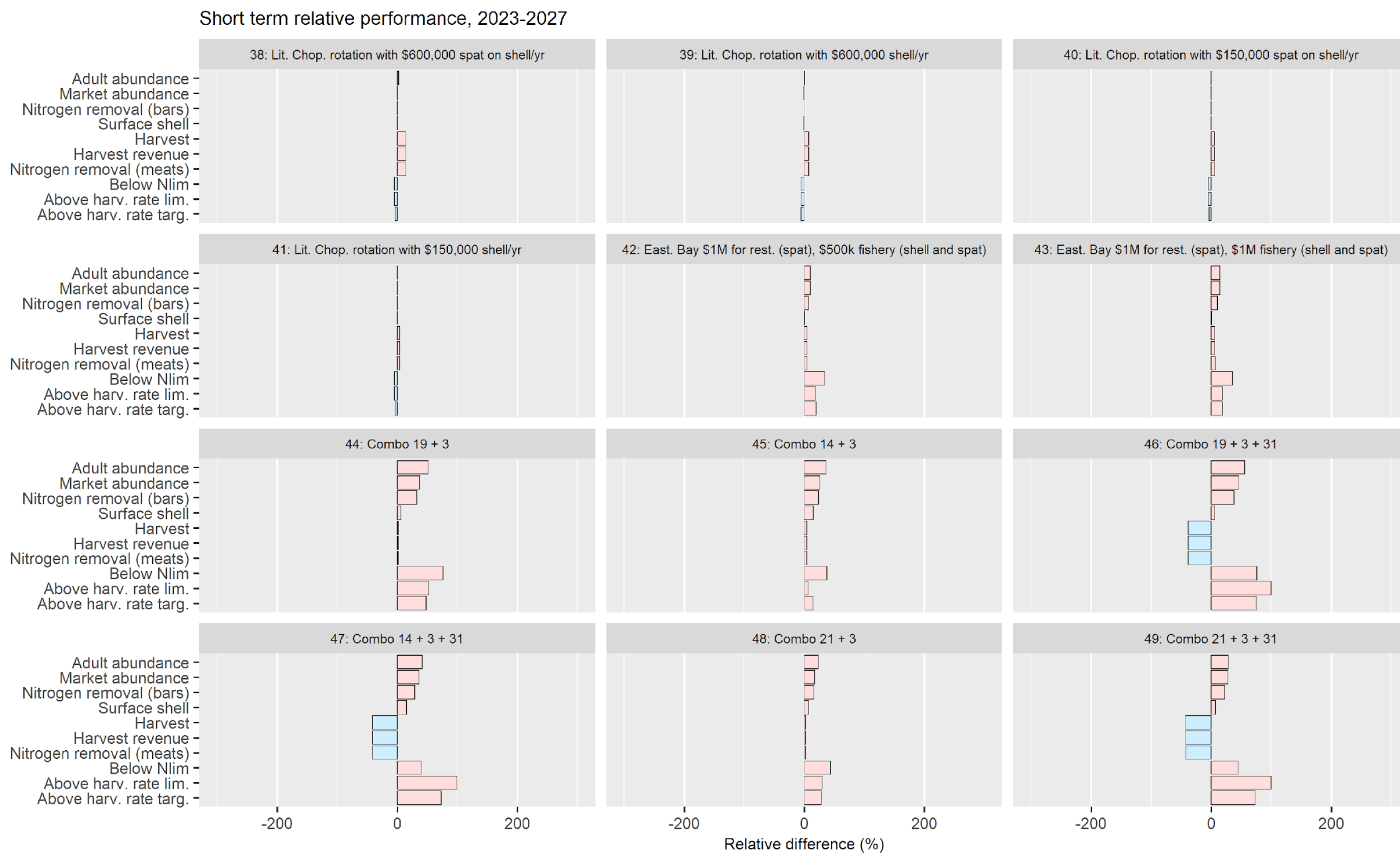

Fig. 4. Relative difference in median short-term performance of options 38 - 49 compared to the status quo during 2023-2027.

Red bars indicate improvements from the status quo and blue bars indicate worse outcomes than the status quo.

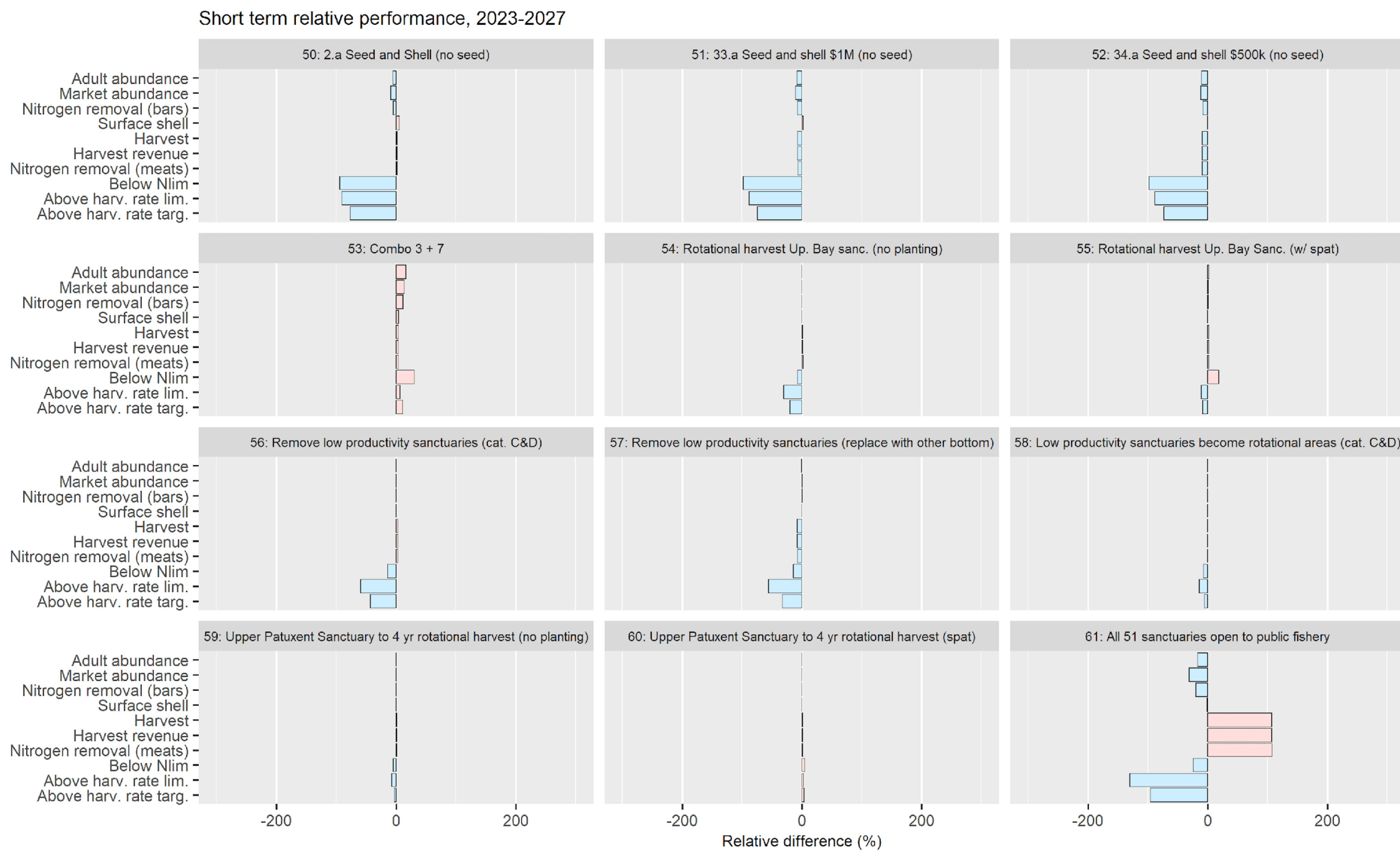

Fig. 5. Relative difference in median short-term performance of options 50 - 61 compared to the status quo during 2023-2027.

Red bars indicate improvements from the status quo and blue bars indicate worse outcomes than the status quo.

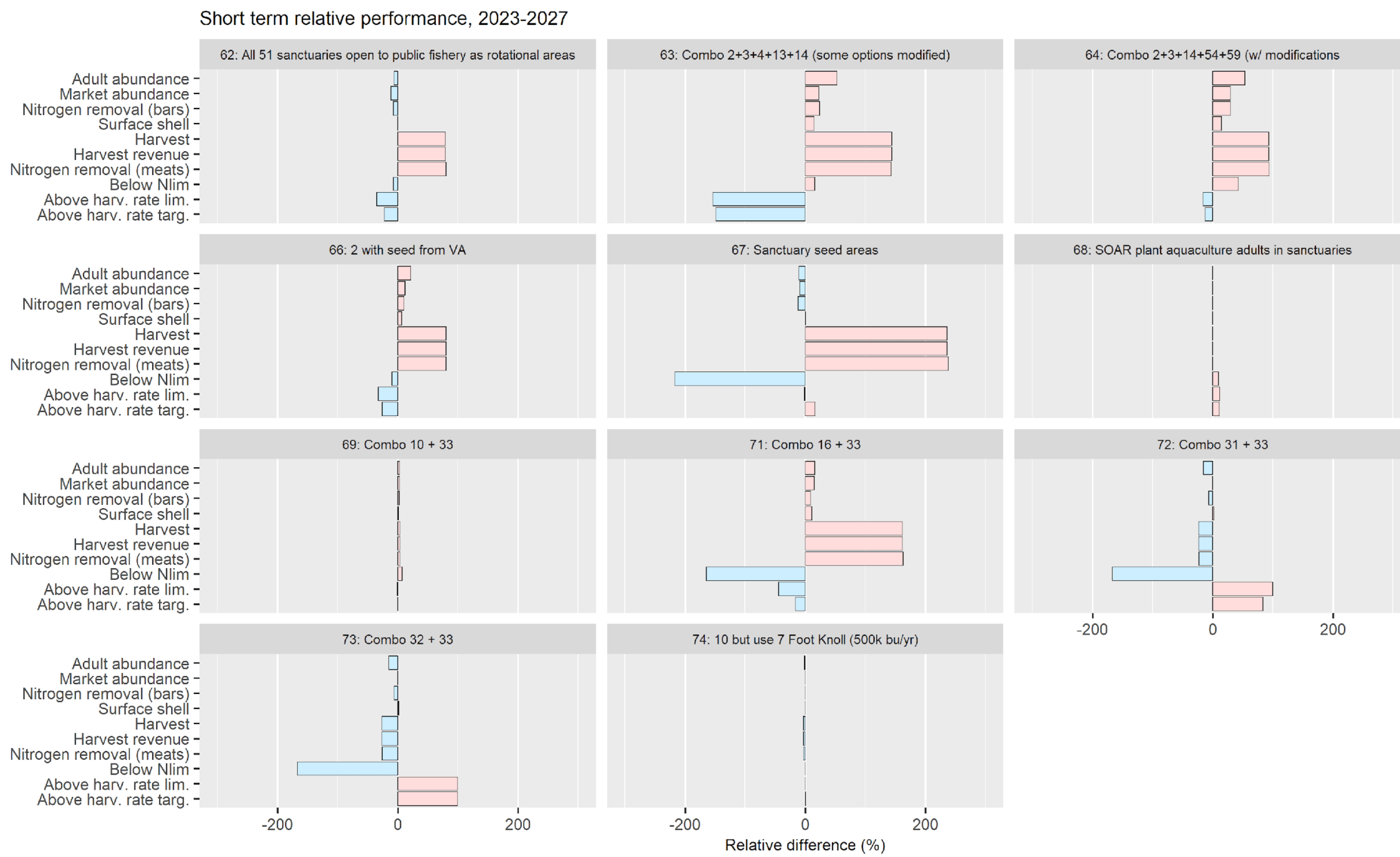

Fig. 6. Relative difference in median short-term performance of options 62 - 74 compared to the status quo during 2023-2027.

Red bars indicate improvements from the status quo and blue bars indicate worse outcomes than the status quo.

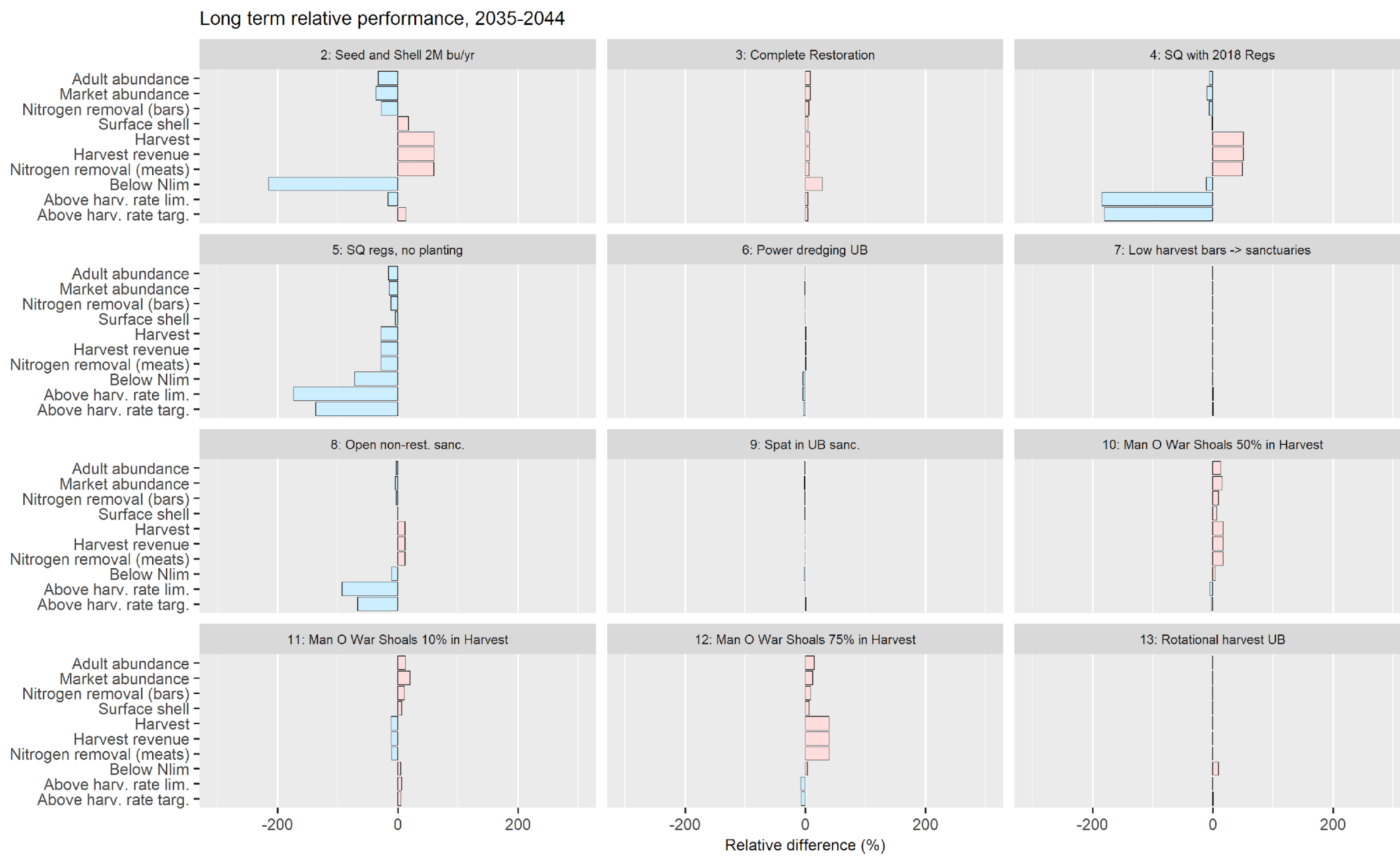

Fig. 7. Relative difference in median long-term performance of options 2 - 13 compared to the status quo during 2035-2044.

Red bars indicate improvements from the status quo and blue bars indicate worse outcomes than the status quo.

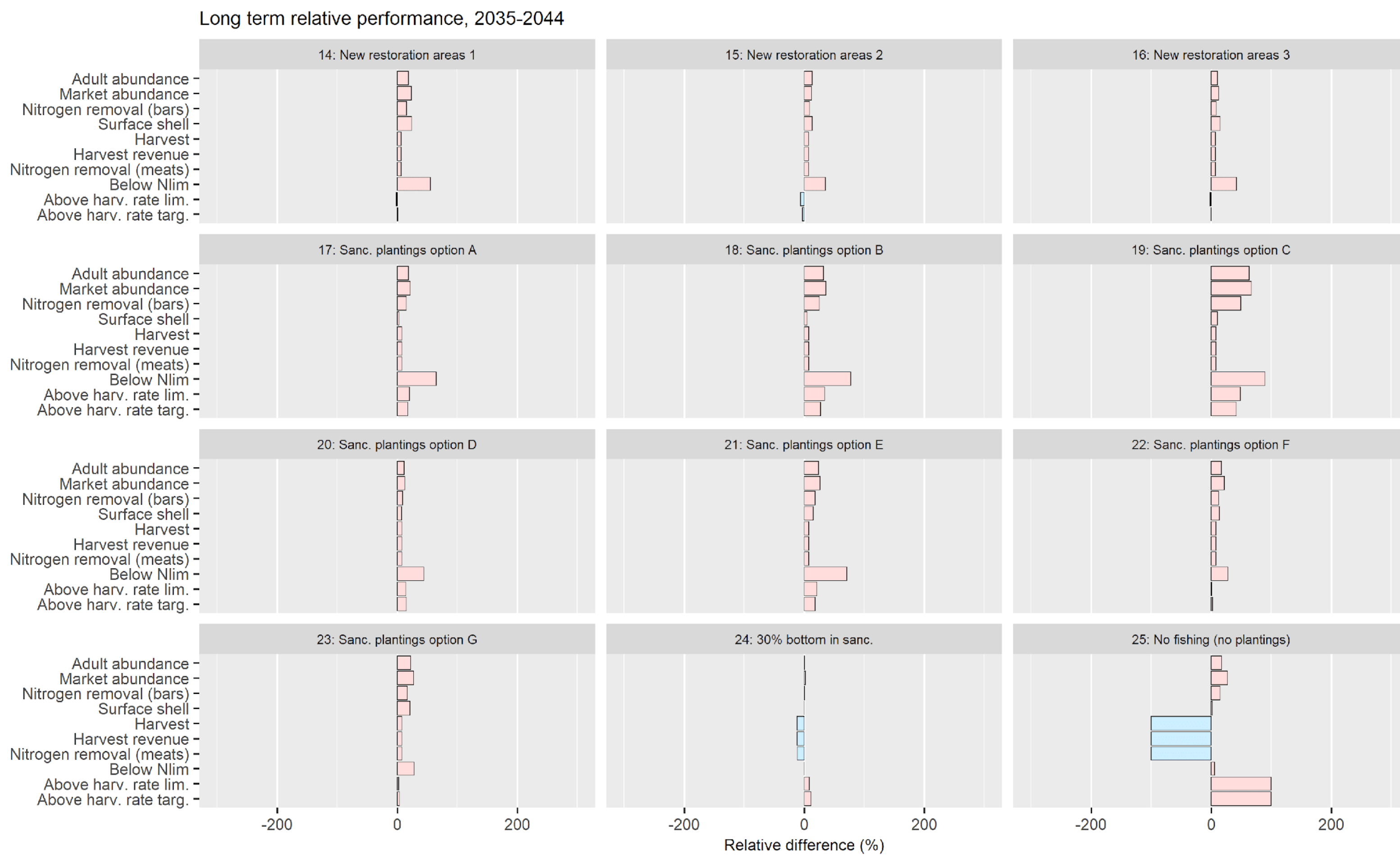

Fig. 8. Relative difference in median long-term performance of options 14 - 25 compared to the status quo during 2035-2044.

Red bars indicate improvements from the status quo and blue bars indicate worse outcomes than the status quo.

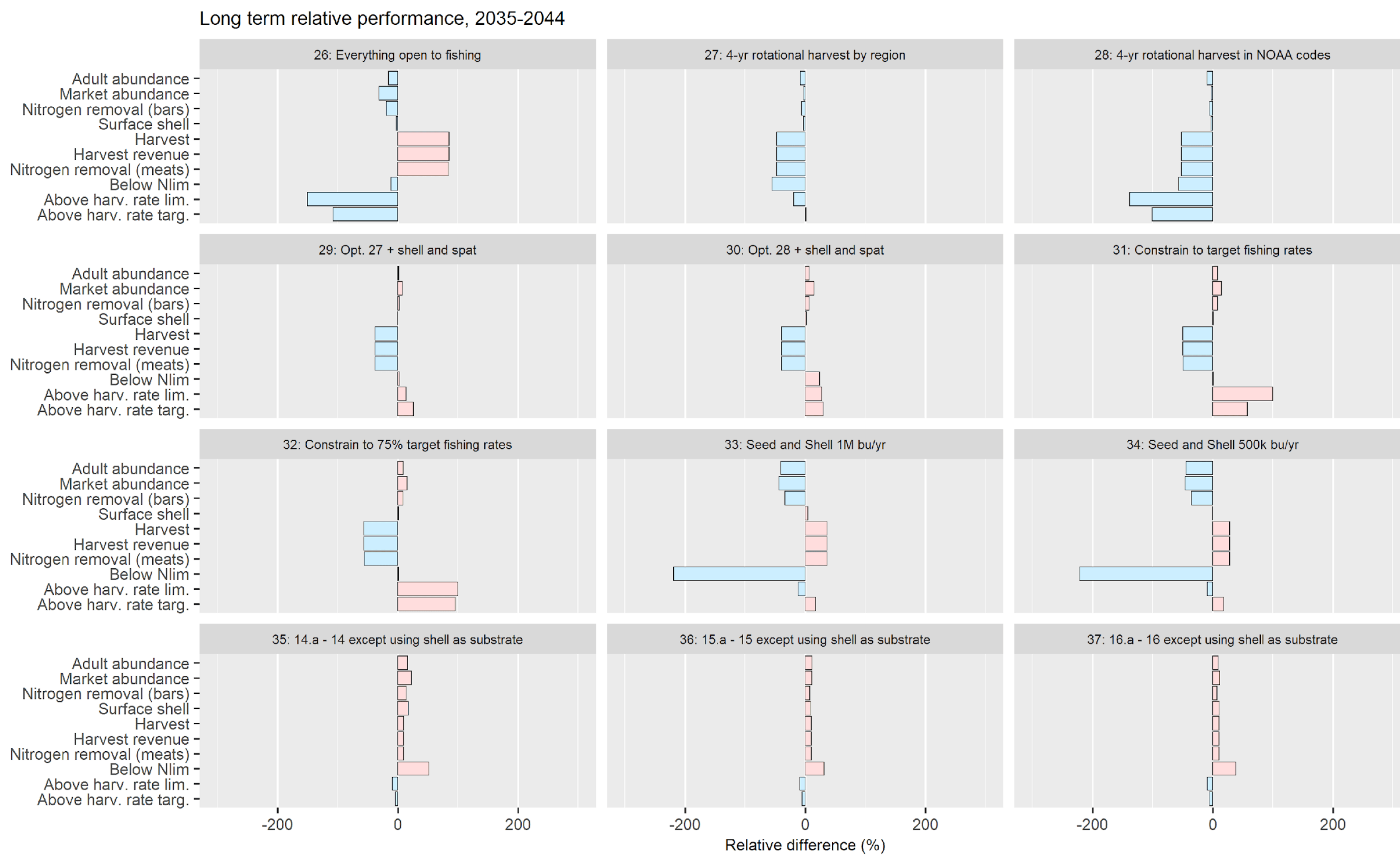

Fig. 9. Relative difference in median long-term performance of options 26 - 37 compared to the status quo during 2035-2044.

Red bars indicate improvements from the status quo and blue bars indicate worse outcomes than the status quo.

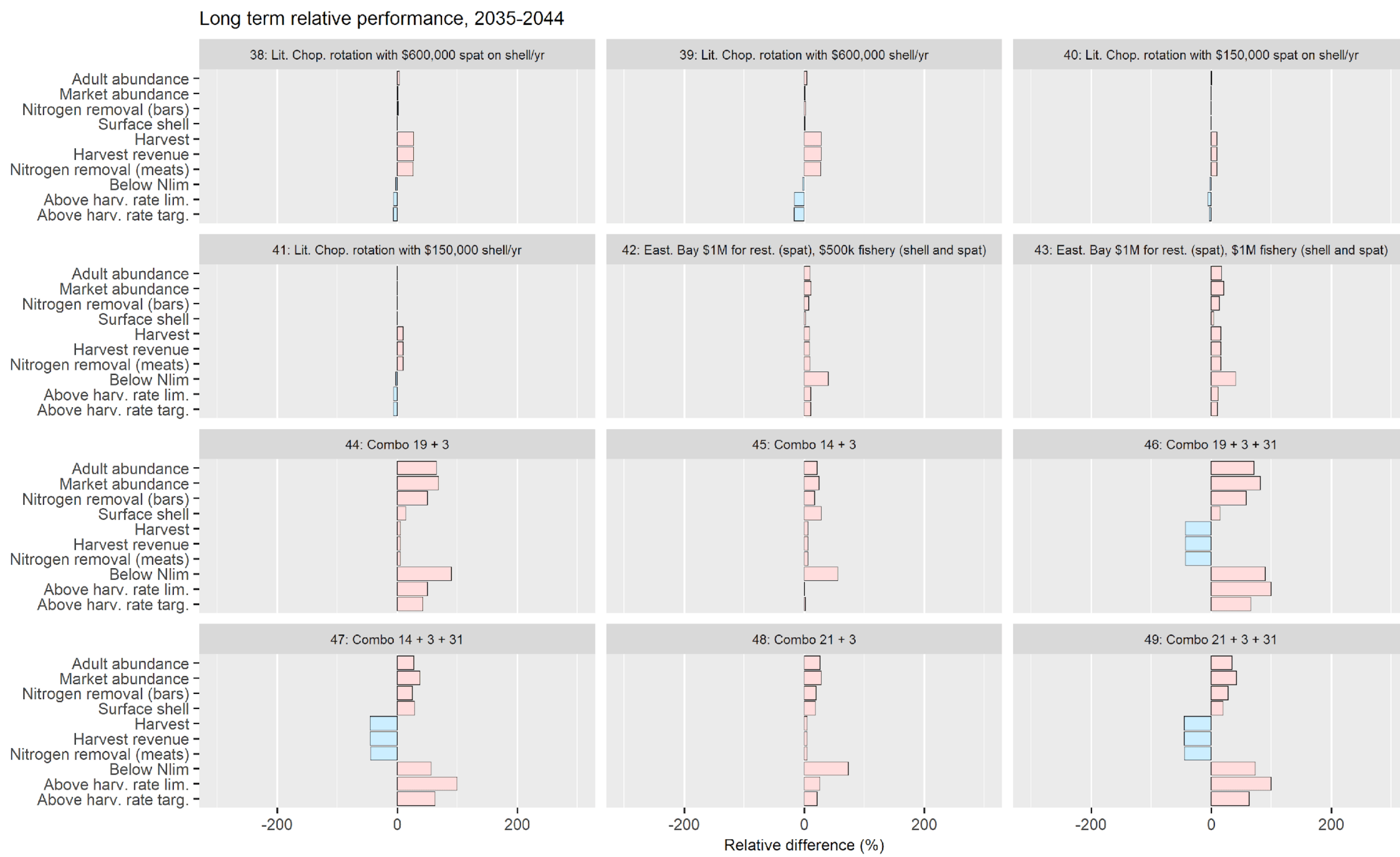

Fig. 10. Relative difference in median long-term performance of options 38 - 49 compared to the status quo during 2035-2044.

Red bars indicate improvements from the status quo and blue bars indicate worse outcomes than the status quo.

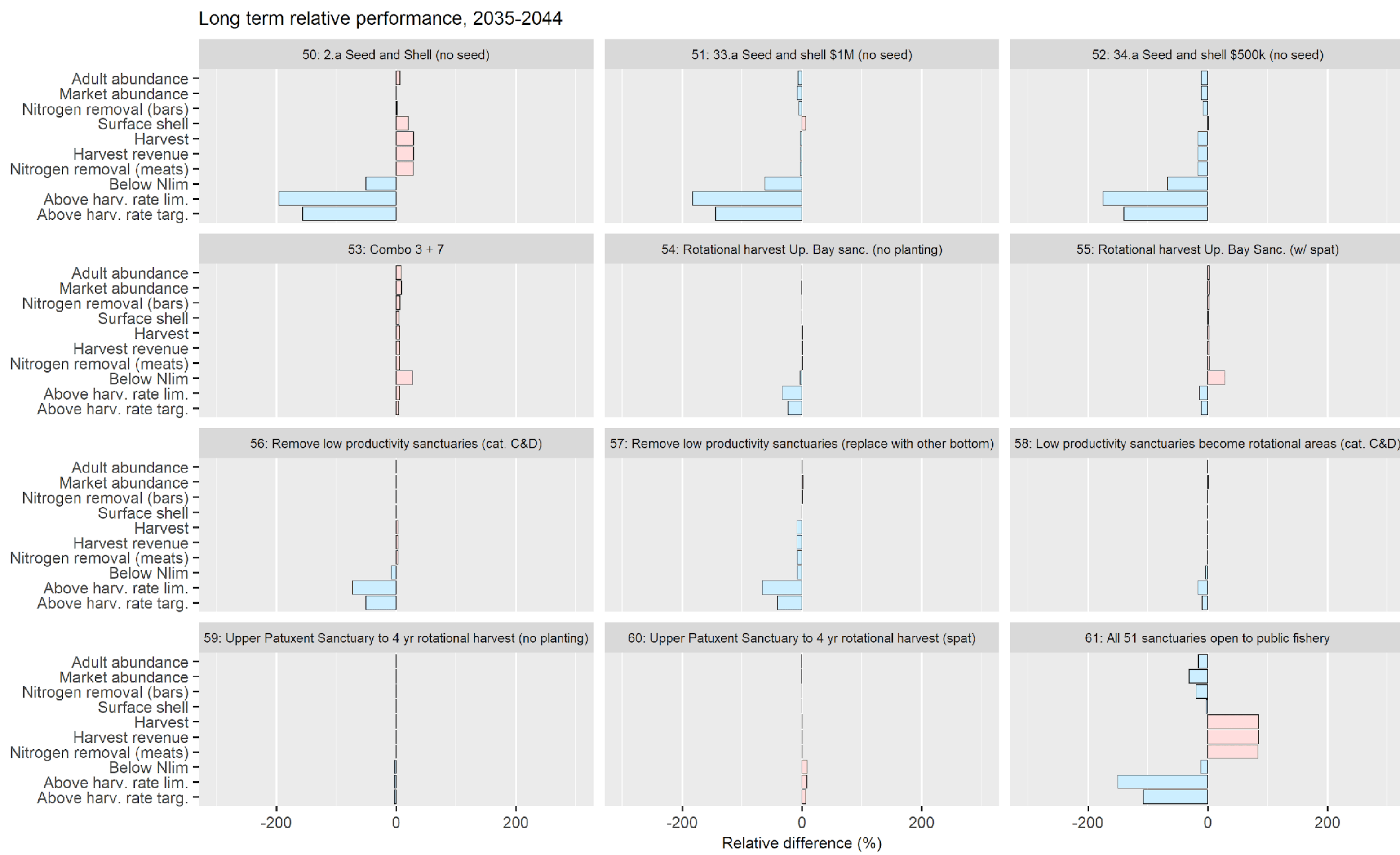

Fig. 11. Relative difference in median long-term performance of options 50 - 61 compared to the status quo during 2035-2044.

Red bars indicate improvements from the status quo and blue bars indicate worse outcomes than the status quo.

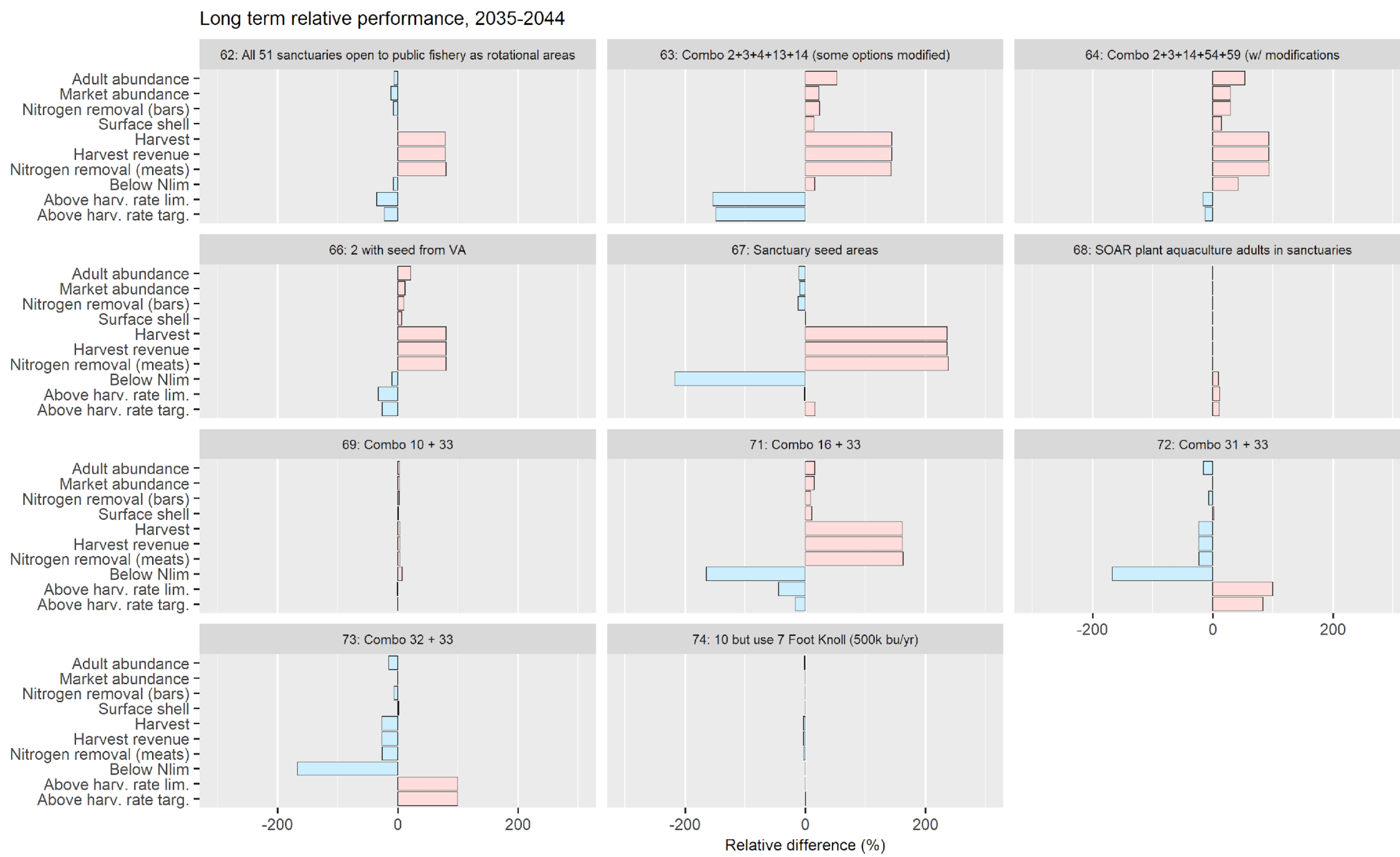

Fig. 12. Relative difference in median long-term performance of options 62 - 74 compared to the status quo during 2035-2044.

Red bars indicate improvements from the status quo and blue bars indicate worse outcomes than the status quo.

Chapter 2. The Larval Transport Model component of the Oyster Advisory Commission Simulation Model

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Introduction

The larval transport model component of the Oyster Advisory Commission (OAC) simulation model focuses on the early life of oysters. The larvae of the eastern oyster (*Crassostrea virginica*) are tiny (less than 1/3rd of a millimeter) and spend the first few weeks of their life swimming in the water, growing and being carried by currents. Most larvae do not return to the same oyster reef where they were spawned and many can travel more than 4 miles from their spawning reef. Because oyster larvae are so tiny, it is impossible to follow individuals in the water so we need another way to understand where they go and if they find the habitat that they need to settle and grow into adults.

The objective of the larval transport model is to predict where oyster larvae could go using our knowledge of water movement and the swimming behavior of oyster larvae. Larval transport models use the predictions of hydrodynamic models that simulate water flow back and forth over the whole depth of the water. These hydrodynamic models use information on water depth, tides, river flow, wind, and temperature to predict the movement of water. The larval transport model uses the structure and predictions of the hydrodynamic model to simulate the movement of particles in the water and adds the swimming behavior of oyster larvae.

The larval transport model used in this effort is called the *Lagrangian TRANSport (LTRANS v.2b) model*. LTRANS is an open-source (free to use) computer model that was developed at University of Maryland Center for Environmental Science (UMCES) and first released online in 2008. Since its release, LTRANS has been implemented by researchers across the globe in 54 peer-reviewed publications that are based on LTRANS (Appendix B). LTRANS has been used for discoveries related to larval transport (e.g., Eastern oyster, Dungeness crab, plaice, Norway lobster, Northern quahog, Japanese eel) as well as physics, harmful algae, and pollutants like plastics and oil spills. In addition to supporting fisheries management, LTRANS supports other industries: the computer code is part of the *Delaware Bay Early Warning System* that notifies power plant operators about chemical spills.

This report describes the components that were used in the larval transport model (the hydrodynamic model and the oyster habitat polygons) as well as the larval transport model itself, including an important new feature that OAC Commissioners requested. This new feature – the mortality that depends on the time that larvae spend in the water – was influential: although it did not greatly alter the spatial patterns in the larval transport model results, it did significantly change the magnitude of the larval transport model predictions.

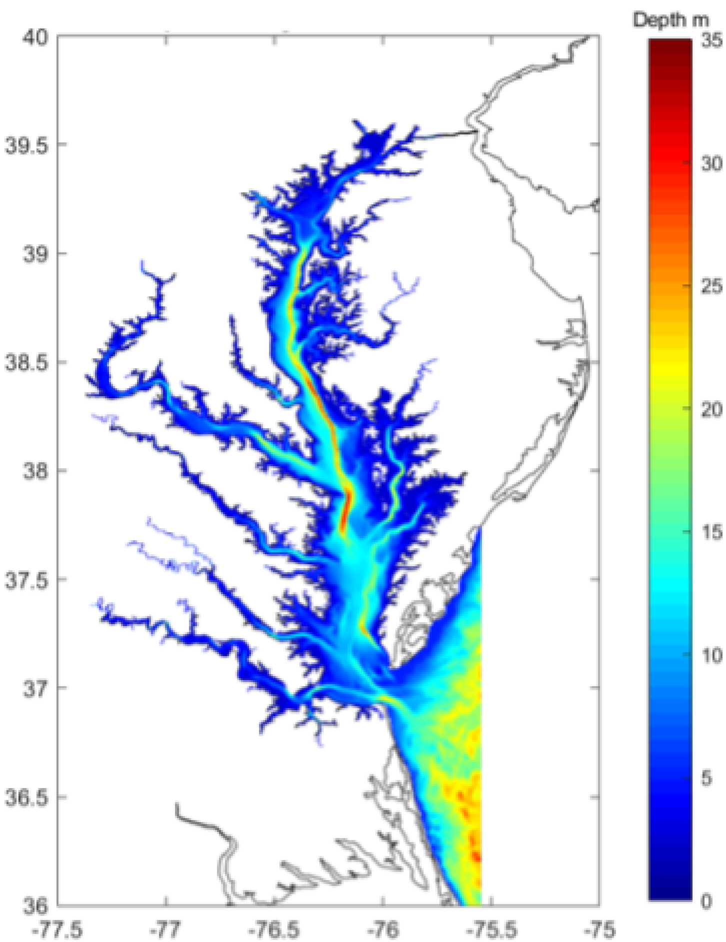


Fig. A.1. Hydrodynamic model domain of Chesapeake Bay. Colors represent depth of the water column in meters (see color bar).

A. Hydrodynamic model

A.1. Description

The hydrodynamic model used in this study was developed with the Regional Ocean Modeling System (ROMS, Haidvogel *et al.* 2008) and was based on the Chesapeake Bay ROMS Community Model (ChesROMS; Xu *et al.* 2012, Scully 2013, 2016, 2018). The model domain included all of the main tributaries to the Chesapeake Bay as well as the shelf region immediately adjacent to the bay mouth (Fig. A.1).

The model set up was as follows: The model used a 1168 by 448 rectilinear grid with uniform horizontal spacing of ~360 m with 20 vertical terrain-following coordinates. Model forcing included river discharge derived from the United States Geological Survey (USGS) gauging stations for 19 individual tributaries, tidal constituents derived from the Advanced Circulation (ADCIRC) model, observed non-tidal water levels (Duck, NC and Lewes, DE), temperature and salinity at the oceanic boundary from the World Ocean Atlas 2001, and surface atmospheric forcing (shortwave solar radiation, long wave radiation, rainfall, surface air humidity, pressure, temperature, and winds at 10 m) from the National Center for Environmental Prediction (NCEP) North American Regional Reanalysis (NARR) model. Turbulence closure was achieved using the k-omega model with the stability functions of Kantha and Clayson (1994), and the background diffusivity for both momentum and scalars was set to 1×10^{-6} m^2/s. No horizontal diffusivity was prescribed and the MPDATA horizontal advection scheme (Smolarkiewicz and Margolin, 1998) was employed.

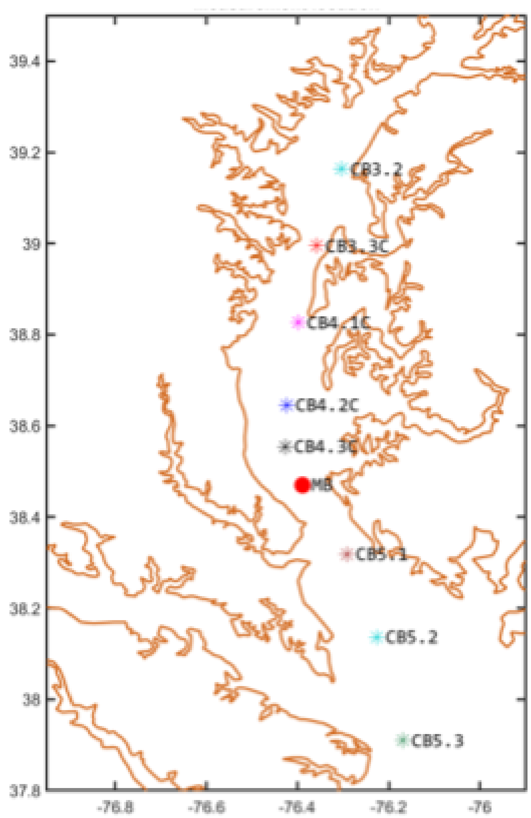


Fig. A.2. Map showing locations of observation sites in the Chesapeake Bay (brown outline). The red circle is the Mid-Bay (MB) monitoring station where current velocities were measured. The asterisks are stations from the Chesapeake Bay Program where salinity and temperature were measured.

For this study, a year-long simulation of calendar year 2013 was conducted. The ROMS model was initialized from idealized conditions and run for a period of two years to ensure that the hydrodynamics were sufficiently equilibrated prior to beginning the 2013 simulation. The model was chosen for the larval transport simulations because it is the highest resolution model available that could resolve important tributaries like the St. Mary's River, a site of large-scale oyster restoration, and provide output files that were compatible with LTRANS. It is important to note that the hydrodynamic model was not developed specifically for this project and hence there was no opportunity to tune the model to improve its predictions.

Predictions from the ROMS model for the June to August interval of 2013 were used in the larval transport model. The ROMS model was run at Woods Hole Oceanographic Institution and the massive output files were transferred to UMCES via temporary web servers, downloaded to hard drives, and then loaded onto Horn Point Lab's High Performance Computer where the larval transport model runs were conducted.

A.2. Validation

The 3D hydrodynamic ROMS framework was validated by comparing model predictions of depth-averaged velocities, sub-surface current velocities (5 m below surface), salinity and temperature to observational data from monitoring stations located in the Chesapeake Bay using two quantitative metrics: model skill and root mean-square difference.

Metrics. Two quantitative validation metrics were used for the model-data comparisons. The first metric, model skill score from Willmott (1981), quantifies overall agreement between model predictions and observations and was computed as:

$$W_{skill} = 1 - \frac{\sum_{i=1}^{n}\left(M_i - O_i\right)^2}{\sum_{i=1}^{n}\left(\left|M_i - \bar{O}\right| + \left|O_i - \bar{O}\right|\right)^2}$$

where O_i is the observation and M_i is the model result, $\bar{O}$ is the mean of the observations, and n is the total number of observations used for comparison with the model results. A value of 1 for the variable W_{skill} indicates that model results and observations are exactly the same, whereas a value of 0 indicates complete disagreement between model and observations (Willmott 1981).

Root-mean-squared difference (RMSD, also referred to as root-mean-square error), the second metric used in this analysis, was calculated using the equation:

$$RMSD = \sqrt{\frac{\sum_{i=1}^{n}\left(M_i - O_i\right)^2}{n}}$$

where O_i is the observation and M_i is the model results, and n is the total number of observations used for comparison with the model results. RMSD values are directly proportional to the agreement between observations and model results: the lower the value of RMSD, the better the agreement between observations and model results.

Calculation of these metrics was spatially and temporally consistent, i.e., model results were sampled at the same location, depth, and time as the observations. The only exceptions to this rule were instances when the measured water column depth was greater than the depth assigned to the hydrodynamic model grid. In these cases, the maximum model depth at that location was used without extrapolation.

Observations. Measurements of current velocity, salinity and temperature were obtained from monitoring stations in the Chesapeake Bay for model-data comparisons (Fig. A.2). Current velocity profiles were measured during the NSF project entitled "Collaborative Research: The Role of Wind in Estuarine Dynamics" (NSF-OCE-1339032, Malcom Scully, Principal Investigator; data from Alex Fisher). Measurements of current velocities were collected from the Mid-Bay (MB) station over the month of August, 2013 using an Acoustic Doppler Current Profiler that was mounted in a lander frame ~0.5 meter above the bottom (Fisher et al. 2015). Depth-averaged and sub-surface (5 m below surface) current velocities were compared to model predictions.

Vertical profiles of salinity and temperature were obtained from the Chesapeake Bay Program (CBP) Water Quality Monitoring Program (data sourced from *https://www.chesapeakebay.net/*) at the mainstem monitoring stations (Fig. A.2) for the sampling season of 2013.

Evaluation. Simulated depth-averaged current velocities for the month of August 2013 showed a strong correspondence with the observations at the Mid-Bay (MB) station in terms of both magnitude and timing: the RMSD was low (0.05 - 0.08 $m \cdot s^{-1}$) and the model skill was greater than 0.9 (Fig. A.3). Sub-surface (5 m below surface) current velocities, isolated into their eastward and northward components, also compared well with the observed values (Fig. A.4). Over the time period observed (August 2013), the high model skill values (0.88 for eastward, 0.91 for northward components), and low RMSD values (0.07 $m \cdot s^{-1}$ for eastward, 0.14 $m \cdot s^{-1}$ for northward components) indicated that there was a strong match between observed and simulated sub-surface velocities. Hence, we concluded that the model made robust predictions of current velocities during August 2013.

The model was very capable at reproducing the spatial and temporal pattern in observed temperature profiles from the CBP monitoring stations over the June - July interval of 2013 (RMSD: 0.66 - 0.99 ^{o}C, model skill: 0.82 - 0.96, Fig. A.5). The point-to-point comparisons in Fig. A.5 showed that the model was able to capture the seasonal changes of warming (e.g., compare temperatures in June in panel A.5.a with those in July in panel A.5.d). The model also captured changes in stratification (compare stratified temperature profile on in June in panel A.5.a with the well-mixed profile in July in panel A.5.d).

The agreement between simulated and observed salinity was not as good as that for temperature, with the model overestimating salinity at all the CBP stations located in the mainstem of the bay (RMSD: 4.69–6.32 psu, model skill: 0.67–0.75, Fig. A.6). This was primarily because the ROMS model was not developed and tuned for this specific project. However, the offset between observed and simulated salinity likely has little impact on short-term circulation patterns, like those during the 3-week interval of each larval transport simulation. The vertical gradient in salinity was important for the larval transport model because the behavior of simulated oyster larvae was cued by the vertical change in salinity. The modeled change in salinity from surface to bottom was reproduced reasonably well (Appendix C), capturing the changes from stratified and well mixed conditions, and the model error was generally consistent with a mean offset that did not significantly impact the vertical or horizontal gradients.

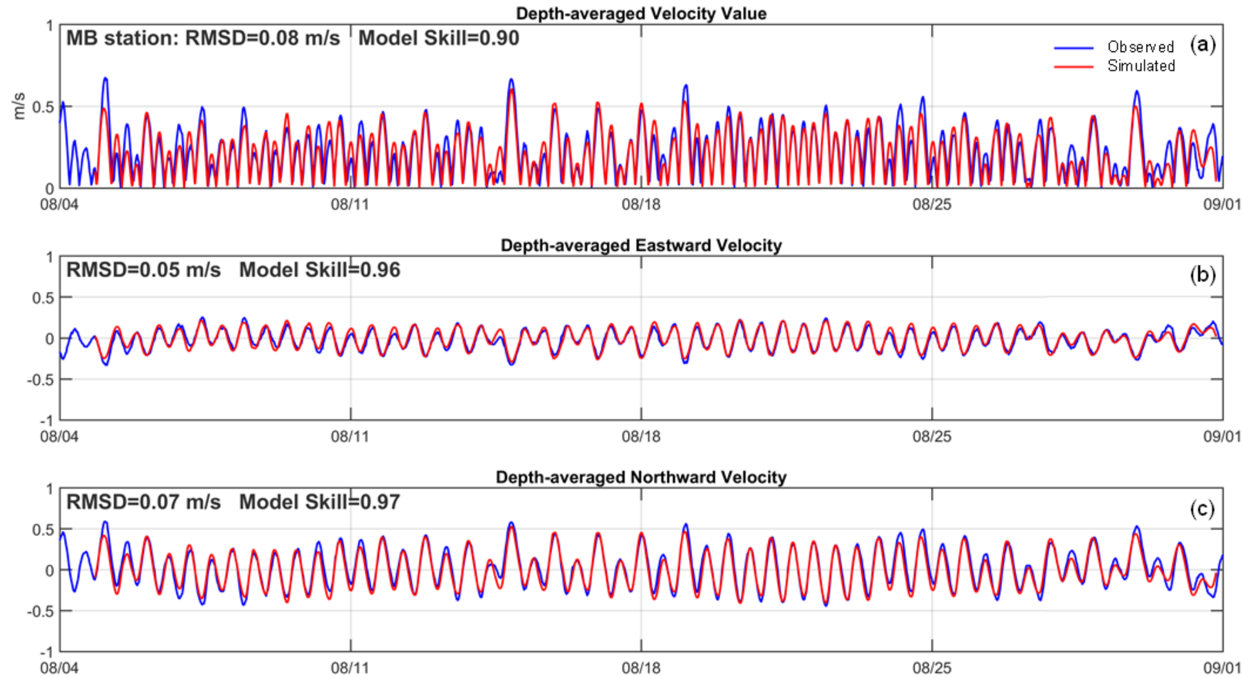


Fig. A.3. Observed (blue) and simulated (red) depth-averaged (a) velocity, (b) eastward component of velocity, and (c) northward component of velocity at the Mid-Bay (MB) station in August, 2013. RMSD and model skill values are included in the upper left of each panel.

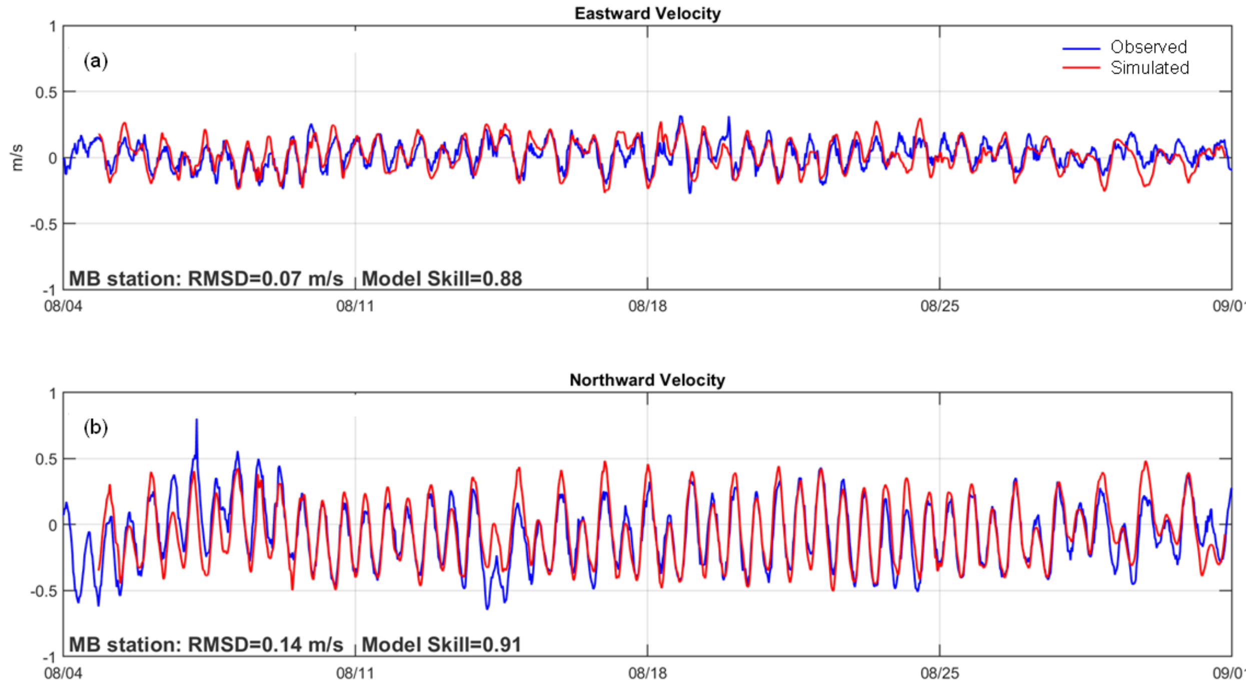


Fig. A.4. Observed (blue) and simulated (red) sub-surface (5 m below surface) (a) eastward component of velocity, and (b) northward component of velocity at the Mid-Bay (MB) in August, 2013. RMSD and model skill values are included in the upper left of each panel.

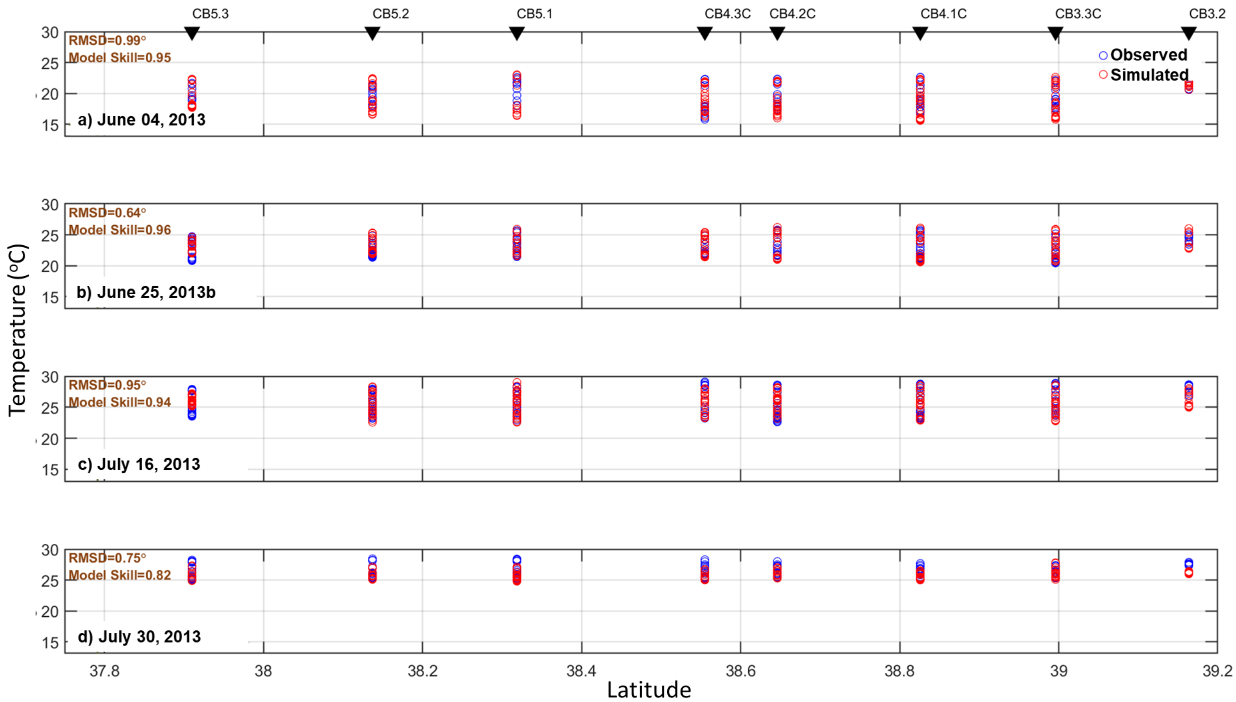


Fig. A.5. Observed (blue) and simulated (red) temperature profiles at CBP monitoring stations (black triangles) located along the estuarine gradient (left to right, lower to upper bay) on (a) June 4, 2013, (b) June 25, 2013, (c) July 16, 2013, and (d) July 30, 2013. RMSD and model skill values are included in the upper left of each panel.

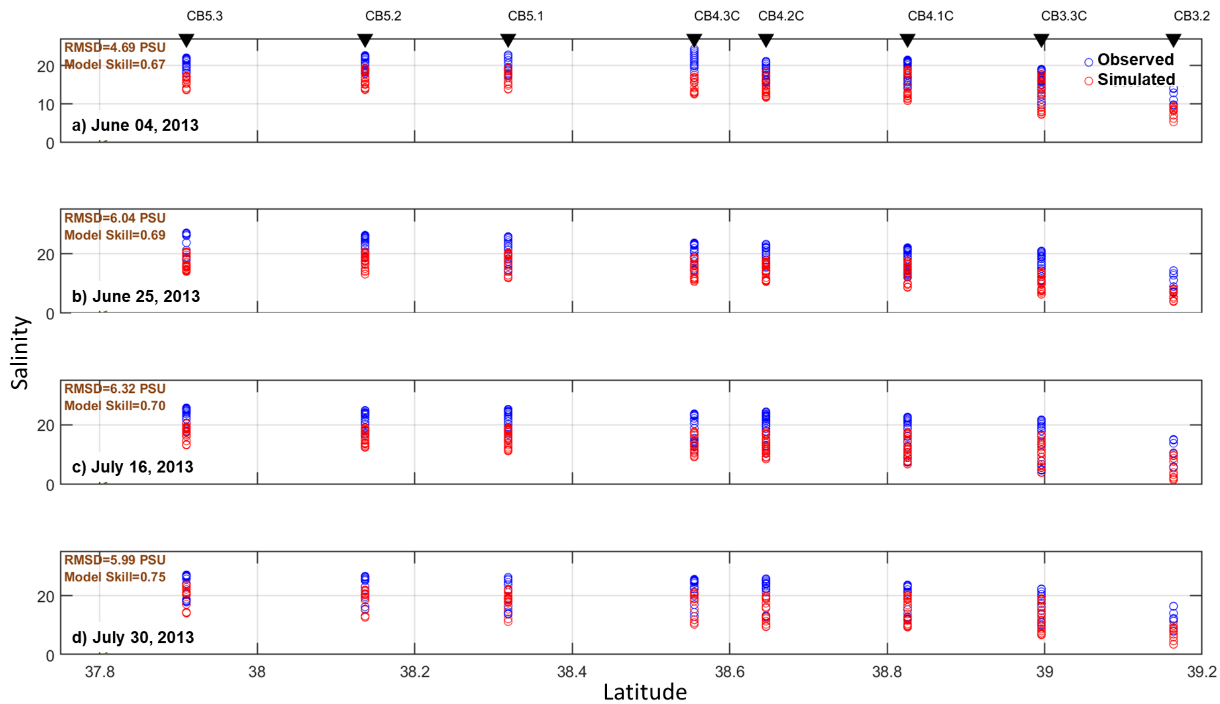


Fig. A.6. Observed (blue) and simulated (red) salinity profiles at CBP monitoring stations (black triangles) located along the estuarine gradient (left to right, lower to upper bay) on (a) June 4, 2013, (b) June 25, 2013, (c) July 16, 2013, and (d) July 30, 2013. RMSD and model skill values are included in the upper left of each panel.

B. Larval transport model

B.1. Description

The larval transport model uses current flow (advective transport), turbulent mixing, and larval swimming behavior to simulate trajectories of particles through time and space. For this project, the LTRANS larval transport model (North et al. 2006b, 2008, Schlag and North 2012, Mitchell 2013) was run using predictions from the ChesROMS hydrodynamic model to simulate the transport of oyster larvae in the Maryland region of Chesapeake Bay.

To calculate particle movement, the larval transport model used an external timestep of 10 min (the interval between hydrodynamic model predictions) and an internal timestep of 75 sec (the interval at which particles moved). This means that the location of particles was calculated every 75 seconds. The internal time step was set to prevent particles from jumping across the model grid and thereby creating inconsistencies between the hydrodynamic and larval transport model predictions. The water properties that were predicted by the hydrodynamic model – including water level and current velocities in three dimensions – were interpolated in time and space before being used in the advection, turbulence, and behavior sub-models to calculate the movement of each larvae-like particle as described in North et al. (2006b, 2008) and Schlag and North (2012).

In the larval transport model, particle motion due to advective transport was calculated using a 4th order Runga-Kutta scheme to compute movement due to currents in the x, y, and z directions. This scheme incorporated an iterative process that used current velocities from previous and future timesteps to obtain the most robust estimate of the movement of particles in the Chesapeake Bay, a water body with complex fronts and eddies that have curvature in flow that need a Runga-Kutta scheme to resolve (Dippner 2004). The second component of movement, sub-grid-scale turbulence, was simulated in the vertical (z) direction by including a random displacement model (North et al. 2006a). In the horizontal direction (x-y plane), a random walk model was used (North et al. 2008). Finally, particle motion due to behavior was based on larval developmental stage and was simulated by assigning vertical swimming speed and direction to each particle (North et al. 2006b, 2008).

Boundary conditions were imposed to ensure that particles remained within the model at each internal timestep while the particle was in motion (described in North et al. 2006b, 2008). If a particle reached the open ocean boundary, the particle stopped moving.

B.2. Simulations

Timing and location of simulated spawning. To simulate pulses in spawning, five releases of 210,601 particles were programmed to occur during the peak spawning period of *C. virginica* in the Chesapeake Bay (June to August) (total particles released = 1,053,005) (Table B.1). The first day on which particles were released in the model (*i.e.*, when simulated spawning began) occurred when water temperatures reached an average of 25 °C (77° F) near bottom across all habitat polygons, a value based on the lower mass spawning temperature of *C. virginica* that was used in North et al. (2006b, 2008) larval transport simulations. To calculate the day when water temperatures in the model were on average 25 °C, water temperatures at the centroid location of each oyster habitat polygon were output and averaged across all polygons every hour. The resulting day was model day 168 (Fig. B.1) which corresponded to June 17, 2013. Following the first release on June 17, 2013, the next four releases (Table B.1) were scheduled as in North et al. (2008) to simulate pulses in settlement that have been observed in Chesapeake Bay (Kennedy 1996, Southworth et al. 2000, 2001,2002, 2003).

Table B.1. Schedule of release dates and the number of particles released for five model runs simulation transport of *C. virginica* larvae in the Maryland waters of Chesapeake Bay.

Particle release scenario	Particle release year day	Particle release date	Number of particles released
I	168	June 17, 2013	210,601
II	174	June 23, 2013	210,601
III	180	June 29, 2013	210,601
IV	205	July 24, 2013	210,601
V	211	July 30, 2013	210,601
		Total particles released	1,053,005

To simulate the location of oyster spawning, habitat polygons were created that encompassed oyster habitat in Maryland's portion of Chesapeake Bay. Oyster Advisory

Commission members decided to use the Historic Named Oyster Bars (HNOB) as habitat in Maryland waters. A total of 1,087 oyster habitat polygons were simulated (Fig. B.2). (Please see Appendix D for more details on how the GIS files of the HNOB were converted into oyster habitat polygons for LTRANS). The particle locations at release (day 0) were programmed to be the same across all five scenarios. Larvae-like particles were randomly distributed across the surface of each habitat polygon within the model domain such that there were 120 particles per km^2 (for polygons larger than 1 km^2) or there were 120 particles on each polygon (for polygons smaller than 1 km^2). Six polygons (#100324, 100522, 100656, 100943, 100945 and 101087) were located outside the hydrodynamic model domain and were, therefore, not assigned any particles and were not simulated. Fig. B.3 illustrates an example of initial particle locations on oyster polygons used in the model.

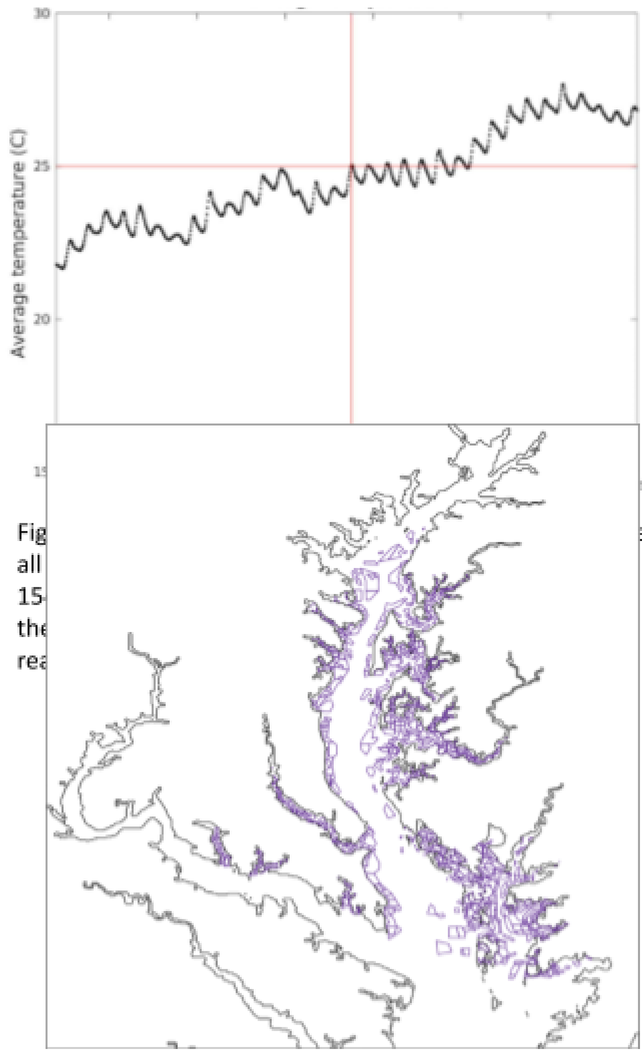


Fig. B.2. Outline of the Chesapeake Bay (black line) with oyster habitat polygons (purple polygons) that were simulated in the larval transport model.

Larval behavior and settlement. After the release of larvae-like particles from the polygons, the model simulated the fate and transport of these particles based on physical conditions and larval behavior. The physical conditions influencing particle transport were governed by hydrodynamic model predictions of current velocities and turbulence. To simulate larval behavior, the complex behaviors of *C. virginica* larvae that were observed in laboratory studies (Newell et al. 2005) were incorporated into the larval transport model (North et al. 2006b, 2008) and are described in brief below.

To program this behavior in the larval transport model, as the first step, each particle was assigned a different duration for the veliger stage (free-swimming larvae) and pediveliger stage (oldest larvae that search for a place on the bottom to settle). To simulate individual variability, the duration of the veliger and pediveliger stages were assigned with a random number generator in a normal distribution around 14 and 7 days for the veliger and pediveliger stages, respectively (North et al. 2008).

Next, the vertical direction and swim speed of the particles was calculated based on the developmental stage (or age) of the particle (North *et al.* 2006b, 2008) as well as the presence (or absence) of a halocline (Newell *et al.* 2005). In their earliest stages as fertilized gametes and early trochophores (between 0 and 0.5 days old), the particles moved passively with the currents. From day 0.5 to 1.5, larvae-like particles swam up with an initial swim speed of 0.25 mm·s^{-1}. Then, and through the remainder of the veliger stage, swim speeds increased from 0.25 mm·s^{-1} to 3 mm·s^{-1}. During the veliger stage, particle movement also included a random component to allow for individual variability in oyster larvae swimming as well as a response to the presence of a halocline that cued upward swimming. In the pediveliger stage, a constant swim speed of 3 mm s^{-1} was assigned to each particle with an inclination to swim downwards so that they remained within 1 m of the bottom.

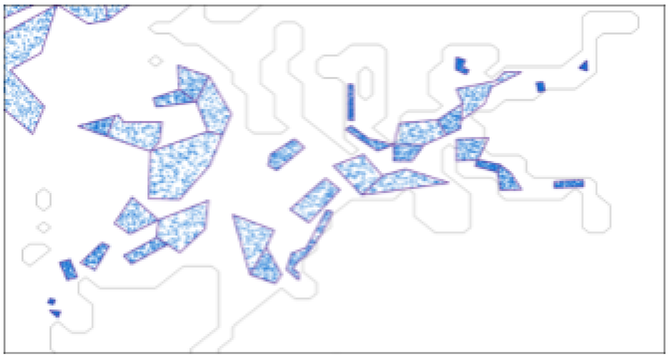


Fig. B.3. An example of the initial location of simulated larvae (blue dots) on oyster habitat polygons (purple polygons) in the Little Choptank River (black outline) domain. The number of larvae on each polygon was proportional to the size of the polygon. For polygons > 1 km^2, 120 larvae per km^2 were allocated for release. For polygons < 1 km^2, a total of 120 larvae were allocated. Note: polygons with no particles are islands.

Additionally, each of the pediveliger larvae was evaluated every internal timestep (75 sec) to determine if it was located within the boundaries of suitable habitat on which to settle. If a particle was located within the boundaries of any of the 1,087 oyster habitat polygons in the model domain, the particle was considered to have successfully encountered suitable habitat and stopped there. If, however, the particle did not encounter habitat polygons before the end of the pediveliger stage, it was considered dead and its motion was stopped.

Larval mortality. The larval transport model simulated two of the many factors that influence larval mortality. The first one, as described in the previous paragraph, was the inability of a particle to encounter oyster habitat during the pediveliger stage. The second factor was duration-dependent mortality that was related to the time that larvae spend in the water. The idea is that the longer an oyster larva spends in the water column, the greater its chances of being eaten by predators or dying from other causes. It is important to note that there are many other types of mortality that are not simulated in the larval transport model (e.g., disease, starvation, predation on spat, etc.). These other sources of mortality are accounted for within the OAC Simulation Model.

To simulate duration-dependent mortality in the larval transport model, a superindividual approach was used and new code was created. In the superindividual approach, each of the 1,053,005 particles was taken to be a ‘superindividual’ that represented a group of 1,000,000 larvae (1 particle = 1,000,000 larvae). Each superindividual particle, and therefore each group of larvae, spent a different length of time in the water column because particles were assigned different stage durations in an effort to mimic individual variability.

The model assigned a mortality rate to each group of larvae that was proportional to the length of time that the superindividual particle spent in the water before settling on a habitat polygon. The mortality rate was set to be 0.38 d^{-1}, based on observations of the change in larval abundances over time in the Choptank River (Table 4.5 of Goodwin (2015)). Essentially, the 1,000,000 larvae assigned to each superindividual particle were reduced in number based on this mortality rate and on the duration of time from the particle's release to settlement.

Connectivity. In order to calculate the exchange of oyster larvae between habitat polygons in the model, connectivity matrices were calculated. As mentioned previously, a total of 1,053,005 particles were released over the June to August interval. The larval transport model tracked the trajectory of each particle released from each habitat polygon, calculated the number of settled and unsettled particles, and stored this information in a connectivity matrix. The matrix included a row for each habitat polygon that particles were released from and a column for each habitat polygon that the particles settled on. The number of particles that were transported between each combination of initial and final oyster habitat polygons was stored in each cell of the matrix.

Two connectivity matrices were used to summarize model predictions; one that was created without duration-dependent mortality (as in North et al. 2008) and a new matrix that was created to summarize superindividuals. The original matrix provided information about the starting and end locations of each particle released from any given oyster habitat polygon. The second matrix summarized the effect of duration-dependent mortality by including the number of larvae of each superindividual. In this matrix, if a superindividual particle did not encounter an oyster habitat polygon, the entire group of larvae represented by that particle was considered dead. If a superindividual particle settled on any habitat polygon, then the Goodwin (2015) mortality rate was applied to that group of larvae to calculate how many larvae made it to that polygon.

The superindividual connectivity matrices from the five scenarios were used to create a "Settlement Matrix" that was supplied to Mike Wilberg for use in the OAC Simulation Model. To create the Settlement Matrix, each cell of the superindividual settlement matrices from the five scenarios were added to the corresponding cell, then the proportions of total superindividuals that were released from each habitat polygon and settled on each habitat polygon was calculated. The OAC Simulation Model used this information to determine where larvae that were spawned from each habitat polygon were transported.

An important note. It is important to note that the larval transport model does not simulate many of the complexities of the early life of oysters. Biological processes of growth and salinity-dependent mortality were not explicitly included. In addition, the model simplifies helical swimming patterns and does not include responses to different concentrations and types of algae, reactions to low dissolved oxygen, and selection of settlement habitat based on quantity and quality. The influences of these factors are accounted for in the OAC Simulation model. The larval transport model uses high resolution physics and analytics to calculate the trajectories of particles from release to settlement areas, fulfilling a major need of the OAC Simulation Model that requires a way to predict where larvae go.

B.3. Analysis

Output from the larval transport model was analyzed to evaluate spatial and temporal patterns in particle dispersal, spatial patterns in transport success and self-recruitment of oyster larvae, and the catching success of the habitat polygons. Water temperatures experienced by larvae and pelagic larval durations (the amount of time that larvae spent in the water) also were calculated.

Model predictions from the two connectivity matrices, one based on particles and one based on superindividuals, were used to calculate metrics of settlement success, natal returns, transport success, self-recruitment and catching success for each of the five particle release scenarios. Total settlement success and total natal returns were determined from the perspective of the entire model domain and not for individual habitat polygons. Total settlement success was calculated as the percent of particles or superindividuals that encountered suitable habitat per number of particles or superindividuals released in each scenario. Similarly, total natal returns were calculated as the percent of particles or superindividuals that returned to settle on the same habitat polygon from which they were released per number of particles or superindividuals released in each scenario.

Transport success, self-recruitment and catching success scores were calculated for each habitat polygon. The transport success score was calculated as the percent of particles or superindividuals that were released from a given polygon and encountered suitable settlement habitat in the model domain per number of particles or superindividuals released from that habitat polygon. Self-recruitment was calculated as the percent of particles or superindividuals that settled on the same habitat polygon from which they were released divided by the total number of particles or superindividuals released from that habitat polygon. The catching success metric was calculated as the percent of particles or superindividuals that settled on a given habitat polygon per number of particles or superindividuals that were released from that polygon and encountered suitable habitat in the model domain.

Average water temperature (°C) as well as median, minimum and maximum larval pelagic duration (d) were calculated for each of the five particle release scenarios. Average water temperature was calculated as the water temperature experienced by each particle at its location in the water column at each timestep that particle spent in the water (prior to settlement or death) averaged across all particles (210,601 particles in each scenario).

Calculations for the median, minimum and maximum pelagic duration values were restricted to those particles that encountered suitable habitat and settled. The pelagic duration of each particle was the time from release from a habitat polygon to settlement on a habitat polygon, i.e., the entire period that each particle spent in the water.

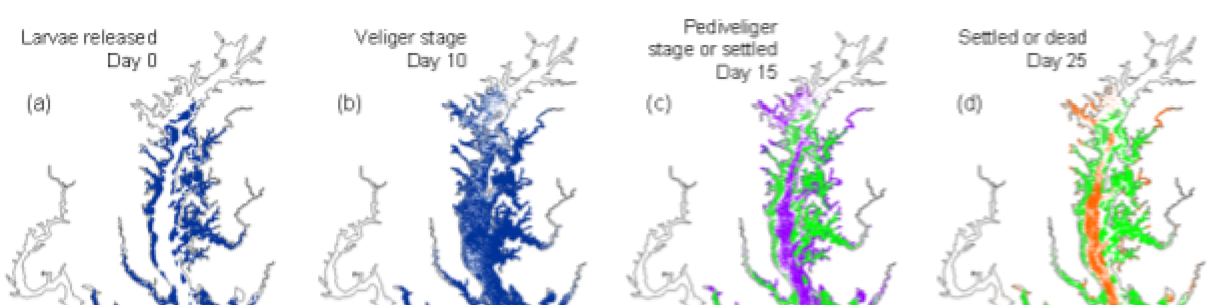
B.4. Predictions

This section summarizes results of the larval transport model runs that provide information about spatial patterns in larval transport success – indicating which oyster habitat polygons are located in good places to send oyster larvae to, or receive oyster larvae from, other polygons. These results also show that changes in wind and freshwater flow could influence the direction and distance that oyster larvae are transported within one year.

Particle dispersal. Visual inspection of the model results indicated that the spatial distribution of particles was different for each of the five scenarios both in the northern and southern parts of the bay (Figs. B.4 - B.8). For example, the southernmost particles were found in Tangier Sound in scenarios II (Fig. B.5b,c) and III (Fig. B.6b,c), whereas they occurred midway between Tangier Sound and the mouth of the Chesapeake Bay in scenarios I (Fig. B.7b,c) and V (Fig. B.8b,c). Particles extended to the mouth of the bay in scenario IV (Fig. B.7b,c). The northernmost particles were found north of the Chester River in all scenarios, but the maximum distance that a particle was dispersed to the north occurred in scenario V (Fig. B.8b,c). Particle locations of settled and dead stages (Fig. B.4d - B.8d) reflected the spatial patterns observed during veliger and pediveliger stages. These results indicate that the changes in wind and freshwater flow influence the direction and distance that oyster larvae are transported.

Water temperature. The average water temperatures experienced by particles across the five scenarios varied by ~2 °C, with a high of 27.1 °C (Scenario IV) and a low of 25.0 °C (Scenario I) (Table B.2). This narrow range in temperature likely was because the five scenarios were conducted during the summer months when water temperatures were high.

Pelagic duration. Median, minimum and maximum values of pelagic duration remained relatively constant through all five scenarios (Table B.2), indicating that the model code executed correctly. The difference between minimum and maximum pelagic duration shows that there was a broad range in the total time that individual larvae were simulated to be in the water.



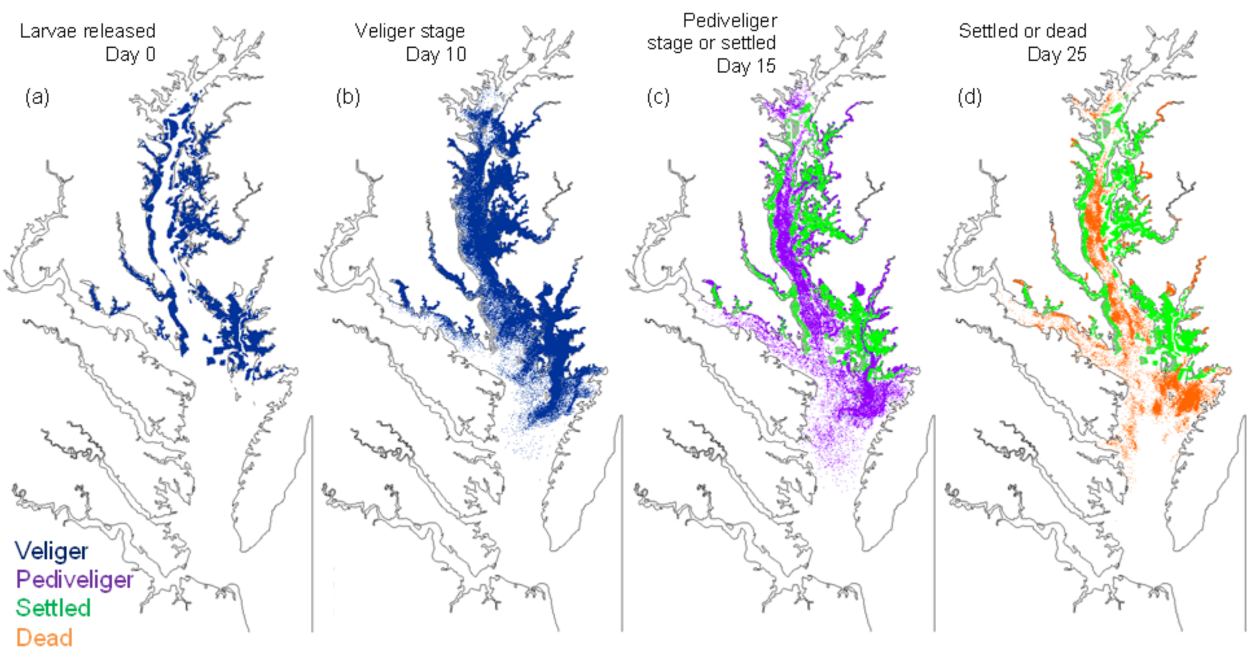


Fig. B.5. Snapshots of particle locations from simulation II (particle release date: June 23, 2013). Panels show particle locations (a) at release, (b) on day 10, c) day 15, and day 25. In panels b-d, colors correspond to particles that were in the veliger stage (blue), the pediveliger stage (purple), settled (green) or 'dead' (orange).

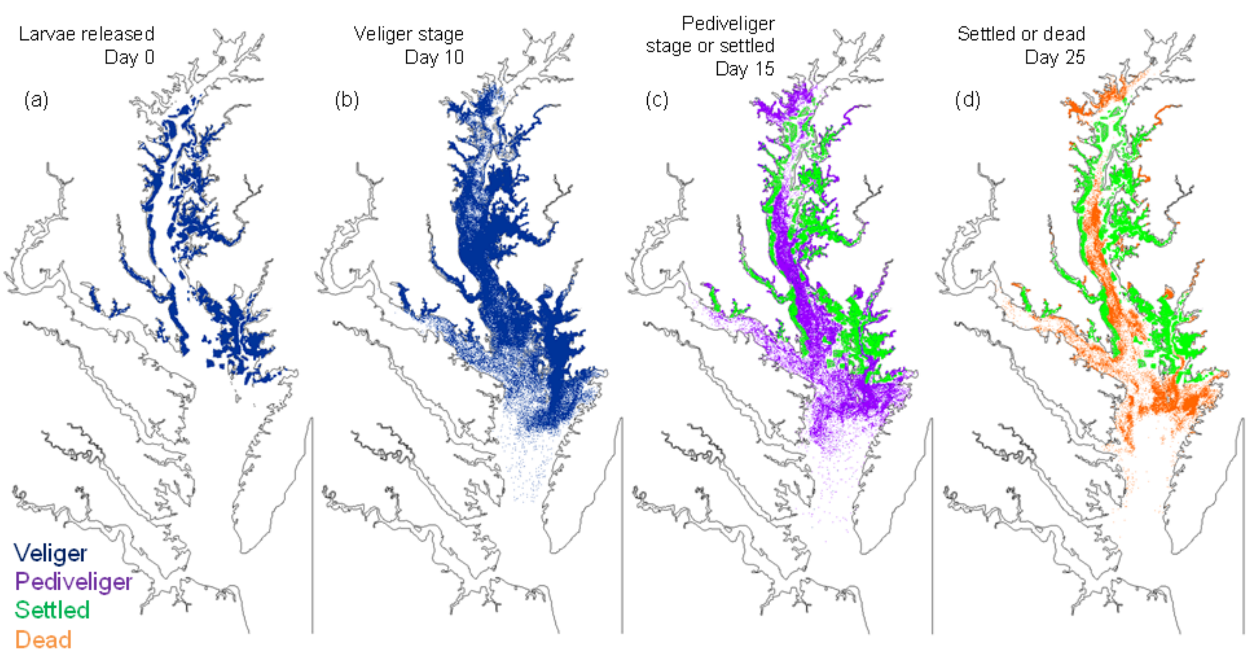


Fig. B.6. Snapshots of particle locations from simulation III (particle release date: June 29, 2013). Panels show particle locations (a) at release, (b) on day 10, c) day 15, and day 25. In panels b-d, colors correspond to particles that were in the veliger stage (blue), the pediveliger stage (purple), settled (green) or 'dead' (orange).

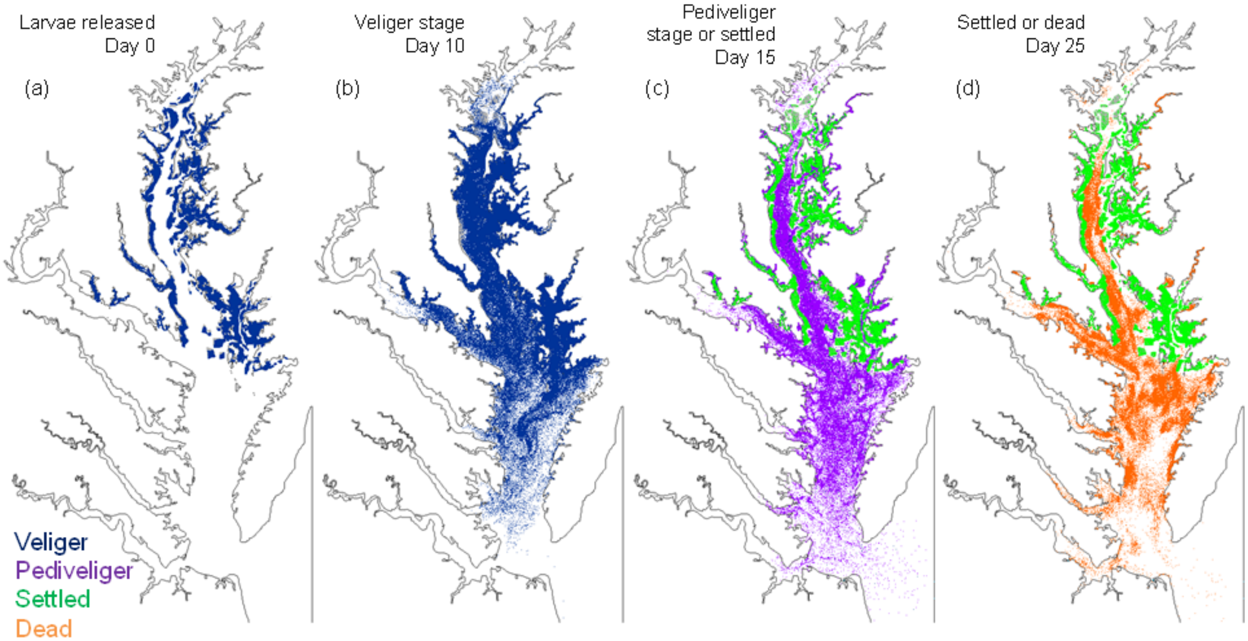


Fig. B.7. Snapshots of particle locations from simulation IV (particle release date: July 24, 2013). Panels show particle locations (a) at release, (b) on day 10, c) day 15, and day 25. In panels b-d, colors correspond to particles that were in the veliger stage (blue), the pediveliger stage (purple), settled (green) or 'dead' (orange).

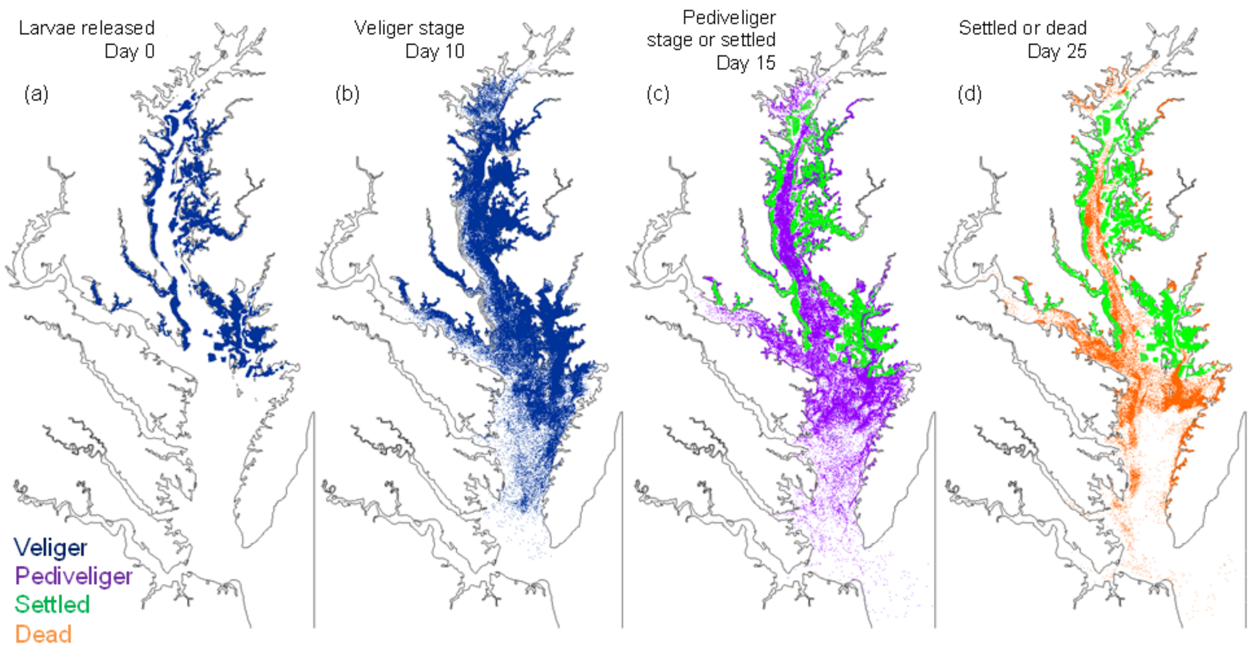


Fig. B.8. Snapshots of particle locations from simulation V (particle release date: July 30, 2013). Panels show particle locations (a) at release, (b) on day 10, c) day 15, and day 25. In panels b-d, colors correspond to particles that were in the veliger stage (blue), the pediveliger stage (purple), settled (green) or 'dead' (orange).

Total settlement and natal returns. Total settlement success and total natal returns scores differed between the five case scenarios and between particle and superindividual connectivity matrices (Table B.3 - B.6). For particles, total settlement success ranged between 66.6% (Scenario IV, Table B.3) and 83.6% (Scenario II, Table B.3), with an average 78.0% of particles successfully settled on suitable habitat in all five scenarios. Alternatively, the average settlement success for superindividuals was much lower (0.31%), with a high of 0.33% (Scenario II, Table B.4) and a low of 0.27% (Scenario IV, Table B.4). This difference in total settlement success scores was a result of larval mortality that was incorporated in the superindividual approach.

Although the total settlement success values differed significantly between the two connectivity matrices, the pattern in magnitude remained the same, i.e., Scenario II had the highest percent of successfully settled particles and Scenario IV had the lowest in both the particle (Table B.3) and superindividual matrices (Table B.4).

Table B.3. Total percent settlement of particles (number and percent of particles that settled on any habitat polygon within the model domain) for the five model runs using the particle connectivity matrix. The last row contains the sum of particles released, the sum of particle settled, and the average of percent settlement across the five scenarios.

Particle release scenario	Total particles released	Particles settled	
		No.	%
I	210,601	165,404	78.5
II	210,601	176,126	83.6
III	210,601	173,895	82.6
IV	210,601	140,337	66.6
V	210,601	165,490	78.6
I - V	1,053,005	821,252	78.0

Compared to total settlement success scores, total natal return scores were much lower (Table B.5, B.6) because few particles and superindividuals returned to the same habitat polygon from which they were released. Averaged across the five scenarios, total natal return scores were 2.7% (Table B.5) for particles and 0.010% (Table B.6) for superindividuals. For both connectivity matrices, the highest natal return occurred in Scenario III (3.3%, Table B.5; 0.012%, Table B.6) while the lowest was recorded for Scenario IV (1.9%, Table B.5; 0.007%, Table B.6). Also, the pattern in natal return scores - Scenario III > Scenario II > Scenario I > Scenario V > Scenario IV - was the same for both particles and superindividuals (Table B.5, B.6), likely because the trajectories of superindividuals and particles were the same.

There were clear spatial patterns in the transport success, self-recruitment and catching success scores for both particles and superindividuals (Fig. B.9 - B.11). Transport success scores (Fig. B.9) showed that the habitat polygons with the highest transport success scores were located in the upper reaches of the Chester, Miles, Choptank, Little Choptank and Nanticoke rivers on the eastern shore of the Chesapeake Bay for both particles and superindividuals. The upper reaches of the tributaries on the western shore also had habitat polygons with relatively high transport scores (Fig. B.9). However, the quantitative value for these ‘high’ transport success differed over orders of magnitude between particles and superindividuals. The transport success score varied between 12.7 - 100% for particles (Fig. B.9a) and between 0.04 - 0.48% for superindividuals (Fig. B.9b).

For self-recruitment scores, no distinctive spatial pattern could be established for both particles and superindividuals. However, for the particles, habitat polygons located in the upper reaches of the tributaries on the eastern and western shores tended towards slightly higher self-recruitment (Fig. B.10a). Habitat polygons with self-recruitment scores greater than 60% were identified for both particles and superindividuals (red circles in Fig. B.10) but they were significantly outnumbered by the polygons with scores below 1%. This was especially true for superindividuals, where more than 75% of the habitat polygons had self-recruitment scores below 0.2% (dark purple circles in Fig. B.10b).

Table B.4. Total percent settlement of superindividuals (number and percent of particles that settled on any habitat polygon within the model domain) for the five model runs using the superindividual connectivity matrix. The last row contains the sum of superindividuals released, the sum of superindividuals settled, and the average of percent settlement across the five scenarios.

Particle release scenario	Total superindividual particles released	No. of larvae in each superindividual	Total larvae settled	
			No.	%
I	210,601	1,000,000	677,890,586	0.32
II	210,601	1,000,000	703,520,037	0.33
III	210,601	1,000,000	678,498,213	0.32
IV	210,601	1,000,000	568,258,455	0.27
V	210,601	1,000,000	675,697,717	0.32
I - V	1,053,005	1,000,000	3,303,865,008	0.31

The spatial distribution and values for catching success scores of habitat polygons were almost identical for particles and superindividuals (Fig. B.11). This coherence between the scores from the two connectivity matrices was largely due to the way catching success was calculated. The influence of larval mortality was greatly reduced because the catching success score was based on the number of particles (or superindividuals) that encountered successful habitat after release instead of the number of particles (or superindividuals) released, resulting in consistent patterns between particles and superindividuals. Habitat polygons located in Tangier Sound had catching success scores greater than 1000% (red circles in Fig. B.11), indicating that more than 10 times the number of particles (or superindividuals) settled on these polygons than were successfully recruited from it – likely due to transport of larvae into Virginia waters where no settlement habitat simulated. On the other hand, there were few habitat polygons with catching success scores lower than 10%, and numerous polygons with scores of 100-1000% throughout the tributaries and main channel of the bay (Fig. B.11).

Table B.5. Total natal returns of particles: the number and percent that settled on the same habitat polygon from which they were released for the five model scenarios using the particle connectivity matrix. The last row contains the sum of particles released, the sum of particle settled, and the average of percent settlement across the five scenarios.

Particle release scenario	Total particles released	Particles returned	
		No.	%
I	210,601	5,755	2.7
II	210,601	6,935	3.3
III	210,601	6,997	3.3
IV	210,601	4,044	1.9
V	210,601	4,743	2.3
I - V	1,053,005	28,474	2.7

Table B.6. Total natal returns of superindividuals: the number and percent that settled on the same habitat polygon from which they were released for the five model scenarios using the superindividual connectivity matrix. The last row contains the sum of superindividuals released, the sum of superindividuals settled, and the average of percent settlement across the five scenarios.

Particle release scenario	Total superindividual particles released	No. of larvae in each superindividual	Total larvae returned	
			No.	%
I	210,601	1,000,000	21,421,462	0.010
II	210,601	1,000,000	25,232,071	0.012
III	210,601	1,000,000	25,441,812	0.012
IV	210,601	1,000,000	15,649,454	0.007
V	210,601	1,000,000	19,288,728	0.009
I - V	1,053,005	1,000,000	107,033,527	0.010

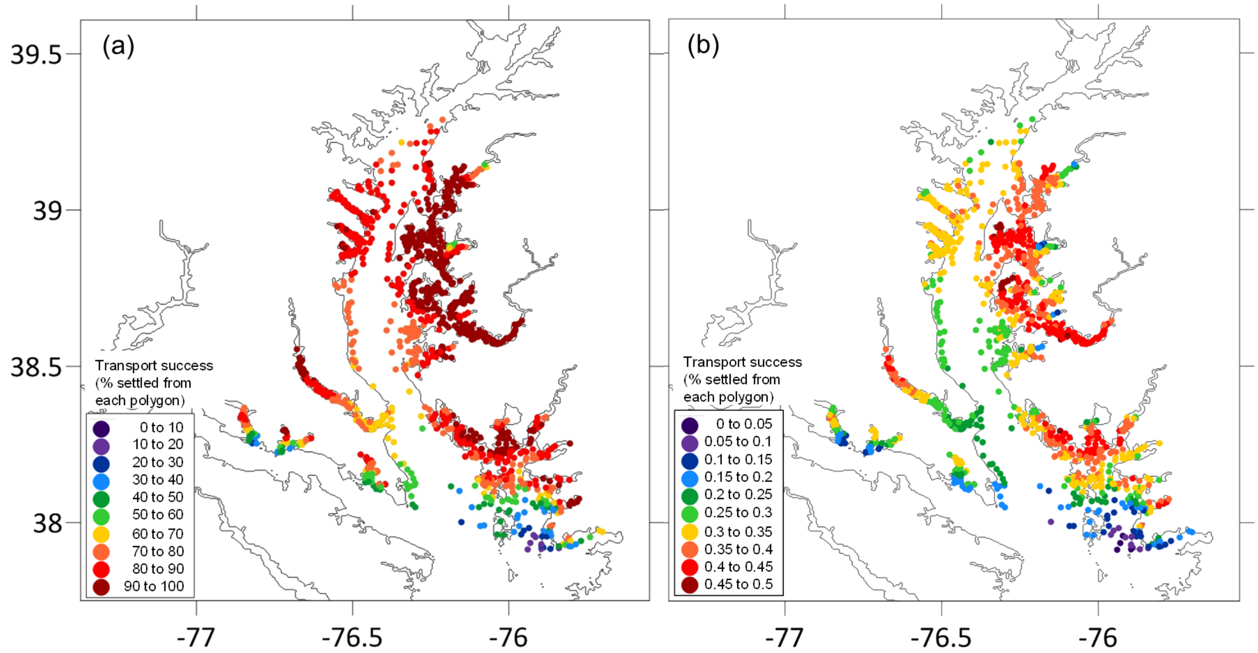


Fig. B.9. Transport success scores for individual habitat polygons using (a) the particle connectivity matrices and (b) the superindividual connectivity matrices, summarized across the five model scenarios. Each habitat polygon, represented by a circle, was color coded according to the percent of particles (or superindividuals) that settled on any habitat polygon within the model domain per number of particles (or superindividuals) released from that polygon.

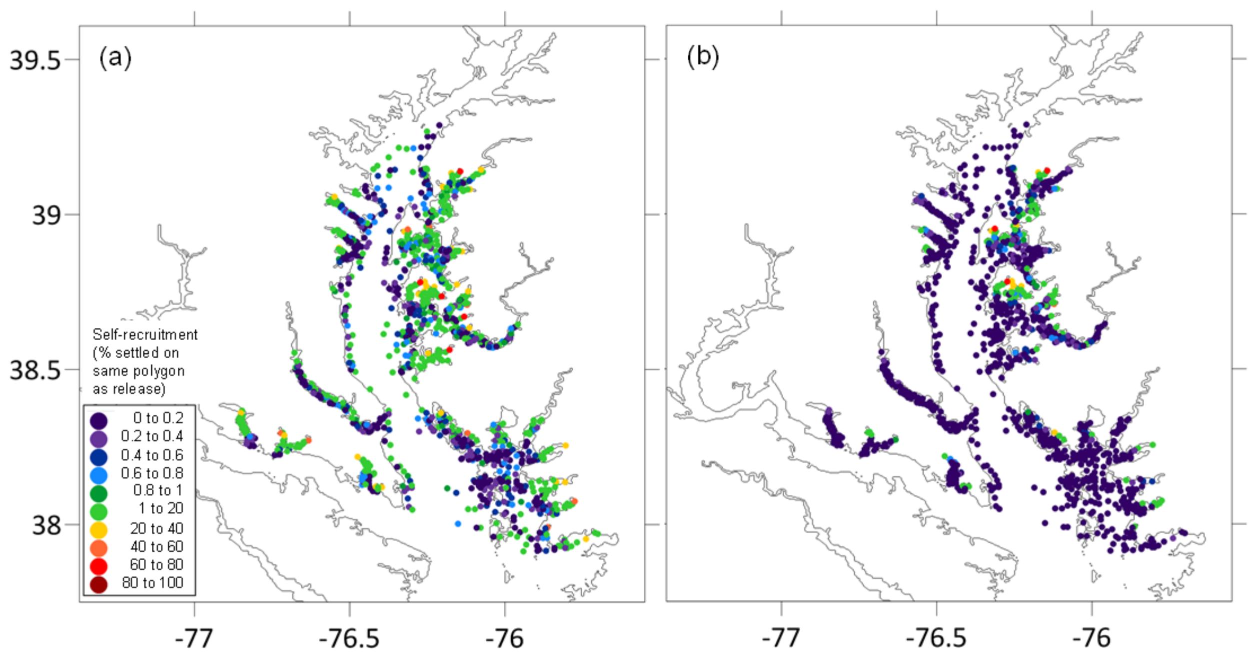


Fig. B.10. Self-recruitment success scores for individual habitat polygons using (a) the particle connectivity matrices and (b) the superindividual connectivity matrices, summarized across the 5 model simulations. Each habitat polygon, represented by a circle, was color coded according to the percent of particles (or superindividuals) that settled on the same habitat polygon that they were released from divided by the total number of particles (or superindividuals) released from that habitat polygon. The color key on the left applies to both panels.

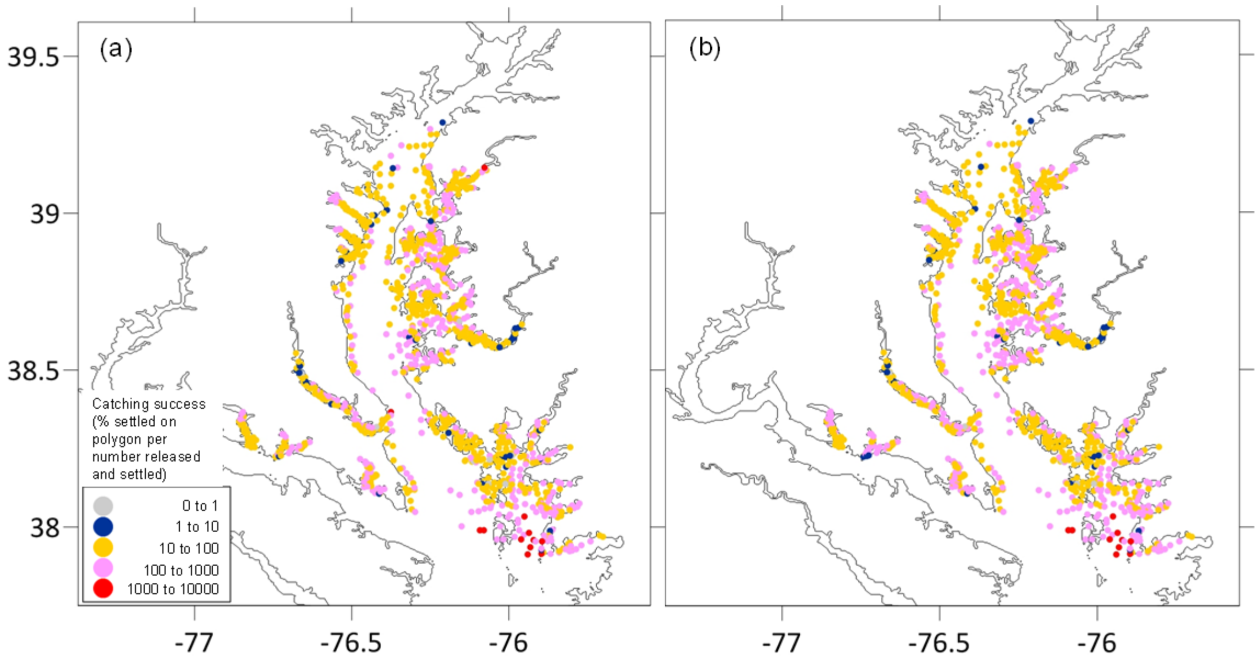


Fig. B.11. Catching success scores for individual habitat polygons using (a) the particle connectivity matrices and (b) the superindividual connectivity matrices, summarized across the five model scenarios. Each habitat polygon, represented by a circle, was color coded according to the percent of particles (or superindividuals) that settled on that habitat polygon per number of particles (or superindividuals) released and settled from that polygon. The color key on the left applies to both panels.

Discussion

This modeling study incorporated a fine resolution ROMS hydrodynamic model of the Chesapeake Bay with a larval transport model to simulate the transport of oyster larvae-like particles. The hydrodynamic model offered the highest possible spatial resolution ROMS model of the Chesapeake Bay currently accessible. This model had a grid scale fine enough to resolve transport of simulated larvae within small tributaries like St. Mary's and the Little Choptank Rivers, both of which are important sites for oyster restoration in the bay. The larval transport model was upgraded to include a superindividual approach that accommodates duration-dependent mortality. Applying this mortality rate resulted in significant changes in the magnitude of larval transport metrics but not in the general spatial patterns of these metrics.

The Chesapeake Bay, supported by major and minor tributaries located on the eastern and western shores, is a relatively shallow estuarine system with a complex coastline. The ROMS model applied in this study offered sufficient spatial resolution to describe the coastline of small tributaries like the Little Choptank and St. Mary's Rivers (Fig. A.1). In the Maryland waters of the Chesapeake Bay, oyster reefs tend to be found in shallow regions of the bay and its tributaries (often < 10 m) due to summer hypoxia/anoxia in the deeper waters (Merritt 1977, Andrews 1979, Kennedy 1991). These reefs, natural or restored, are sites where the transit of oyster larvae begins and/or ends. It is therefore important to resolve both the complex shorelines and shallow (< 10 m deep) regions to simulate oyster larval transport and predict connectivity between reefs.

A significant difference between previous larval transport models for oysters in Chesapeake Bay and this modeling study was the addition of a superindividual approach that simulates the effect of duration-dependent mortality on larval transport predictions. Here, duration-dependent larval mortality was used to represent loss of larvae due to predation and other biological processes. By including duration-dependent larval mortality, the average percentage of successful settlement drops from 78% (Case I-V, Table B.3) to 0.31% (Case I-V, Table B.4), while average percent natal return scores decrease from 2.7% (Case I-V, Table B.5) to 0.01% (Case I-V, Table B.6). The reduction in the magnitude of transport success due to duration-dependent mortality also has been found in previous larval transport studies (Cowen et al. 2000, Werner et al. 2007, Treml et al. 2015).

During the simulation interval of June to August 2013, model results show that transport of larvae released from oyster habitat was strongly influenced by changes in physical conditions, most likely from differences in winds, river flow, and tides. Chesapeake Bay has two-layer circulation patterns, with net outflow at the surface and net inflow near bottom (Elliott et al. 1978, Wang 1979, Schubel and Pritchard 1986). Through all five scenarios, particles were subjected to the two-layer circulation patterns, oscillating tidal flows, and net seaward transport towards the open ocean boundary (Fig.B.4 - B.8). This transport of larvae to the south is accentuated in simulations IV (Fig. B.7) and V (Fig. B.8), likely due to wind forcing because no large freshwater discharge events occurred during this time period (https://waterdata.usgs.gov/monitoring-location/01578310/). Although the relative contribution of wind forcing is site-specific, previous transport simulations (Zhang et al. 2016, Goodwin et al. 2019) also have shown that seasonal trends in wind direction influence larval transport.

The present model framework used the highest spatial resolution available to simulate larval transport in the main channel, and the major and minor tributaries of the Chesapeake Bay over the summer interval (June - August) of 2013. Because the ROMS model was not developed specifically for this project, there was no opportunity to fine tune the model to improve hydrodynamic predictions, particularly the salinity distributions. For future efforts, we recommend using a hydrodynamic model with comparable spatial resolution and allow time to tune the model to ensure coherence between observed and predicted salinity gradients. Further improvements should also include conducting larval transport simulations over multiple years to capture interannual variability in environmental forcing (esp., years with differences in river flow).

From the biological perspective for larval transport, the reproductive effort or number of larvae generated on each oyster habitat polygon was not taken into account in this model – it was taken into account in the OAC Simulation Model. Reproductive effort is important for determining source and sink characteristics of the habitat polygons. Future investigations could combine larval transport and reproductive effort to identify whether a given oyster habitat polygon (1) would be a significant contributor to future generations (produce more progeny) i.e., be a source polygon or (2) would give priority to settlement over reproductive effort i.e., be a sink polygon. Information on oyster abundance and spatfall could be used to create maps like Fig. B.9 – B.11 that show source and sink dynamics.

Overall, larval transport model predictions indicate that there are spatial patterns in transport success, self-recruitment, and catching success, and that these patterns differ between tributaries and between the mainstem and tributaries due to differences in hydrodynamics. By including larval transport model predictions, the OAC Simulation model has the ability to account for the influence of different hydrodynamics patterns on larval transport – an important part of the early life of oysters that connects populations across separate reefs.

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Chapter 3. Value of nutrient removal by oysters

Lisa Wainger and Elizabeth Price

Abstract

Reducing nutrients within Chesapeake Bay waters creates benefits to those who use or simply appreciate the Bay by increasing the enjoyment of recreational experiences, improving fisheries, and enhancing habitat for all aquatic life. Oysters reduce nutrients in surface waters when they incorporate nutrients into their tissue and shell, promote burial of nutrients in the bottom sediments as a byproduct of their feeding behavior, and enhance denitrification. We analyzed the annual unit value of nitrogen removal, representing nutrient reduction costs that would be avoided from increasing oyster restoration in the Maryland portion of the Chesapeake Bay. Currently, Maryland government is requiring pollution emission permit holders, including county governments in Maryland, to reduce nutrients by implementing stormwater practices. Using previously developed data on spending by Maryland's Municipal Separate Storm Sewer System (MS4) permit-holders (Price et al., 2021), we estimated a weighted average annual cost of nitrogen removal. Costs per pound of nitrogen removed for each practice were weighted by the nutrient removal efficiency and total level of implementation of that practice. The result is that the costs are weighted by the level of use of any given stormwater practice to achieve overall nutrient runoff reduction goals. This method results in a value estimate of $1,036/pound of nitrogen reduced.

Because governments are spending money on nitrogen reduction to protect the public interest, the dollar value of $1,036/lb nitrogen can also be considered a value of the improvement in societal well-being from water quality improvements. This value is much higher than the cost per pound of nitrogen removed from agricultural practices, which we estimate at $5.39/lb nitrogen. However, it is worth noting that the true costs of agricultural nutrient management would be much higher, if the price included the costs associated with engaging with farmers to encourage and support them to voluntarily implement projects. We also conclude that the cost avoided may be a conservative estimate of the public's willingness to pay for water quality improvements, based on a study of oyster consumer behavior in Delaware. Oyster buyers were willing to pay substantially more for oysters that they knew had removed nutrients from an impaired water body. We estimate that the willingness to pay (based on a market price premium) is more than $2,800/lb of nitrogen. Finally, we estimate a potential average trading market value of $254/lb of nitrogen. This value is an average credit price based on the assumption that trades could happen among buyers and sellers located anywhere in Maryland. However, current trading market rules constrain who can make transactions to relatively small watersheds and, therefore, prices are likely to vary widely, based on local watershed credit supply and demand conditions.

Background

Reducing nutrients within Chesapeake Bay waters creates benefits to those who use or simply appreciate the Bay by increasing the enjoyment of recreational experiences, improving fisheries, and enhancing habitat for all aquatic life. Maryland is currently required to reduce nutrient and sediment runoff to the Chesapeake Bay to comply with a nutrient cap that has been established under federal regulation to restore water quality and aquatic habitat. A Watershed Implementation Plan (WIP), created by the Maryland government, documents how nutrient reductions will be achieved, primarily by upgrading wastewater treatment plants, implementing stormwater practices, and implementing management practices on farms. Practices implemented by wastewater treatment plant operators and stormwater permittees are required by regulations, while most practices implemented by farmers are voluntary.

Oysters are an alternative method of reducing nutrients in surface waters. They incorporate nutrients into their tissue and shell, promote burial of nutrients in the bottom sediments as a byproduct of their feeding behavior, and enhance denitrification. Denitrification is an ecological process that removes nitrogen from the water by converting it to an atmospheric gas. Oysters support this process by creating the conditions appropriate for denitrification, on and around their shells.

We analyzed the value of removing a nutrient, nitrogen, from the Chesapeake Bay by calculating the costs that would be avoided if that same nitrogen had to be removed through stormwater practices. We only consider stormwater costs because these are the practices are generating a large portion of new reductions and we have high quality data documenting what permit-holders are currently spending to remove nitrogen. These costs avoided also represent what policy makers, who are acting in the public interest, think is appropriate to pay to achieve water quality and aquatic habitat goals. As a result, they also represent the social value for these nitrogen reductions. We compare our cost avoided values to social values developed through alternative economic approaches, to evaluate consistency of values.

Methods

Costs avoided of nitrogen reductions from oysters

Using data that we previously developed of spending by Maryland's Municipal Separate Storm Sewer System (MS4) permit-holders (Price et al., 2021), we analyzed the annual weighted average cost of nitrogen removal for the stormwater sector. Project-specific data that were reported to the Maryland Department of the Environmental from MS4 counties (from 2007-2017) were annualized and then averaged to generate an average annual cost of nitrogen removal per project. Then, cost per pound by project type were weighted by the amount of nutrients that were reduced from that practice over the full reporting period (Table 1). Annualized costs reflect planning, management, capital and land costs distributed over the project life span and add annual maintenance costs. Nutrient removal efficiencies for projects were drawn from the Chesapeake Assessment and Scenario Tool (CAST) (Chesapeake Bay Program, 2021). Details are available in Price et al. (2021). All values in this report were adjusted to 2019 dollars using the Construction Cost Index (CCI), which tracks costs of construction goods and services.

Our cost study included 17 stormwater project types, but three practice types were removed when calculating the effort-weighted average. These three practices, street sweeping (mechanical and advanced) and storm drain cleaning, were eliminated from our database because counties have incentives to conduct these actions without the MS4 permit requirements. Therefore, these practices are not representative of costs for new nutrient reduction efforts.

We attributed the full project cost to the value of nitrogen removal per pound because, for the Oyster Advisory Commission (OAC) study, nitrogen is meant to represent restored water quality benefits. Nitrogen reductions generated using stormwater practices also reduce phosphorus and sediment. However, it would not be appropriate to view those values separately, when using nitrogen to represent water quality benefits. Over the course of a year, nitrogen is most often the nutrient that affects aquatic habitat quality (via algal growth) in the Bay mainstem, but phosphorus can be important at some times of year and is typically most important in freshwater portions of the Bay. Therefore, it is not appropriate to divide the total costs across nutrients and sediments because the cost represents the value of improving water quality. Value for phosphorus removal is provided for comparison.

Alternative nitrogen value

To provide additional context to our nitrogen value, we considered three other ways of valuing the nitrogen reductions.

Agricultural reductions. For comparison purposes, we evaluate the cost per pound removed of nitrogen from agricultural practices using the same methods as for stormwater. The Price et al. (2021) report includes an accounting of spending on agricultural practices to reduce nutrients as part of the Maryland Agricultural Cost Share (MACS) program. Those data were used to estimate effort-weighted price per pound of nitrogen and phosphorus removed per year. We used the subset of agricultural cost share practices that have efficiencies documented as percent removal of loads in CAST. Agricultural practices are highly cost-effective as implemented, but these costs do not cover the costs of outreach and technical assistance required to generate the voluntary efforts.

Price premiums for pollution reduction. An economic market study evaluated the degree to which oyster buyers were willing to pay a price premium for half-shell oysters that have removed nutrients from waterways with impaired water quality (Kecinski et al., 2018). Results from that study demonstrated that buyers were willing to pay the highest price premium from waters with intermediate or uncertain water quality. Price premiums were lower from waterways that were classified as highly impaired, which is the case for the Chesapeake Bay. We converted the range of price premiums per oyster from highly impaired waters from that study ($0.77-$0.90 per oyster) to the price of pounds of nitrogen reduced, based on calculations done by an expert panel (Cornwell et al., 2016). We then applied the rate of 0.13 g nitrogen/3" triploid oyster to convert to dollars per pound. Similar calculations were made for phosphorus reductions, using a removal rate of 0.01 g phosphorus per 3" triploid oyster were used to estimate costs per pound of removal. Using a price premium for half-shell oysters may overestimate the value of reductions for a mix of oysters going to the shucked and half-shell market.

Trading market value. We assume that credit buyers are entities with emission permits from the National Pollution Discharge Elimination System (NPDES) and MS4 programs that require them to meet pollution emission standards. Although other entities (governments, non-governmental organizations) may voluntarily buy nutrient credits in the market, those with regulatory requirements and high costs of compliance will be the most motivated credit buyers. The market value of nitrogen reductions is based on the current spending in the stormwater sector, because those costs represent the alternative nutrient reduction options available to credit buyers.

Starting with the effort-weighted price calculated for the stormwater sector, we conducted three adjustments to this value to generate a market value. First, we divided the value by three to represent the fact that credit sellers are able to stack credits, meaning that they can sell separate nitrogen, phosphorus and sediment credits from the same practice. Second, the pounds of nitrogen, phosphorus and sediment removed were reduced by 5% and rounded down to the nearest integer, following credit calculation guidance from the Maryland Department of the Environment (MDE), COMAR 26.08.11. Finally, we reduced the value by 30%, to represent risks and transaction costs for the buyer (Chesapeake Bay Commission, 2012). This reduction reflects the assumption that buyers would want to see a substantial savings from trading, compared to their own costs of reducing nutrients, in order to cover the logistical costs and legal or other risks of buying credits while retaining the legal liability for those reductions.

Results

We estimate an annual average value of $1,036/pound of nitrogen removal, as the most reliable estimate of the costs avoided or social value of nitrogen removal within the Maryland portion of the Chesapeake Bay. The estimates of value per pound of nitrogen estimated using alternative methods ranged from $5 - $3,300/lb N per year (Table 1). The cost per pound of phosphorus values show the effect of making alternative assumptions about which nutrient is most important to water quality. However, the nitrogen and phosphorus values should not be summed since they attribute total cost of the reduction to a single nutrient. Since phosphorus removal is generally less efficient in stormwater practices, the prices are much higher.

Table 1. Nitrogen and Phosphorus Cost Effectiveness ($/pound nutrient shown, shown in 2019$)

Method	Average annual value of nitrogen removal ($/ lb)	Average annual value of P removal ($/ lb)
Average effort-weighted value (stormwater sector)	$1,036	$3,163
Average effort-weighted value (agricultural sector)	$5.39	$33.55
Price premium value	$2,859-$3,341	$37,163-$43,438
Trading market value	$254	$756

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Chapter 4. Estimation of effects of fishing on bottom habitat for oysters in the Chesapeake Bay, Maryland

Michael Wilberg, Jerelle Jesse, Marvin Mace III

Introduction

Hard-bottom is essential habitat for eastern oyster *Crassostrea virginica*. In Maryland, most hard-bottom habitat available to oysters is oyster shell. Fishing for oysters has been shown to reduce the height of man-made shell oyster reefs (Lenihan and Peterson 2004) and natural oyster reefs (DeAlteris 1988). Alternatively, a common view in the oyster industry is that fishing practices remove sediment from the oyster cultch, thus "cleaning" it and making more habitat available for spat. Fishing for oysters removes some shell because oysters are not harvested without also taking their shells. Therefore, some shell loss should be expected from fishing activities for oysters. To our knowledge, no comprehensive studies have been conducted to evaluate the effects of fishing on oyster habitat, particularly on natural oyster reefs.

The Maryland Department of Natural Resources conducted hydraulic patent tong monitoring of several areas that were opened to dredging. Because of complications in the study (such as inconsistent amounts of fishing among sites and over time), simple statistical tests are not appropriate for determining the effects of fishing on the bottom. Similarly, data on the amount of cultch have been collected in the Maryland Fall Dredge Survey (FDS), and the amount of fishing activities are reported on daily harvester reports, including amount of harvest, gear used, and location.

Our goal was to conduct an analysis of the available data to determine the effect of fishing on the amount of bottom habitat for oysters in the Chesapeake Bay, Maryland. We conducted an analysis of the monitoring data from areas that were opened to power dredging during 2010-2016. Additionally, we analyzed data from all FDS sites during 2003-2019 to evaluate effects of fishing on the amount of cultch and spat settlement.

Methods and Results

Power Dredge Area Methods

Four bars (Swan Point, Wild Ground, Parsons Island, and Holland Straits East) in three areas (Upper Bay, Eastern Bay, Holland Straits) were opened to power dredging in 2010 and slated for increased monitoring. The Maryland DNR selected comparison sites near each area that was opened for power dredging (Bodkin Shoals and Peach Orchard). The comparison sites were sanctuaries. All sites were monitored using hydraulic patent tongs (2010-2016) and the total volume of cultch and number of oysters in spat, small, and market categories per m^2 were recorded. Daily harvester reports were used to describe the amount of catch and effort by gear type on each bar.

We tested for effects of fishing on cultch and spat production. We used generalized linear models to test for effects of fishing activity on the amount of cultch present and the amount of spat the next year. The response variables were the change in volume of cultch from one year to the next and number of spat per m^2. The explanatory variables were bushels of oysters harvested per hectare, year, location, and treatment type (power dredge area or comparison area). We summarized the amount of fishing activity as the number of bushels of oysters removed in a season divided by the area of the bar. This approach allows for standardization of the effect of fishing on bars of different sizes.

Power Dredge Area Results

We did not find significant (at the $p < 0.05$ level) effects of fishing on either the change in cultch from one year to the next (Table 1; Figure 1) or spat set in the year after fishing (Table 2). The estimated effect of fishing on the amount of cultch was negative (bushels_hect; -0.002 per bushels harvested per hectare), but this estimate was highly uncertain (standard error 0.024). Similarly, the estimated effect of fishing on future spat set as positive (0.043) but was also highly uncertain (standard error 0.070).

This study had a limited ability to determine the effects of power dredging because most of the fishing in these areas was not done by power dredging (Table 3). In the Upper Bay, the dominant gear was patent tonging, and in Eastern Bay, the dominant gear was diving. Holland Straits was the only area where power dredging was the only gear.

Table 1. Results of linear model examining the effects of fishing, year, location, and treatment type on the change in cultch from one year to the next.

Parameter	Estimate	Standard Error	P-value
(Intercept)	-0.080	0.517	0.878
bushels_hect	-0.002	0.024	0.923
Year2011-2012	0.156	0.530	0.771
Year2012-2013	-0.056	0.534	0.917
Year2013-2014	-0.477	0.536	0.382
Year2014-2015	0.281	0.528	0.599
Year2015-2016	1.020	0.791	0.209
LocationHolland Straits	0.430	0.413	0.308
LocationUpper Bay	0.159	0.371	0.671
site_typetreatment	-0.322	0.322	0.326

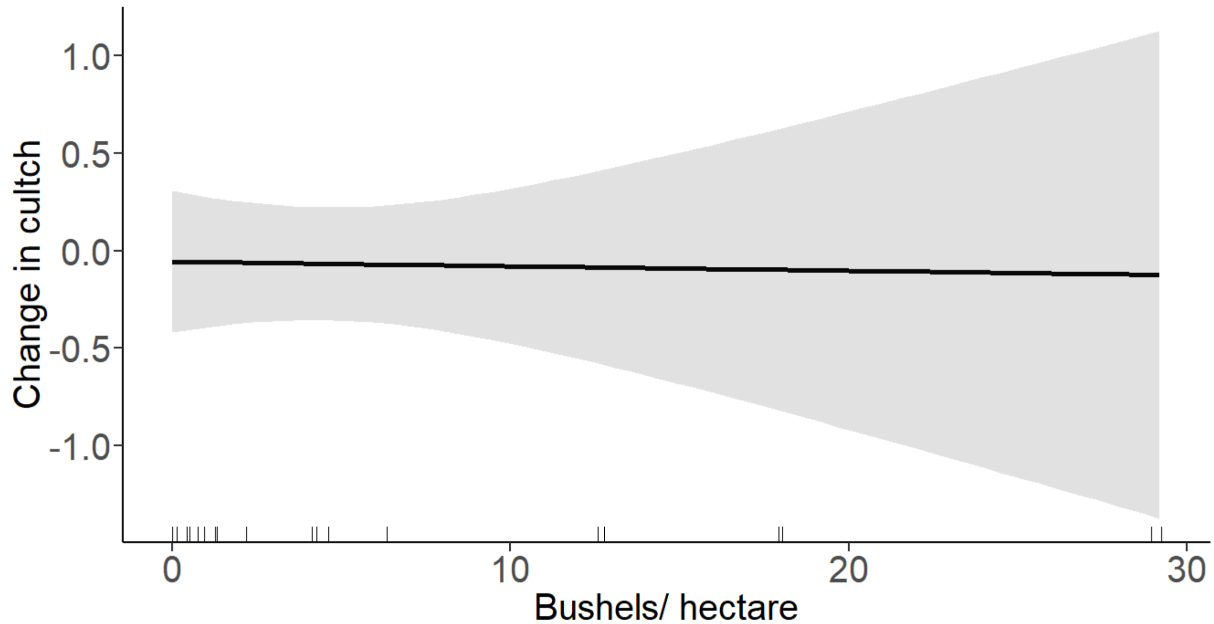

Figure 1. Estimated relationship between change in cultch (in bushels per m2) and harvest (in bushels per hectare). The solid line indicates the best estimate, and the shaded area represents the 95% confidence interval.

Table 2. Results of linear model examining the effects of fishing, year, location, and treatment type on the spat per m^2 in the year after fishing.

Parameter	Estimate	Standard Error	P-value
(Intercept)	2.326	1.701	0.182
bushels_hect	0.043	0.070	0.546
Year2011	-2.153	1.796	0.241
Year2012	-1.332	1.760	0.455
Year2013	-1.515	1.888	0.429
Year2014	-1.947	1.898	0.313
Year2015	0.177	1.838	0.924
Year2016	-1.289	2.489	0.608
LocationHolland Straits	3.021	1.101	0.010
LocationUpper Bay	-0.162	1.009	0.874
site_typetreatment	-1.824	0.904	0.053

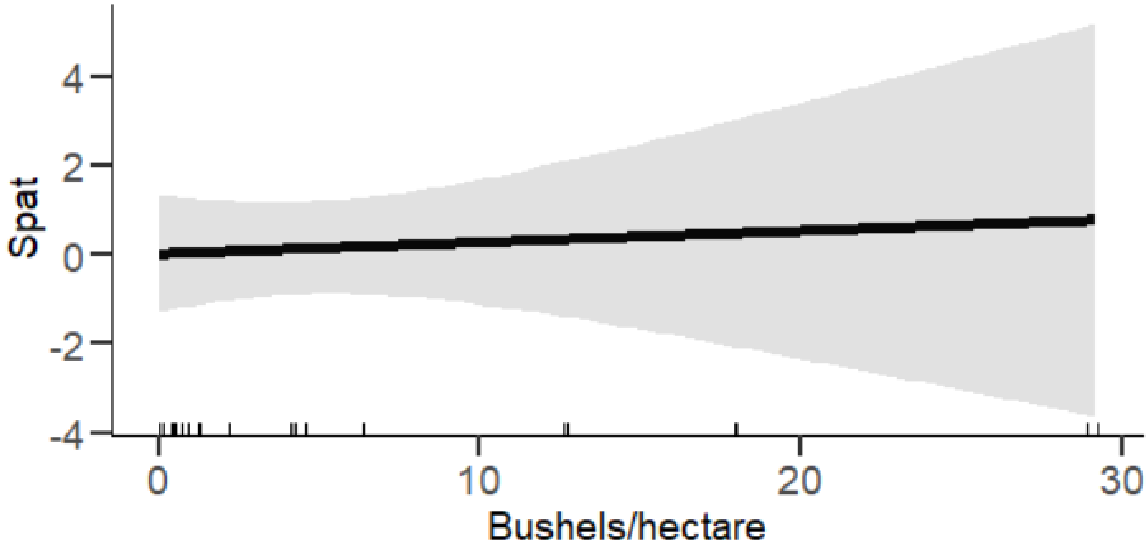

Figure 2. Estimated relationship between spat (in number per m^2) and harvest (in bushels per hectare). The solid line indicates the best estimate, and the shaded area represents the 95% confidence interval.

Table 3. Summary of percentage of effort (vessel days) and harvest (bushels) by gear and location for the study of areas that were opened to power dredging.

Gear	% vessel days	% bushels harvested
Upper Bay		
Diver	2.29	2.98
Power dredge	42.7	41.3
Patent tong	54.3	55.4
Hand tong	0.57	0.28
Eastern Bay		
Diver	56.7	68.2
Power dredge	39.3	29.8
Patent tong	0.54	0.31
Hand tong	3.52	1.69
Holland Straits		
Diver	0	0
Power dredge	100	100
Patent tong	0	0
Hand tong	0	0

Harvester Reports and Fall Dredge Survey Analysis Methods

We used information from harvester reports on daily catches and gears and the Maryland Fall Dredge survey for the amount of cultch. Data on catches per area of the bar were summarized from the harvester reports by bar, gear, and year. Data from the Fall Dredge Survey were summarized by the difference in the mean amount of cultch in the dredge (by bar and year) and the mean number of spat per bushel (by bar and year). We included data from the 2010-2011 season to 2018-2019 because these were the seasons for which the harvester report data were available and considered complete.

We used mixed effects linear models to estimate the effects of types of fishing on the mean amount of cultch ($C_{y,b}$) in the fall dredge survey and the number of spat per bushel (S_y). The mixed models included an intercept (α), effects of harvest per m^2 of bar area ($X_{y,b}$) by gear (β , ϕ_g), a gear effect (δ_g) and a random year effect (γ_{year}),

$$\log\left(\frac{(C_{y+1,b}+0.1)}{(C_{y,b}+0.1)}\right)=\alpha+\beta\times X_{y,b}+\gamma_{year}+\delta_g+\phi_g\times X_{y,b}+\varepsilon_{y,b},$$

and

$$\log(S_y+1)=\alpha+\beta\times X_{y,b}+\gamma_{year}+\delta_g+\phi_g\times X_{y,b}+\lambda_b+\varepsilon_{y,b}.$$

The spat model also included a random bar effect (λ_b). We added small constants to avoid taking the logarithm of zero.

Harvester Reports and Fall Dredge Survey Analysis Results

Effects of fishing on change in cultch (Table 4; Figure 3) or the amount of spat (Table 5; Figure 4) were not significant. Diving had the largest estimated negative effect on change in cultch, followed by power dredging and patent tonging. Sail dredging and hand tonging had estimated positive effects on change in cultch. However, none of these effects were significantly different from zero, nor were they significantly different from each other as indicated by their large standard errors (Table 4). The estimated effect of fishing on spat abundance was negative for divers and power dredging, but was positive for hand tonging, patent tonging, and sail dredging. However, none of these effects were significantly different from zero, nor were they significantly different from each other as indicated by their large standard errors (Table 5).

Table 4. Fixed effect parameter estimates from linear mixed effects model of effects of harvest on change in amount of cultch collected during the Fall Dredge Survey.

Parameter	Estimate	Std. Error
(Intercept)	-0.021	0.063
bushels_meter2	-91.450	70.580
Hand Tong	0.001	0.030
Patent Tong	-0.023	0.031
Power Dredge	-0.012	0.029
Sail Dredge	0.000	0.043
bushels_meter2: Hand Tong	91.620	71.430
bushels_meter2: Patent Tong	88.070	72.450
bushels_meter2: Power Dredge	73.870	72.580
bushels_meter2: Sail Dredge	97.270	113.400

Table 5. Parameter estimates from linear mixed effects model of effects of harvest on amount of spat per bushel collected during the Fall Dredge Survey.

Parameter	Estimate	Std. Error
(Intercept)	1.820	0.247
bushels_meter2	-63.777	155.733
Hand Tong	-0.011	0.061
Patent Tong	0.054	0.064
Power Dredge	0.098	0.060
Sail Dredge	-0.045	0.089

bushels_meter2: Hand Tong	80.361	157.804
bushels_meter2: Patent Tong	75.667	159.783
bushels_meter2: Power Dredge	55.463	160.326
bushels_meter2: Sail Dredge	84.651	243.921

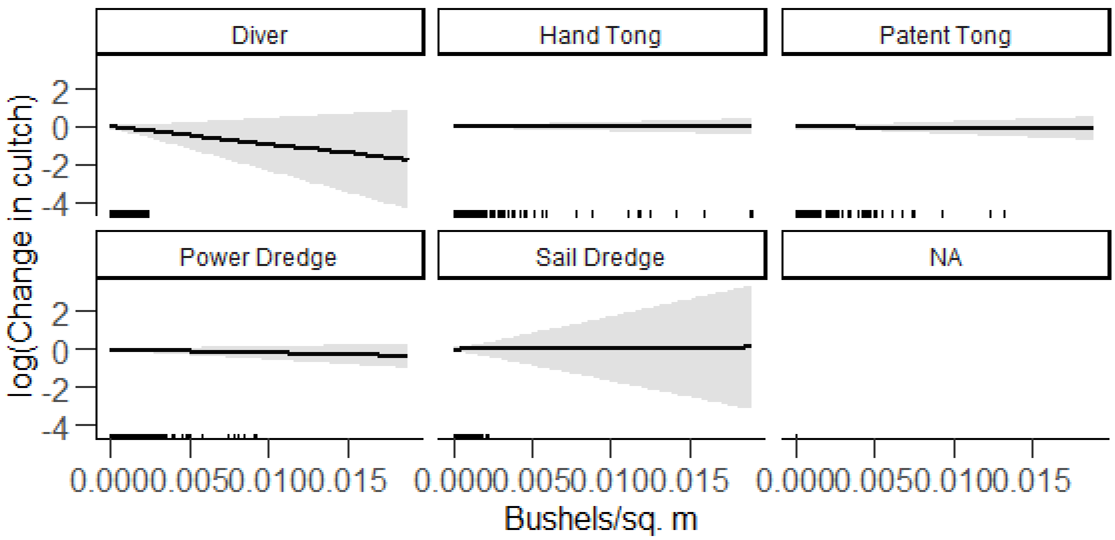

Figure 3. Estimated relationships between the change in cultch in the Maryland DNR Fall Dredge Survey and the amount of harvest per m^2 for oysters in the Chesapeake Bay, Maryland.

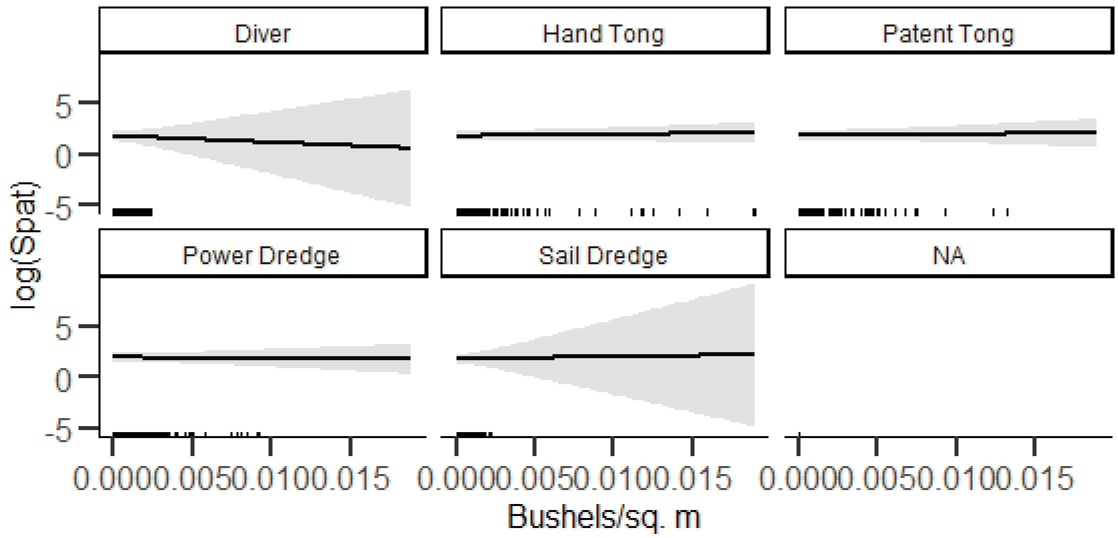

Figure 4. Estimated relationships between the spat per bushel in the Maryland DNR Fall Dredge Survey and the amount of harvest per m^2 for oysters in the Chesapeake Bay, Maryland.

Caveats

The data could be summarized in alternative ways for the analyses, and the way the data are summarized may affect the results. However, given the limited time available for these analyses, we were not able to fully explore all the different ways of analyzing these data. Future studies may want to look at different metrics for spat and cultch in the fall dredge survey (e.g., standardized by area swept) or consider different ways of summarizing the effect of fishing (total fishing activity on each bar). Additionally, the Fall Dredge Survey data have some limitations because the survey occurs after the start of fishing at some locations. If fishing affects cultch or spat, this mismatch between the start of the fishing season and when sampling occurs could cause bias in the estimates, with the sign and magnitude of the bias depending on the effect of fishing on the dependent variable.

Conclusions

We conducted analyses to examine the effects of oyster fishing on the amount of cultch present and on the amount of spat. We conducted analyses using data from monitoring done on areas that were opened to power dredging along with comparison sites that were closed to fishing and data from the Fall Dredge Survey and harvester reports to test for effects of fishing on cultch and spat. All analyses failed to reject the hypothesis that there was no effect of fishing on cultch or spat. Given limitations in the data used for these analyses and time constraints for conducting the analyses, the results had a substantial amount of uncertainty. However, if there were strong and consistent effects of fishing on cultch or on spat, we would expect more consistent results from the analyses we conducted.

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Chapter 5. Estimation of amount of shell on named oyster bars in the Maryland portion of the Chesapeake Bay

Michael Wilberg, Jerelle Jesse, Marvin Mace III

Introduction

Hard bottom habitat is critical for eastern oysters (i.e., oyster bottom; Beck et al. 2011). Oyster bottom in the Maryland portion of Chesapeake Bay was initially surveyed by Yates during 1906-1912 (Yates 1912). In the late 1970s-early 1980s, the Maryland bottom of Chesapeake Bay was again surveyed in the Maryland Bay Bottom Survey (MBBS; MBBS citation). The surveys used a variety of techniques to determine the bottom type. The method used over most of the survey area for the Yates survey was to drag a chain behind a vessel to identify oyster bars. The MBBS used a similar technique in which a microphone was dragged on the bottom to survey much of the Maryland portion of Chesapeake Bay. These surveys identified large and relatively homogenous areas that were designated as natural oyster bars (Yates 1912) or as areas with specific bottom habitat categories (e.g., cultch, mud with cultch, sand with cultch). Maryland maintains a map of natural oyster bars (NOBs), which were originally based on the Yates survey, but include additional areas that were identified as oyster habitat (Kennedy and Breisch 1981).

A current (2021) map of oyster bottom habitat is not available for the Maryland portion of the Chesapeake Bay. In more recent years, sonar and other remote sensing technologies have been used to map the bottom in several parts of the Bay (http://www.mgs.md.gov/coastal_geology/oysterindex.html). These data have been used for planning oyster restoration efforts in the five restoration areas identified in Maryland (Harris Creek, Little Choptank River, Tred Avon River, St. Mary's River, and the Manokin River) as well as other purposes.

Other data sources on bottom habitat are also available. The Maryland DNR conducts an annual Fall Dredge Survey that samples approximate 300 sites per year. The fall dredge survey collects information on the amount of cultch collected in the dredge and the distance of the tow. Maryland DNR also conducts sampling using hydraulic patent tongs at specific locations. Data are collected on the volume of shell recovered from each grab using hydraulic patent tongs.

Our goal was to develop estimates of the volume of available oyster bottom on each of the NOBs in Maryland (Figure 1). We ranked data sets for their perceived reliability, and we developed relationships among datasets to develop estimates of the amount of oyster bottom available for use in the Maryland Oyster Consensus Model.

Methods

Data

We used several sources of data, which we rated for their reliability, including hydraulic patent tong survey data, Fall Dredge Survey data, side-scan sonar data, and MBBS data.

Hydraulic patent tong

The Maryland DNR conducts hydraulic patent tong surveys for a variety of purposes (Figure 2). Within a site, patent tong surveys are conducted using a stratified random sampling design, with the strata based on substrate type. The number of sampling points generally ranges from 50 to 300 and is based on the estimated amount of potential oyster habitat within the sampling area. The amount of cultch is measured as the volume m^{-2}.

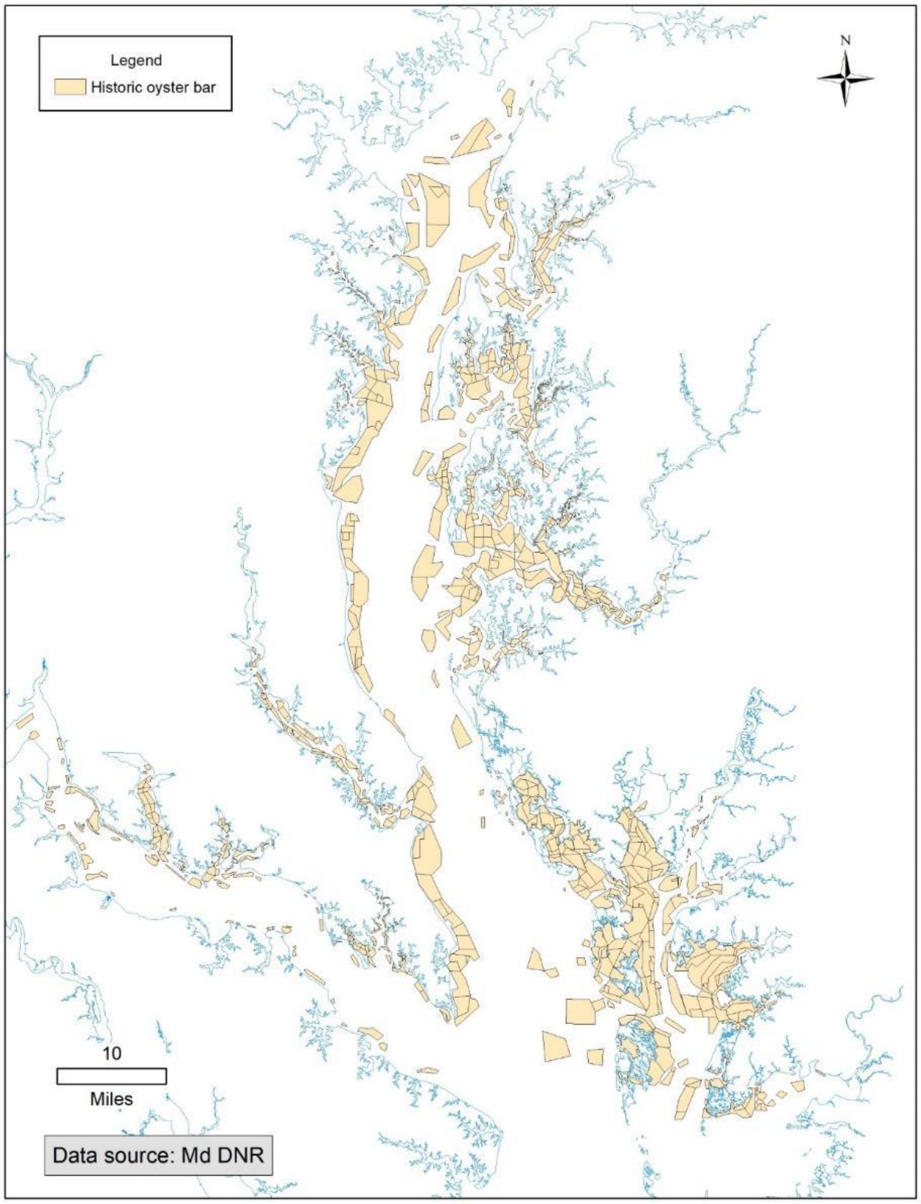

Figure 1. Natural oyster bars in the Maryland portion of the Chesapeake Bay. Oyster bars in the mainstem of the Potomac River were not included in the analysis.

Fall Dredge Survey

The Maryland DNR Fall Dredge Survey is a fisheries independent survey that is conducted annually from October through December (Figure 3). Oysters are sampled using a motorized vessel that tows an 81-cm-wide oyster dredge. The amount of dredged material (cultch) is recorded, and since 2003, the distance of the tow was also recorded. During 1999-2017 the mean number of oyster bars sampled each year was 261 and included bars located in public fishery areas and bars located within oyster sanctuaries.

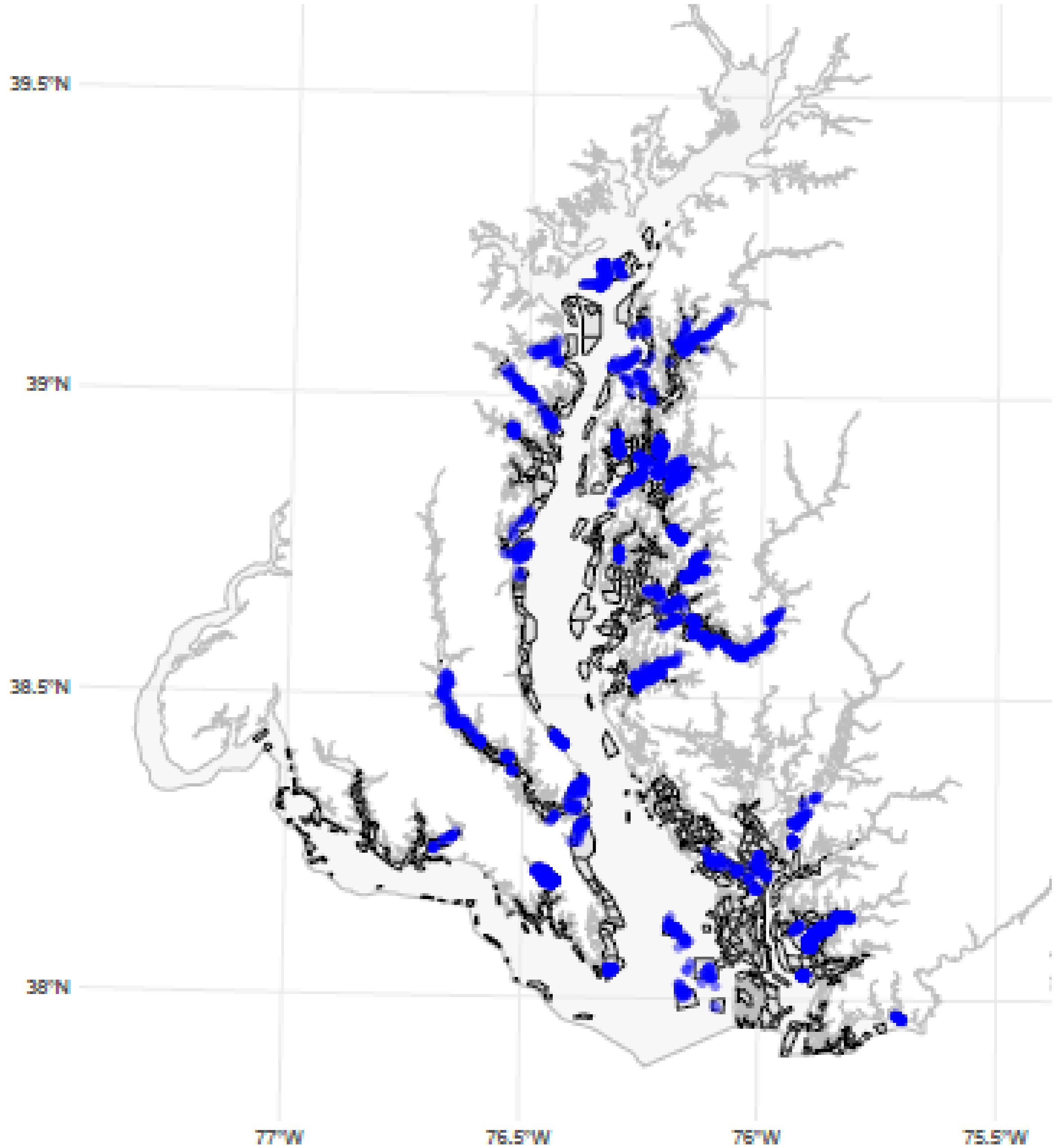

Figure 2. Hydraulic patent tong sampling locations (blue).

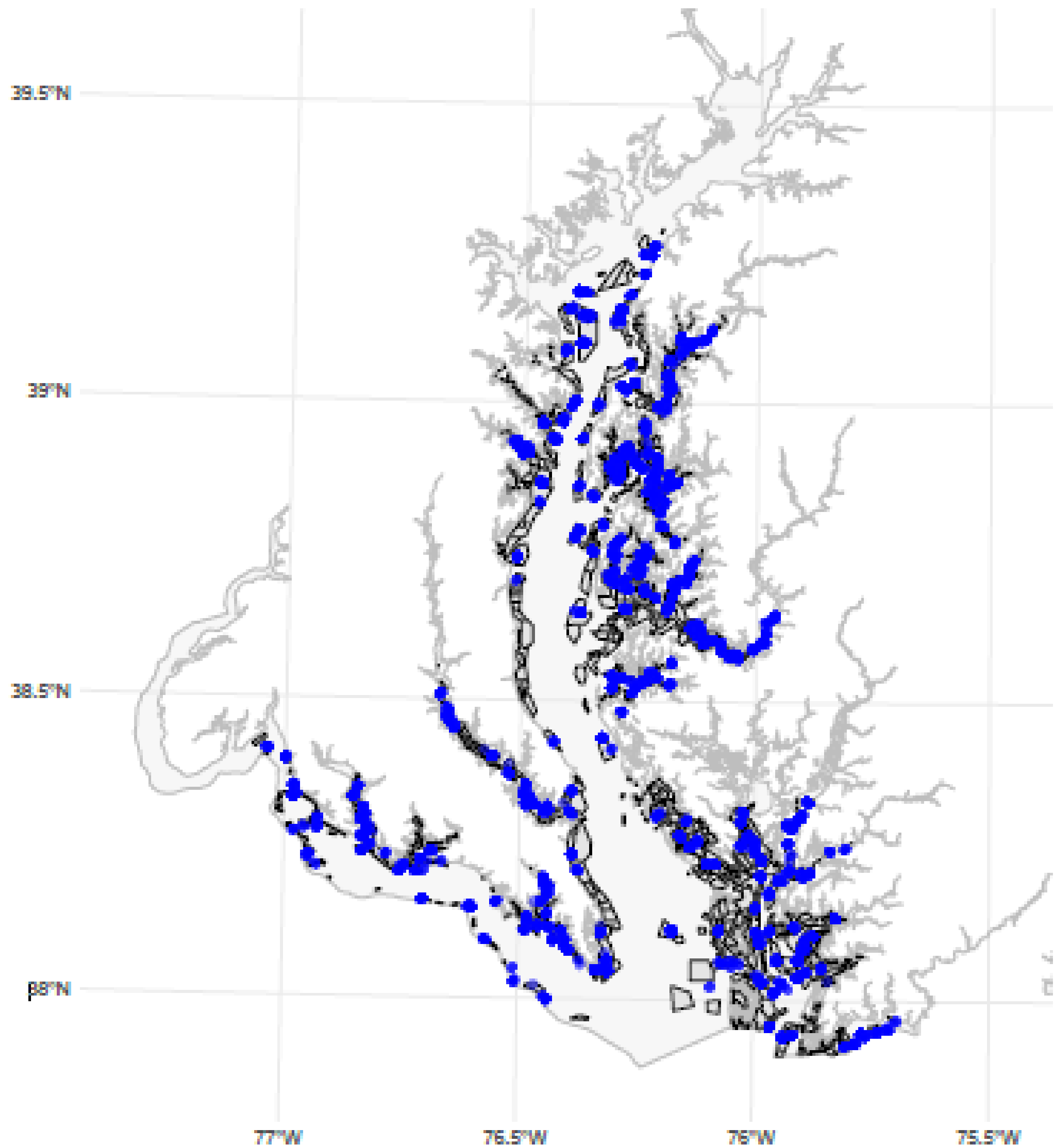

Figure 3. Sampling sites for the Maryland Fall Dredge Survey during 2003-2019 (blue).

Sonar mapping areas

The Maryland Geological Survey and NOAA Chesapeake Bay Office have conducted sonar bottom mapping to identify oyster habitat (Figure 4). We aggregated the CMECS categories of the mapping data to five categories for our analyses (Table 1).

Table 1. CMECS biogenic shell categories and habitat codes used in analyses.

Habitat_code	CMECS_Unit_Code	Substrate_Subclass	Notes
4	S2.5.1.1	Biogenic_Shell_Reef	Natural 3 dimensional oyster shell (some relief)
4	S2.5.1.1(AI08)	Biogenic_Shell_Reef	Natural 3 dimensional oyster shell (some relief) planted with hatchery spat on shell
3	S2.5.2.3	Biogenic_Shell_Rubble	Natural 2 dimensional oyster shell (little relief)
3	S2.5.2.3(AI08)	Biogenic_Shell_Rubble	Natural 2 dimensional oyster shell (little relief) planted with hatchery spat on shell
2	S2.5.2.3	Biogenic_Shell_Rubble	Natural 2 dimensional oyster shell (little relief) on bottom that is more shell than sand
2	S2.5.2.3	Biogenic_Shell_Rubble	Natural 2 dimensional oyster shell (little relief) on bottom that is more shell than mud
5	S3.1.1	Anthropogenic_Rock_Reef	Man made 3 dimensional rock reef (some relief)
5	S3.1.1(AI08)	Anthropogenic_Rock_Reef	Man made 3 dimensional rock reef (some relief) planted with hatchery spat on shell
5	S3.6.1	Anthropogenic_Shell_Reef	(Provisional-Not in CMECS yet) Man made 3 dimensional non-native shell reef (some relief)
5	S3.6.1(AI08)	Anthropogenic_Shell_Reef	Man made 3 dimensional non-native shell reef (some relief) planted with hatchery spat on shell
3	S3.6.2	Anthropogenic_Shell_Rubble	(Provisional-Not in CMECS yet) Man made 2 dimensional transported shell rubble (little relief)
3	S3.6.2(AI08)	Anthropogenic_Shell_Rubble	Man made 2 dimensional transported shell rubble (little relief) planted with hatchery spat on shell

Maryland Bay Bottom Survey (MBBS)

Several attempts have been made to estimate the area of oyster habitat in Chesapeake Bay. The first was the Yates survey from 1906 to 1912. The purpose of this survey was to identify the boundaries of "Natural Oyster Bars" within Maryland's portion of the bay, so that areas outside of oyster bars could be used for oyster aquaculture leases. The original Yates survey and subsequent surveys identified approximately 1,100 oyster bars and over 300,000 acres of oyster habitat. The NOBs were used to provide the area and location of each oyster bar.

The Bay Bottom Survey was conducted from 1975-1983, generating maps that updated the Yates bars. This survey used a dragged acoustical device, patent tongs and sonar, to produce bottom classifications that included sand, mud, cultch (oyster shells) and hard bottom. Cultch and mixed-cultch categories are substrate types that provide habitat for oyster spat. These surveys (and other, more recent, side-scan sonar surveys conducted in sanctuaries) can be used to estimate the amount of habitat available for oysters.

Analyses

To estimate the volume of surface shell on each bar that was available to oysters, we took the product of the area of each oyster bar and a bar-specific estimate of the amount of cultch per m^2. Cultch included oyster shell, live oysters, and other rubble. We ranked data sources with those that had samples of the bottom being considered highest quality followed by those that were indirect or older. We used the following hierarchy of assumed data quality for estimating the amount of shell m^2:

1) Patent tong surveys in areas with survey data. We estimated the mean volume of cultch m^{-2} as the weighted average cultch per m^2 for each habitat type, weighted by the proportion of each habitat type on that bar. Three bars had patent tong data, but the survey reported zero cultch. Those bars were assigned the average cultch from other no habitat bars according to the surveys (see step 4),

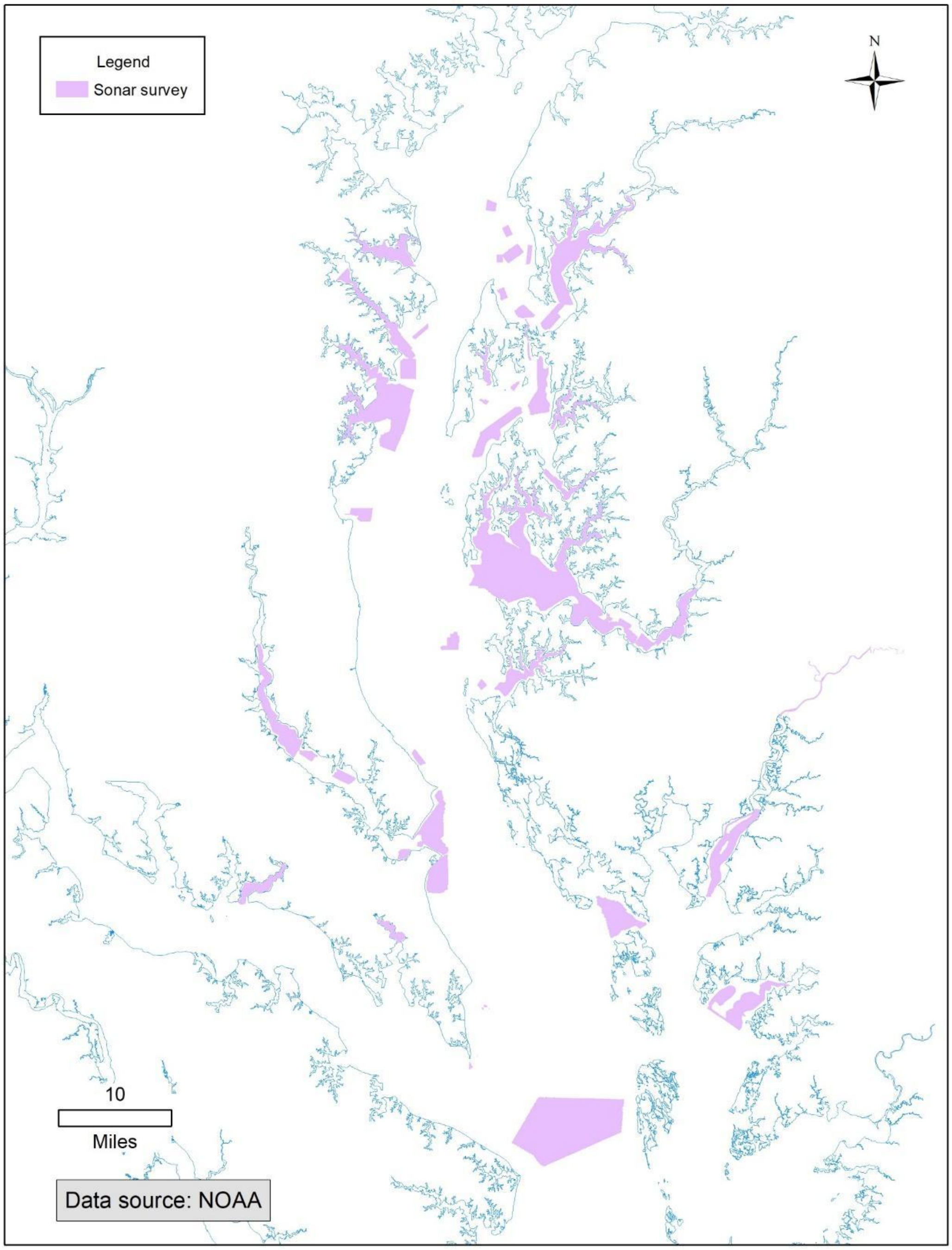

Figure 4. Sonar mapping locations.

2) Fall Dredge Survey adjusted for efficiency in places with fall dredge survey sampling (but no patent tong data). Dredge surveys have been shown to not collect all cultch (Powell et al. 2007). We calculated the mean volume of cultch per distance towed for each bar. We estimated a linear relationship with a zero intercept to convert between the average volume of cultch m^{-2} from patent tongs and the fall dredge survey (Figure 5). Calculating the cultch per area swept for the Fall Dredge Survey was done by assuming 46 L per MD bushel and area was calculated as the product of tow distance (m) and the width of the dredge (0.8128 m).

3) In places with sonar data (but no fall dredge survey or patent tong data), we used relationships between sonar habitat quality scores (Table 1) and patent tong and fall dredge survey cultch. We used data from bars that had both patent tong surveying and sonar mapping to develop an estimated mean amount of cultch per m^2 for each habitat type using an ANOVA with sonar mapping habitat quality scores as the independent variable and the average amount of cultch per m^2 from patent tongs as the dependent variable. If 50% or more of bar had sonar survey coverage, then the sonar data was assumed to be a representative of the whole bar. Additionally, for bars with less than 50% sonar, but MBBS indicating no oyster habitat, we used the sonar information because it was more recent.

4) In the rest of the Maryland portion of the Bay that did not have estimates using approaches 1-3, we used the MBBS data with estimates of the average amount of shell m^{-2} from patent tong surveys. Similar to 3, we used data from bars that had both patent tong surveying and MBBS habitat estimates to develop an estimated mean amount of cultch per m^2 using an ANOVA with MBBS habitat quality scores as the independent variable and the average amount of cultch per m^2 from patent tongs as the independent variable. For bars where the MBBS indicated no oyster habitat was available, we estimated the average shell in MBBS "no habitat" areas using patent tong survey data (1.57 L/m^2).

Results

We were able to estimate the volume of oyster habitat on all NOBs. For bars with hydraulic patent tong surveys, the amount of cultch was estimated as the product of the sample mean and the bar area. We estimated that the Fall Dredge Survey collected, on average, 62% of the cultch as hydraulic patent tong surveys (Figure 5). Bars with Fall Dredge Survey samples had their estimates scaled up by 1/0.62 using this estimated relationship. For bars with only sonar data for habitat, we used relationships between habitat classification and L cultch/m^2 from hydraulic patent tongs (Table 2; Figure 6). Note that the amount of cultch did not differ substantially among categories (Figure 6). The last set of habitat estimates per bar were from the MBBS and hydraulic patent tong surveys (Table 3; Figure 7). Bars that were predominately cultch or cultch with mud had more cultch, on average than bars with sand with cultch (Figure 7). Locations that were not designated as oyster habitat in the MBBS but were sampled with hydraulic patent tongs had an average of 1.57 L/m^2 of cultch.

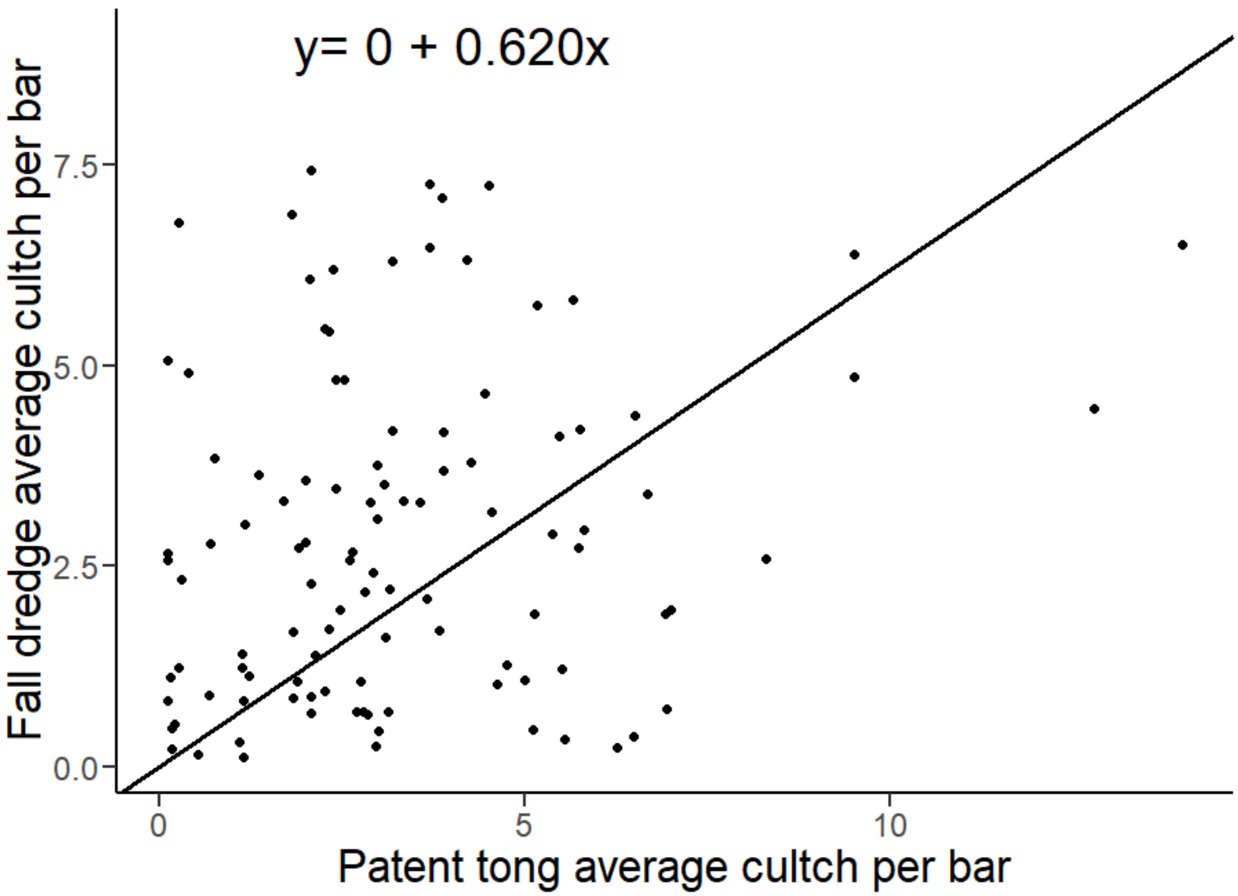

Figure 5. Relationship between average L cultch per m^2 in hydraulic patent tong surveys and the Maryland Fall Dredge survey. The best fit relationship with a zero intercept is displayed on the graph.

Table 2. Average L per m^2 of cultch in patent tong sampling for locations with sonar habitat classification.

Habitat Code	Average Cultch (L/ m^2)
2 – no relief- manmade or biogenic – shell with sand or mud	2.770
3 – no relief- manmade or biogenic - shell	3.636
4 – relief – biogenic – shell material	3.357
5 – relief – manmade – shell and nonshell material	3.105

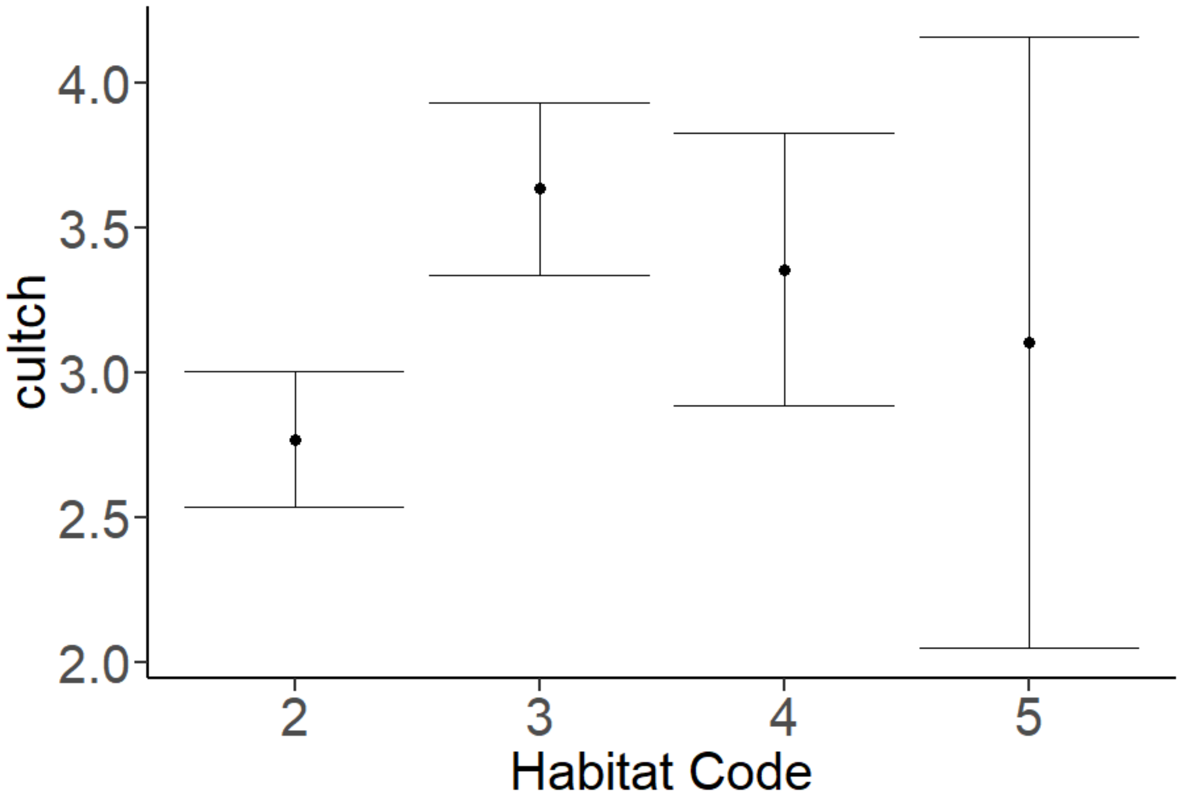

Figure 6. Average L per m^2 of cultch in patent tong sampling for locations with sonar habitat classification with 95% confidence intervals.

Table 3. Average L per m^2 of cultch in patent tong sampling for locations with Maryland Bay Bottom Survey habitat classification.

Habitat Code	Cultch (L /m^2)
Cultch	2.756
Mud with cultch	3.184
Sand with cultch	2.111

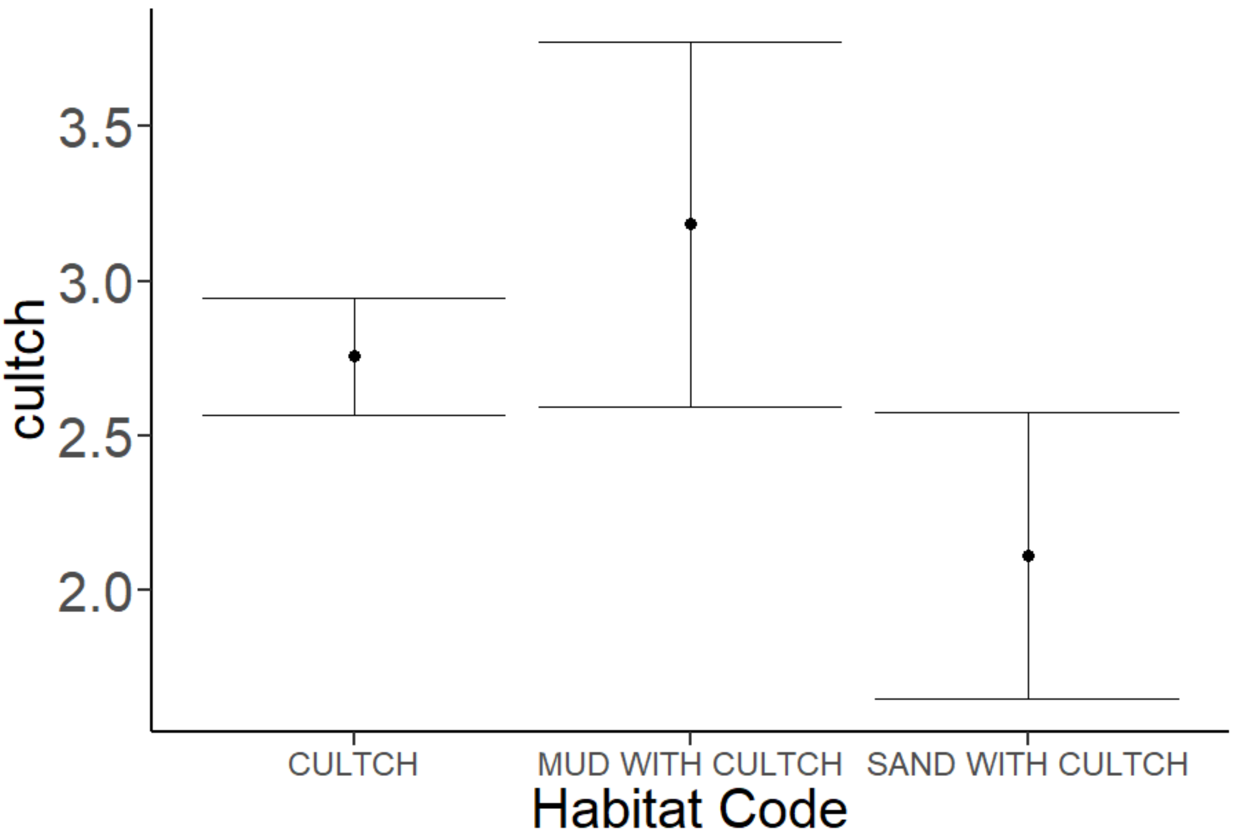

Figure 7. Average L per m^2 of cultch in patent tong sampling for locations with Maryland Bay Bottom Survey habitat classification with 95% confidence intervals.

References

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Appendix A. Model option set up and detailed results

Table A1. Costs, amounts of planting materials, social value of nitrogen removal[1] per year, and value of harvest per year for each option. All dollar values are in millions except for value of nitrogen (bottom), which is in billions.

Planting type					Option											
Cost	Status quo (1)	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Hatchery spat ($million)	$ 29.0	$ -	$ 63.4	$ 29.0	$ -	$ 29.0	$ 29.0	$ 29.0	$ 25.2	$ 29.0	$ 29.0	$ 29.0	$ 28.0	$ 98.2	$ 73.4	$ 92.6
Nat. seed ($million)	$ 4.2	$ 36.0	$ 4.2	$ 4.2	$ -	$ 4.2	$ 4.2	$ 4.2	$ 4.2	$ 4.2	$ 4.2	$ 4.2	$ 4.2	$ 3.5	$ 4.2	$ 3.8
Shell ($million)	$ 26.6	$ 271.8	$ 32.5	$ 26.6	$ -	$ 26.6	$ 26.6	$ 26.6	$ 25.9	$ 95.0	$ 95.0	$ 95.0	$ 26.4	$ 38.5	$ 34.2	$ 37.6
Art. Substrate ($million)	$ 0.1	$ -	$ 14.0	$ 0.0	$ -	$ 0.0	$ 0.0	$ 0.0	$ 0.0	$ 0.0	$ 0.0	$ 0.0	$ 0.0	$ 90.6	$ 49.7	$ 59.5
Total ($million)	$ 59.9	$ 307.9	$ 114.2	$ 59.8	$ -	$ 59.8	$ 59.8	$ 59.8	$ 55.3	$ 128.3	$ 128.3	$ 128.3	$ 58.6	$ 230.8	$ 161.5	$ 193.5
Average cost per year ($million)	$ 2.4	$ 12.3	$ 4.6	$ 2.4	$ -	$ 2.4	$ 2.4	$ 2.4	$ 2.2	$ 5.1	$ 5.1	$ 5.1	$ 2.3	$ 9.2	$ 6.5	$ 7.7
Amount (25 yr)																
Hatchery spat (billions)	7.3	0.0	15.9	7.3	0.0	7.3	7.3	7.3	6.3	7.3	7.3	7.3	7.0	24.6	18.3	23.2
Nat. seed (millions)	348.3	13840.2	348.3	348.3	0.0	348.3	348.3	348.3	348.3	348.3	348.3	348.3	348.3	290.8	348.3	311.7
Shell (million bushels)	5.3	54.4	6.5	5.3	0.0	5.3	5.3	5.3	5.2	19.0	19.0	19.0	5.3	7.7	6.8	7.5

Art. Substrate (million bushels)	0.0	0.0	3.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	25.2	13.8	16.6
Value of N (bottom)	$87.6	$70.5	$93.8	$82.6	$79.5	$87.6	$87.8	$86.3	$86.1	$94.0	$92.9	$93.8	$86.5	$103.2	$97.7	$100.4
Value of N (harvest)	$14.0	$22.1	$14.7	$21.6	$11.5	$14.2	$13.9	$15.9	$14.0	$15.4	$13.0	$17.1	$14.0	$14.7	$14.7	$14.7
Harvest value	$10.5	$16.6	$11.1	$16.5	$8.6	$10.7	$10.5	$12.0	$10.5	$11.6	$9.8	$12.9	$10.5	$11.1	$11.1	$11.1

Table A1. Continued.

Planting type					**Option**											
Cost	**Status quo (1)**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**	**31**
Hatchery spat ($million)	$29.0	$95.4	$143.0	$255.5	$61.0	$95.4	$54.5	$54.5	$29.0	$ -	$29.0	$ -	$ -	$25.6	$41.6	$29.0
Nat. seed ($million)	$4.2	$3.4	$3.4	$3.4	$3.4	$3.4	$3.4	$3.4	$4.2	$ -	$4.2	$4.2	$4.2	$4.2	$4.2	$4.2
Shell ($million)	$26.6	$38.0	$46.2	$65.6	$32.0	$38.0	$30.9	$30.9	$23.6	$ -	$26.6	$ -	$ -	$31.6	$39.7	$26.6
Art. Substrate ($million)	$0.1	$0.1	$0.1	$0.1	$33.1	$66.2	$66.2	$110.4	$0.0	$ -	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0
Total ($million)	$59.9	$136.9	$192.7	$324.6	$129.6	$203.1	$155.1	$199.3	$56.9	$ -	$59.8	$4.2	$4.2	$61.4	$85.5	$59.8

Average cost per year ($million)	$ 2.4	$ 5.5	$ 7.7	$ 13.0	$ 5.2	$ 8.1	$ 6.2	$ 8.0	$ 2.3	$ -	$ 2.4	$ 0.2	$ 0.2	$ 2.5	$ 3.4	$ 2.4
Amount (25 yr)																
Hatchery spat (billions)	7.3	23.8	35.8	63.9	15.2	23.8	13.6	13.6	7.3	0.0	7.3	0.0	0.0	6.4	10.4	7.3
Nat. seed (millions)	348.3	282.3	282.3	282.3	282.3	282.3	282.3	282.3	344.6	0.0	348.3	348.3	348.3	348.3	348.3	348.3
Shell (million bushels)	5.3	7.6	9.2	13.1	6.4	7.6	6.2	6.2	4.7	0.0	5.3	0.0	0.0	6.3	7.9	5.3
Art. Substrate (million bushels)	0.0	0.0	0.0	0.0	9.2	18.5	18.5	30.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Value of N (bottom)	$87.6	$98.4	$106.1	$122.1	$94.2	$100.8	$96.6	$98.8	$88.5	$85.6	$72.2	$84.8	$84.8	$89.8	$93.1	$94.2
Value of N (harvest)	$ 14.0	$ 14.8	$ 14.9	$ 14.9	$ 14.8	$ 14.8	$ 14.8	$ 14.8	$ 12.2	$ -	$ 31.6	$ 7.1	$ 7.2	$ 7.7	$ 8.4	$ 7.1
Harvest value	$ 10.5	$ 11.2	$ 11.2	$ 11.2	$ 11.2	$ 11.2	$ 11.2	$ 11.2	$ 9.2	$ -	$ 23.9	$ 5.3	$ 5.4	$ 5.7	$ 6.3	$ 5.3

Table A1. Continued.

Planting type					Option											
Cost	Status quo (1)	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46
Hatchery spat ($million)	$ 29.0	$ 29.0	$ -	$ -	$ 102.2	$ 77.2	$ 96.1	$ 44.6	$ 29.0	$ 32.9	$ 29.0	$ 64.6	$ 86.2	$ 264.5	$ 107.1	$ 264.5
Nat. seed ($million)	$ 4.2	$ 4.2	$ 32.6	$ 31.1	$ 3.5	$ 4.2	$ 3.8	$ 4.2	$ 4.2	$ 4.2	$ 4.2	$ 4.2	$ 4.2	$ 3.4	$ 3.5	$ 3.4
Shell ($million)	$ 26.6	$ 26.6	$ 117.1	$ 58.5	$ 189.0	$ 119.8	$ 139.0	$ 29.3	$ 42.2	$ 27.3	$ 30.5	$ 40.8	$ 53.0	$ 67.1	$ 40.1	$ 67.1
Art. Substrate ($million)	$ 0.1	$ 0.0	$ -	$ -	$ 0.1	$ 0.1	$ 0.1	$ 0.0	$ 0.0	$ 0.0	$ 0.0	$ 0.0	$ 0.0	$ 14.0	$ 104.5	$ 14.0
Total ($million)	$ 59.9	$ 59.8	$ 149.7	$ 89.6	$ 294.8	$ 201.3	$ 239.0	$ 78.1	$ 75.4	$ 64.4	$ 63.7	$ 109.7	$ 143.4	$ 349.0	$ 255.2	$ 349.0
Average cost per year ($million)	$ 2.4	$ 2.4	$ 6.0	$ 3.6	$ 11.8	$ 8.1	$ 9.6	$ 3.1	$ 3.0	$ 2.6	$ 2.5	$ 4.4	$ 5.7	$ 14.0	$ 10.2	$ 14.0

Amount (25 yr)																
Hatchery spat (billions)	7.3	7.3	0.0	0.0	25.5	19.3	24.0	11.2	7.3	8.2	7.3	16.2	21.6	66.1	26.8	66.1
Nat. seed (millions)	348.3	348.3	12532.5	11938.0	290.8	348.3	311.7	348.3	348.3	348.3	348.3	348.3	348.3	282.3	290.8	282.3
Shell (million bushels)	5.3	5.3	23.4	11.7	37.8	24.0	27.8	5.9	8.4	5.5	6.1	8.2	10.6	13.4	8.0	13.4
Art. Substrate (million bushels)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.9	29.1	3.9
Value of N (bottom)	$87.6	$94.9	$67.0	$65.4	$103.0	$97.3	$100.1	$89.2	$89.4	$87.6	$87.6	$94.0	$98.2	$124.1	$105.2	$130.2
Value of N (harvest)	$ 14.0	$ 6.2	$ 19.8	$ 18.9	$ 15.1	$ 15.1	$ 15.1	$ 17.0	$ 17.3	$ 15.1	$ 15.2	$ 15.1	$ 15.8	$ 14.5	$ 14.7	$ 8.0
Harvest value	$ 10.5	$ 4.6	$ 14.9	$ 14.2	$ 11.4	$ 11.4	$ 11.4	$ 12.8	$ 13.0	$ 11.4	$ 11.4	$ 11.4	$ 11.9	$ 10.9	$ 11.1	$ 6.0

Table A1. Continued.

Planting type					Option											
Cost	**Status quo (1)**	**47**	**48**	**49**	**50**	**51**	**52**	**53**	**54**	**55**	**56**	**57**	**58**	**59**	**60**	**61**
Hatchery spat ($million)	$ 29.0	$ 107.1	$ 104.3	$ 104.3	$ -	$ -	$ -	$ 63.4	$ 29.0	$ 42.9	$ 29.0	$ 29.0	$ 29.0	$ 29.0	$ 30.4	$ 29.0
Nat. seed ($million)	$ 4.2	$ 3.5	$ 3.4	$ 3.4	$ -	$ -	$ -	$ 4.2	$ 4.2	$ 4.2	$ 4.2	$ 4.2	$ 4.2	$ 4.2	$ 4.2	$ 4.2
Shell ($million)	$ 26.6	$ 40.1	$ 39.5	$ 39.5	$ 271.8	$ 117.1	$ 58.5	$ 32.5	$ 26.6	$ 29.0	$ 26.6	$ 26.6	$ 26.6	$ 26.6	$ 26.8	$ 26.6
Art. Substrate ($million)	$ 0.1	$ 104.5	$ 80.2	$ 80.2	$ -	$ -	$ -	$ 14.0	$ 0.0	$ 0.0	$ 0.0	$ 0.0	$ 0.0	$ 0.0	$ 0.0	$ 0.0
Total ($million)	$ 59.9	$ 255.2	$ 227.4	$ 227.4	$ 271.8	$ 117.1	$ 58.5	$ 114.2	$ 59.8	$ 76.1	$ 59.8	$ 59.8	$ 59.8	$ 59.8	$ 61.5	$ 59.8
Average cost per year ($million)	$ 2.4	$ 10.2	$ 9.1	$ 9.1	$ 10.9	$ 4.7	$ 2.3	$ 4.6	$ 2.4	$ 3.0	$ 2.4	$ 2.4	$ 2.4	$ 2.4	$ 2.5	$ 2.4
Amount (25 yr)																
Hatchery spat (billions)	7.3	26.8	26.1	26.1	0.0	0.0	0.0	15.9	7.3	10.7	7.3	7.3	7.3	7.3	7.6	7.3
Nat. seed (millions)	348.3	290.8	282.3	282.3	0.0	0.0	0.0	348.3	348.3	348.3	348.3	348.3	348.3	348.3	348.3	348.3
Shell (million bushels)	5.3	8.0	7.9	7.9	54.4	23.4	11.7	6.5	5.3	5.8	5.3	5.3	5.3	5.3	5.4	5.3
Art. Substrate (million bushels)	0.0	29.1	22.3	22.3	0.0	0.0	0.0	3.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Value of N (bottom)	$87.6	$112.2	$102.8	$108.7	$87.8	$83.2	$81.3	$94.0	$83.7	$85.4	$87.6	$88.3	$87.8	$87.6	$87.8	$72.2
Value of N (harvest)	$ 14.0	$ 7.7	$ 14.5	$ 7.7	$ 16.2	$ 13.3	$ 12.3	$ 14.6	$ 13.3	$ 13.3	$ 14.2	$ 12.8	$ 13.9	$ 14.2	$ 14.2	$ 31.6
Harvest value	$ 10.5	$ 5.8	$ 10.9	$ 5.8	$ 12.2	$ 10.0	$ 9.3	$ 11.0	$ 10.1	$ 10.1	$ 10.7	$ 9.7	$ 10.4	$ 10.7	$ 10.7	$ 23.9

Table A1. Continued.

Planting type					Option								
Cost	**Status quo (1)**	**62**	**63**	**64**	**65**	**66**	**67**	**68**	**69**	**71**	**72**	**73**	**74**
Hatchery spat ($million)	$ 29.0	$ 29.0	$ 70.5	$ 66.3	$ 29.0	$ -	$ 29.0	$ 29.0	$ 29.0	$ 92.6	$ -	$ -	$ 29.0
Nat. seed ($million)	$ 4.2	$ 4.2	$ 60.1	$ 63.9	$ 6.3	$ 60.1	$ 35.8	$ 68.6	$ 1.4	$ 44.1	$ 32.9	$ 32.9	$ 4.2
Shell ($million)	$ 26.6	$ 26.6	$ 360.8	$ 354.4	$ 26.6	$ 274.2	$ 76.2	$ 26.6	$ 95.0	$ 127.6	$ 117.1	$ 117.1	$ 27.5
Art. Substrate ($million)	$ 0.1	$ 0.0	$ -	$ 0.0	$ 0.0	$ -	$ 0.0	$ 0.0	$ 0.0	$ 59.5	$ -	$ -	$ 0.0
Total ($million)	$ 59.9	$ 59.8	$ 491.4	$ 484.7	$ 62.0	$ 334.3	$ 141.1	$ 124.2	$ 125.4	$ 323.9	$ 150.0	$ 150.0	$ 60.8
Average cost per year ($million)	$ 2.4	$ 2.4	$ 19.7	$ 19.4	$ 2.5	$ 13.4	$ 5.6	$ 5.0	$ 5.0	$ 13.0	$ 6.0	$ 6.0	$ 2.4
Amount (25 yr)													
Hatchery spat (billions)	7.3	7.3	17.6	16.6	7.3	0.0	7.3	7.3	7.3	23.2	0.0	0.0	7.3
Nat. seed (millions)	348.3	348.3	4946.6	5258.8	521.2	4946.6	13765.1	343.0	521.2	16938.8	12634.6	12644.7	348.3
Shell (million bushels)	5.3	5.3	72.2	70.9	5.3	54.8	15.2	5.3	19.0	25.5	23.4	23.4	5.5
Art. Substrate (million bushels)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	16.6	0.0	0.0	0.0
Value of N (bottom)	$87.6	$79.1	$113.1	$122.5	$88.1	$105.8	$67.2	$87.6	$94.4	$76.9	$73.6	$74.0	$87.6
Value of N (harvest)	$ 14.0	$ 23.9	$ 41.3	$ 33.1	$ 14.5	$ 30.5	$ 51.0	$ 14.0	$ 15.7	$ 26.5	$ 9.0	$ 8.8	$ 13.2

Harvest value	$ 10.5	$ 18.0	$ 31.4	$ 24.9	$ 10.9	$ 23.0	$ 38.4	$ 10.5	$ 11.8	$ 20.0	$ 6.8	$ 6.6	$ 9.9

Reducing nutrients within Chesapeake Bay waters creates benefits to those who use or simply appreciate the Bay by increasing the enjoyment of recreational experiences, improving fisheries, and enhancing habitat for all aquatic life. Oysters reduce nutrients in surface waters when they incorporate nutrients into their tissue and shell, promote burial of nutrients in the bottom sediments as a byproduct of their feeding behavior, and enhance denitrification. We analyzed the annual unit value of nitrogen removal, representing nutrient reduction costs that would be avoided from increasing oyster restoration in the Maryland portion of the Chesapeake Bay. Currently, Maryland government is requiring pollution emission permit holders, including county governments in Maryland, to reduce nutrients by implementing stormwater practices. Using previously developed data on spending by Maryland's Municipal Separate Storm Sewer System (MS4) permit-holders ADDIN ZOTERO_ITEM CSL_CITATION {"citationID":"HP0Rfi9O","properties":{"formattedCitation":"(Price et al., 2021)","plainCitation":"(Price et al., 2021)","noteIndex":0},"citationItems":[{"id":9999,"uris":["http://zotero.org/users/1083162/items/EMGBT9K2"],"uri":["http://zotero.org/users/1083162/items/EMGBT9K2"],"itemData":{"id":9999,"type":"report","abstract":"This report provides updated cost estimates for nonpoint source nutrient management practices (stormwater and agricultural) using data collected from Maryland state and local governments and federal agencies. Costs were evaluated for a subset of the practices defined by the Chesapeake Bay Partnership in the Chesapeake Assessment Scenario Tool (CAST). For urban stormwater practices, costs were also estimated for practices defined in Maryland's Municipal Separate Storm Sewer System (MS4) permit program. CAST cost information or assumptions were maintained, if new data were not available for those components of the cost calculation. \nCosts were estimated with data available for Maryland and may not be directly transferable to other areas. For stormwater, median implementation costs were calculated from project data provided by counties that are regulated under the MS4 program (hereafter MS4 counties), which are relatively urbanized counties. The number of projects that were evaluated per practice varied from one to more than 70. Costs based on one or few projects may not provide robust estimates of typical costs due to variability of project costs. Data for agricultural practices were derived from two sources, 1) projects funded by the Maryland Agricultural Cost Share (MACS) program and 2) cost share reimbursement rates for Maryland from the 2017 USDA Natural Resources Conservation Service (NRCS) Environmental Quality Incentives Program (EQIP).\nCosts per pound reduction were considerably higher for stormwater practices than for agricultural BMPs. For stormwater practices, the median costs were $1,558/lb N and $9,639/lb P. For agricultural practices, median costs were $16/lb N and $489/lb P. Only practices with three or more projects were used to calculate medians.\nIn general, annualized costs per unit of stormwater practice were comparable to or higher (4%-4000%) than those in CAST. However, three practices had lower costs than CAST: stream restoration, filtering practices, and mechanical street sweeping. The main factors driving higher costs were higher average implementation costs and higher estimated operations and maintenance (O&M) costs. For many urban practices, annual O&M estimates were based on a percent of implementation or construction costs. The updated multipliers used here were 8.2% to 13.4%, compared with 2.5% to 6% in CAST. Another factor contributing to higher costs was that updated lifespan estimates were shorter for some practices (e.g., 20 years for infiltration practices instead of the 50 years used in CAST).\nFor agricultural practices, our analysis estimated that about 75% of the practices evaluated had higher estimated annualized cost per unit than CAST estimates, while 25% of practices had lower costs. Higher implementation, O&M costs and different lifespans (usually higher for MACS practices and lower for EQIP practices) were responsible for these cost differences. Agricultural land rental rates (opportunity costs) were also updated but generally had a modest effect on costs. Costs for exclusion fencing with narrow or streamside grass buffer dropped dramatically compared to CAST costs, although costs for this practice were highly variable (see box and whiskers plots in Appendix).","language":"en","number":"UMCES Technical Report # TS-772-21","publisher":"Univ of MD Center for Environmental Science","title":"Cost Analysis of Stormwater and Agricultural Practices for Reducing Nitrogen and Phosphorus Runoff in Maryland","title-short":"DOI: 10.13140/RG.2.2.28896.74246/1","URL":"https://www.researchgate.net/publication/332275400_Cost_Analysis_of_Stormwater_and_Agricultural_Practices_for_Reducing_Nitrogen_and_Phosphorus_Runoff_in_Maryland","author":[{"family":"Price","given":"Elizabeth"},{"family":"Hollady","given":"Taylor"},{"family":"Wainger","given":"Lisa"}],"accessed":{"date-parts":[["2020",1,30]]},"issued":{"date-parts":[["2021",3]]}}}],"schema":"https://github.com/citation-style-

1: Status Quo

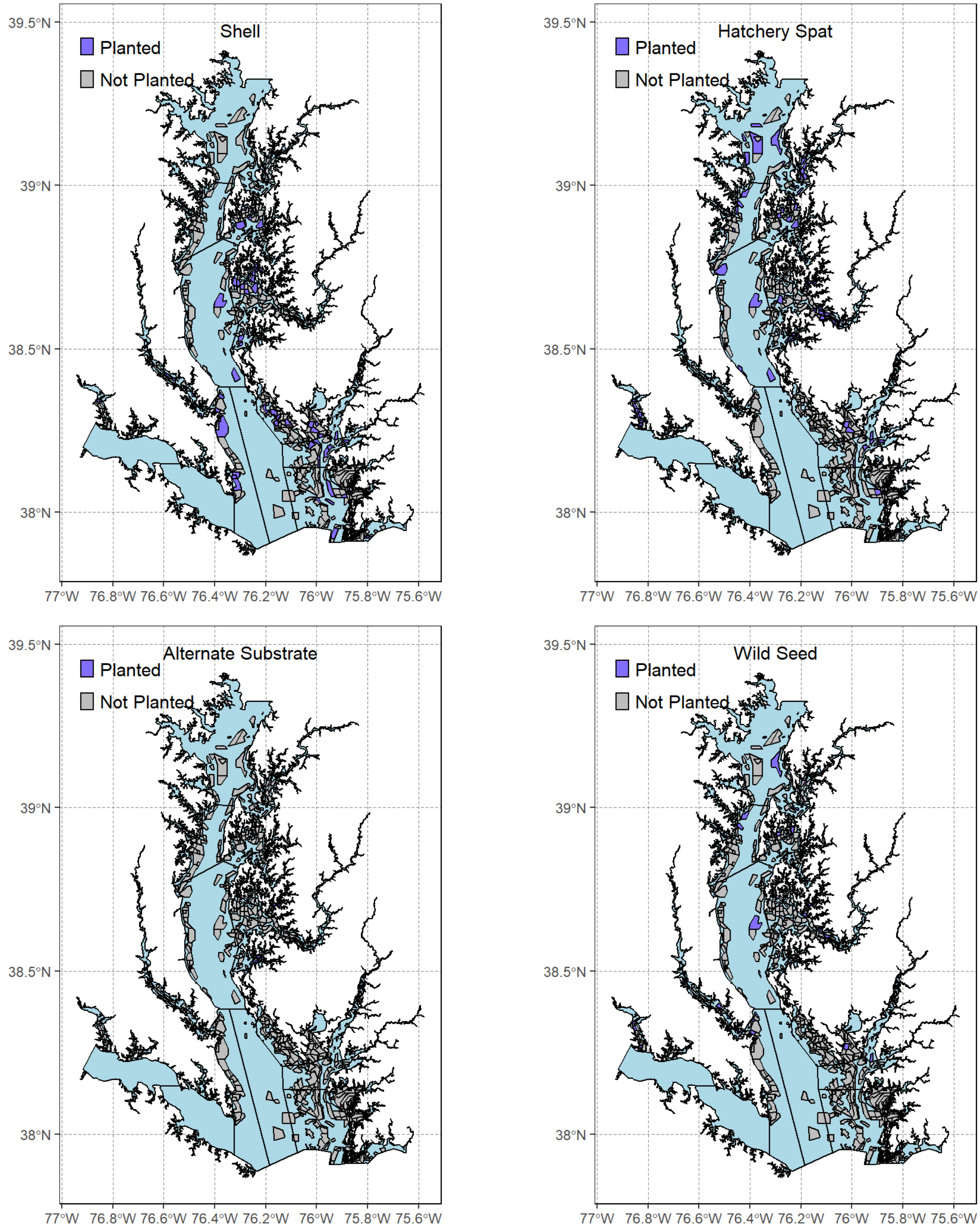

Fig. A1. Locations of shell, hatchery spat, alternate substrate, and wild seed plantings for option 1.

1: Status Quo

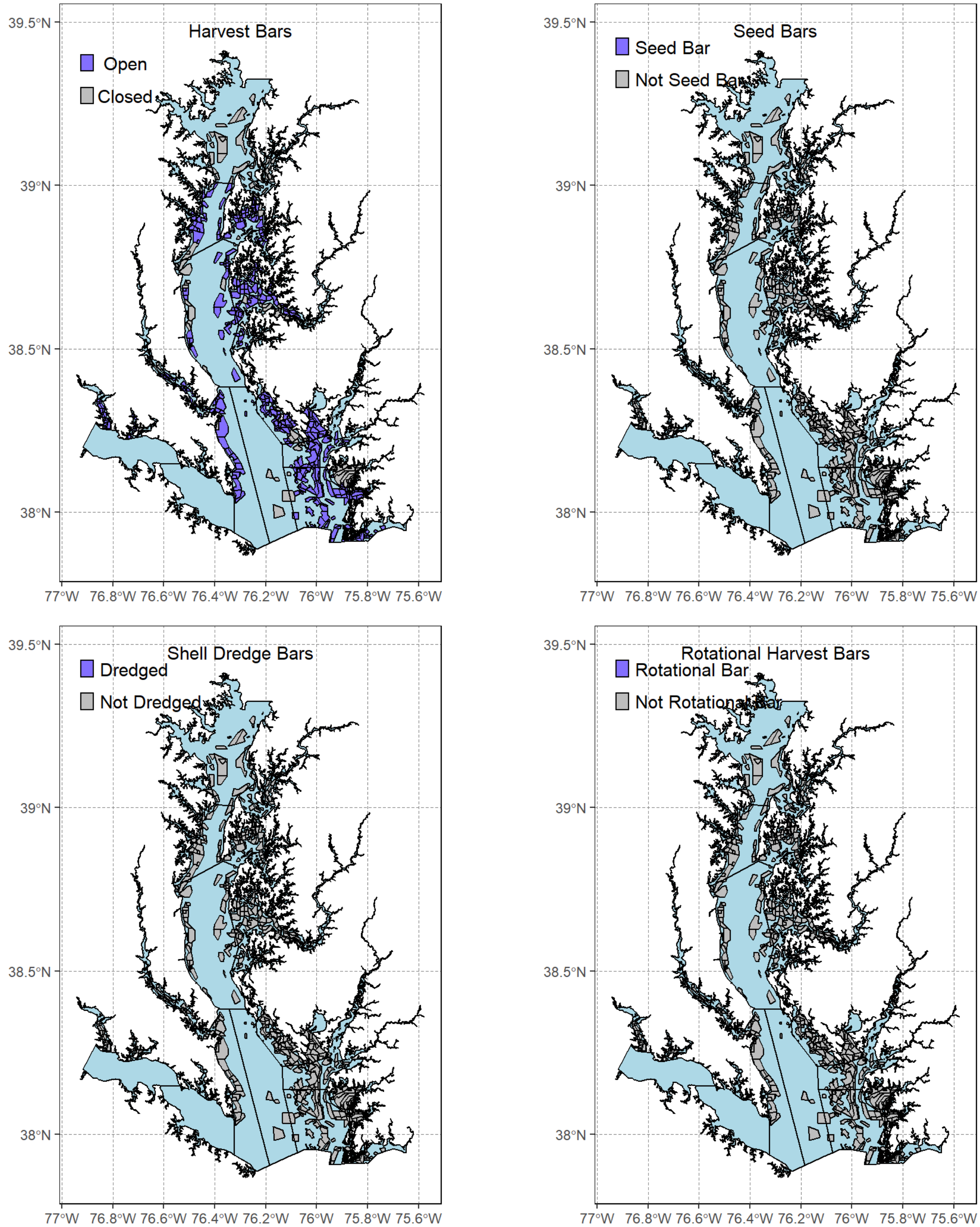

Fig. A2. Bars open to harvest, seed bars, bars open to rotational harvest, and shell dredging bars for option 1.

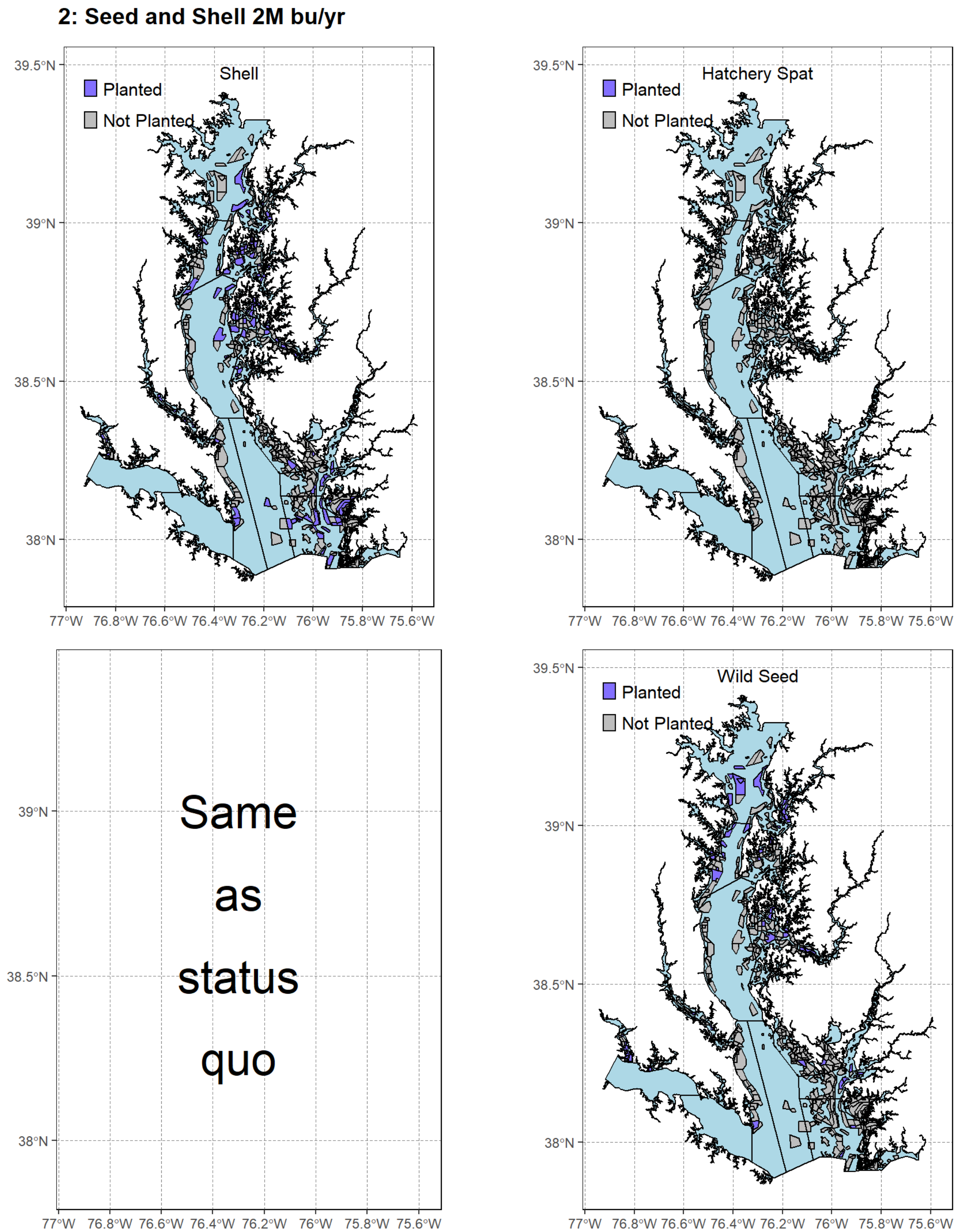

Fig. A3. Locations of shell, hatchery spat, alternate substrate, and wild seed plantings for option 2.

2: Seed and Shell 2M bu/yr

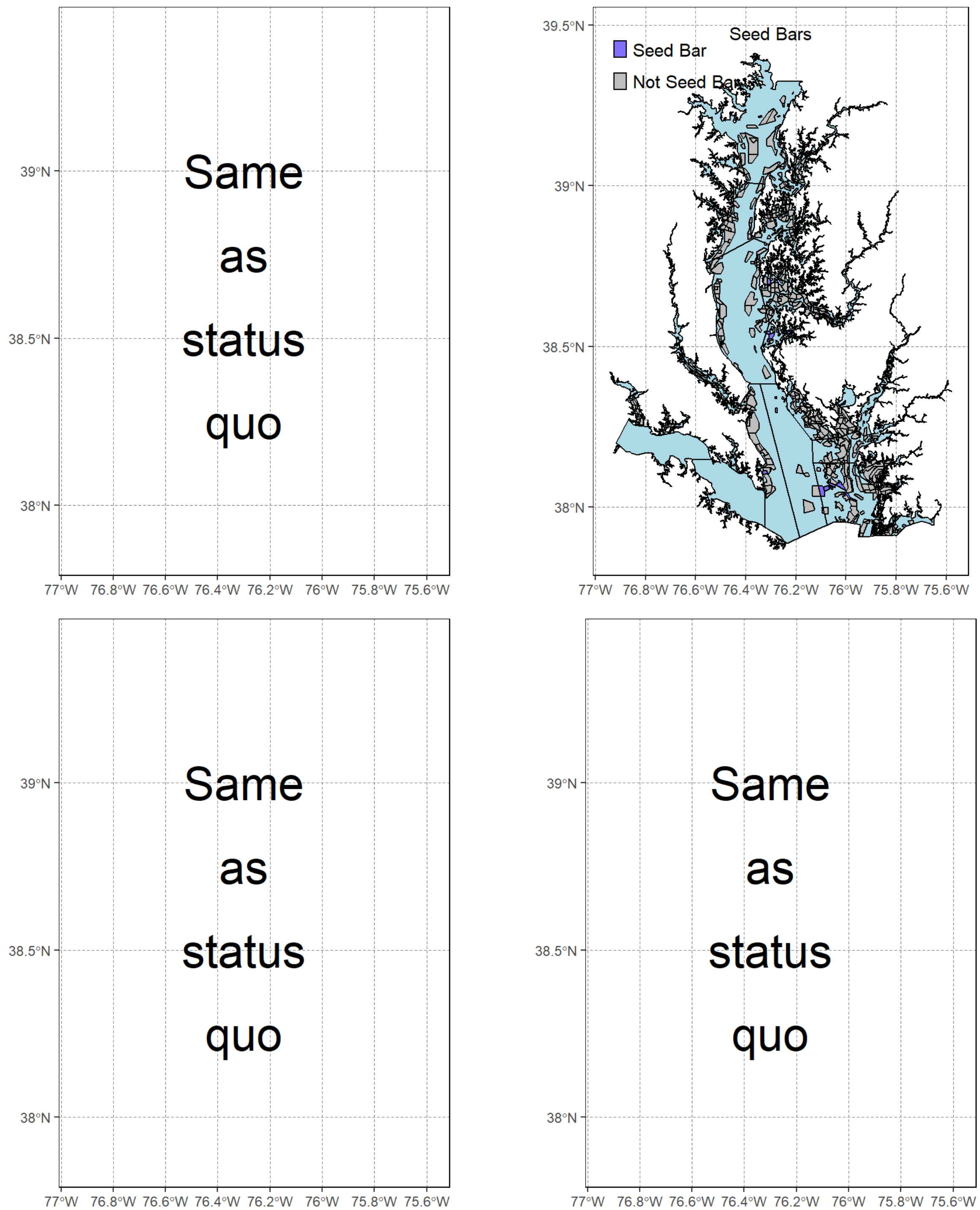

Fig. A4. Bars open to harvest, seed bars, bars open to rotational harvest, and shell dredging bars for option 2.

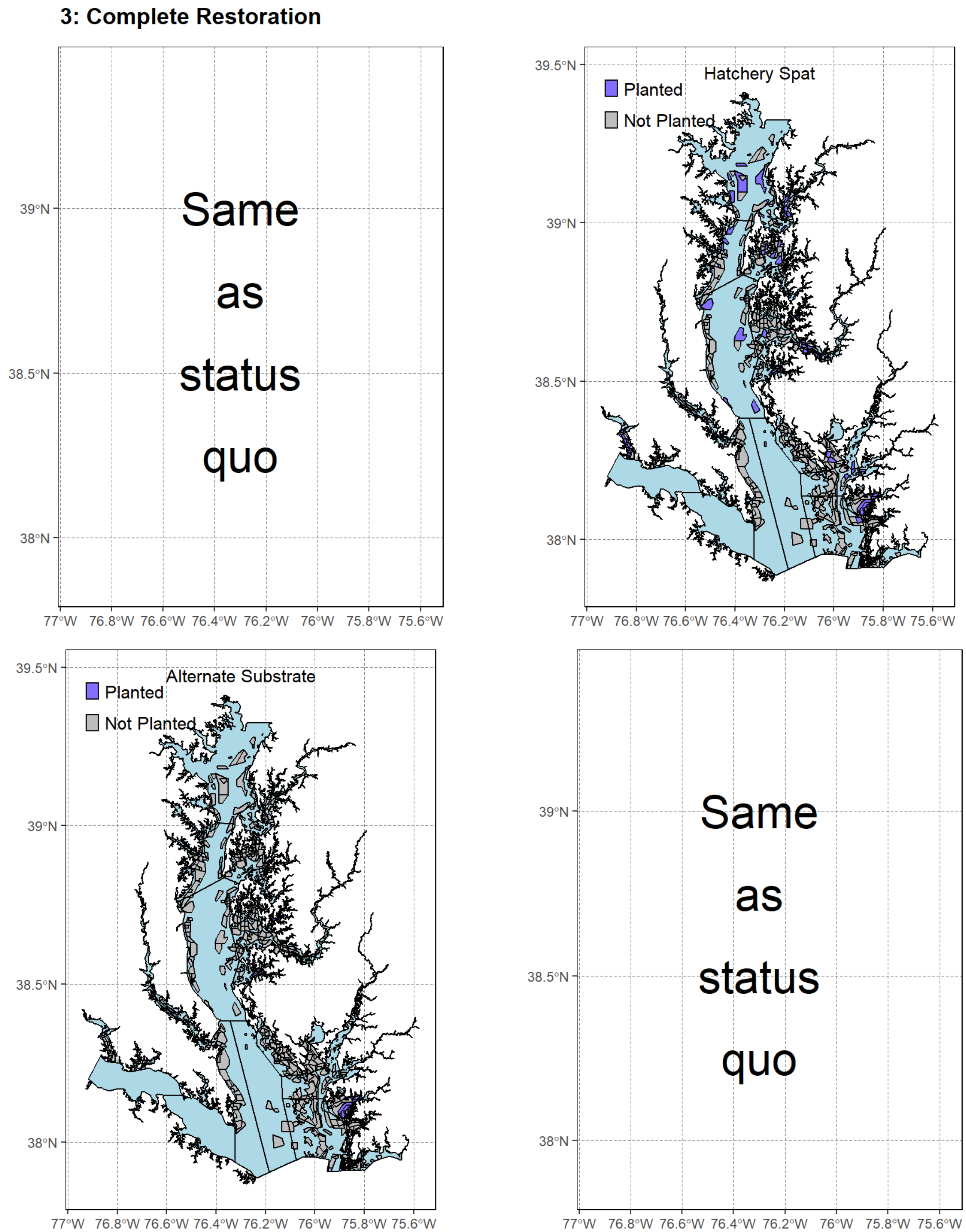

Fig. A5. Locations of shell, hatchery spat, alternate substrate, and wild seed plantings for option 3.

Fig. A6. Bars open to harvest, seed bars, bars open to rotational harvest, and shell dredging bars for option 3.

Fig. A7. Locations of shell, hatchery spat, alternate substrate, and wild seed plantings for option 4.

Fig. A8. Bars open to harvest, seed bars, bars open to rotational harvest, and shell dredging bars for option 4.

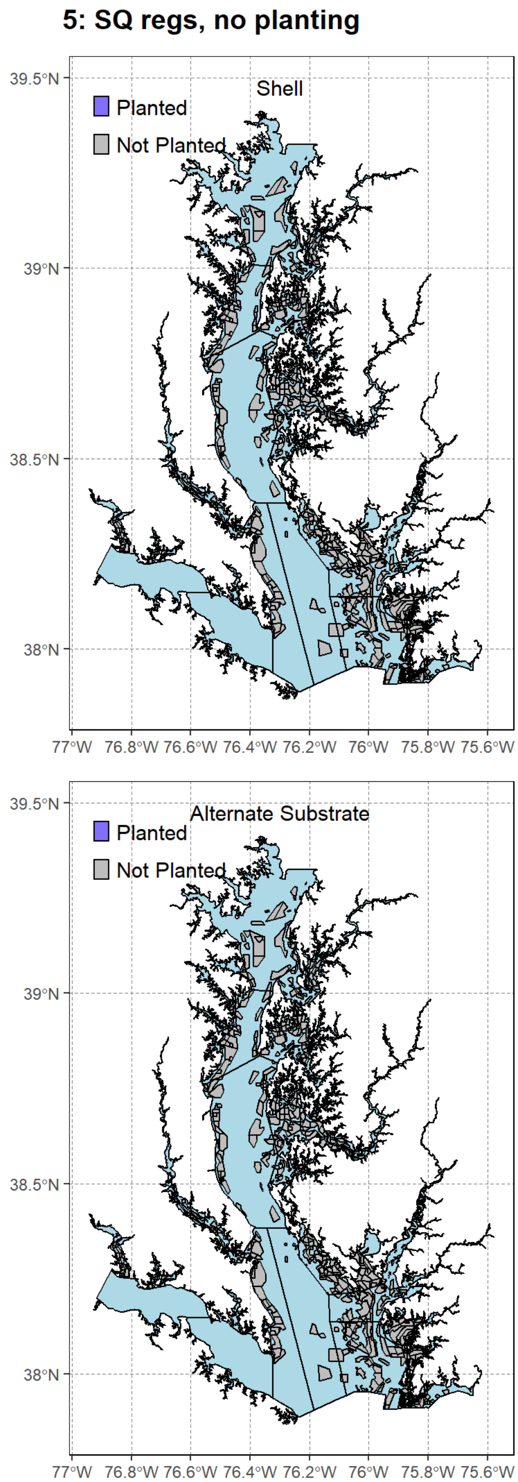

Fig. A9. Locations of shell, hatchery spat, alternate substrate, and wild seed plantings for option 5.

Fig. A10. Bars open to harvest, seed bars, bars open to rotational harvest, and shell dredging bars for option 5.

Fig. A11. Locations of shell, hatchery spat, alternate substrate, and wild seed plantings for option 6.

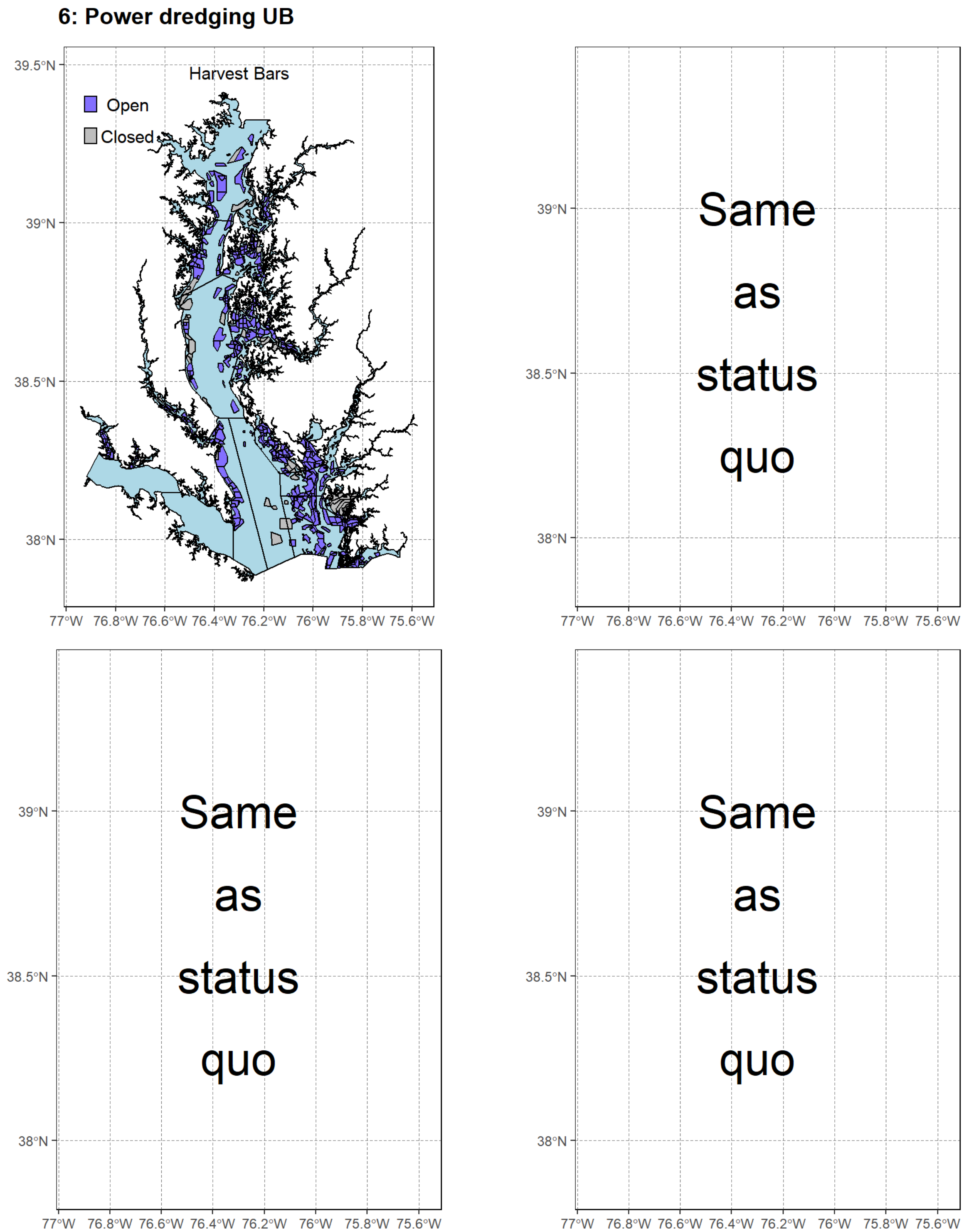

Fig. A12. Bars open to harvest, seed bars, bars open to rotational harvest, and shell dredging bars for option 6.

Fig. A13. Locations of shell, hatchery spat, alternate substrate, and wild seed plantings for option 7.

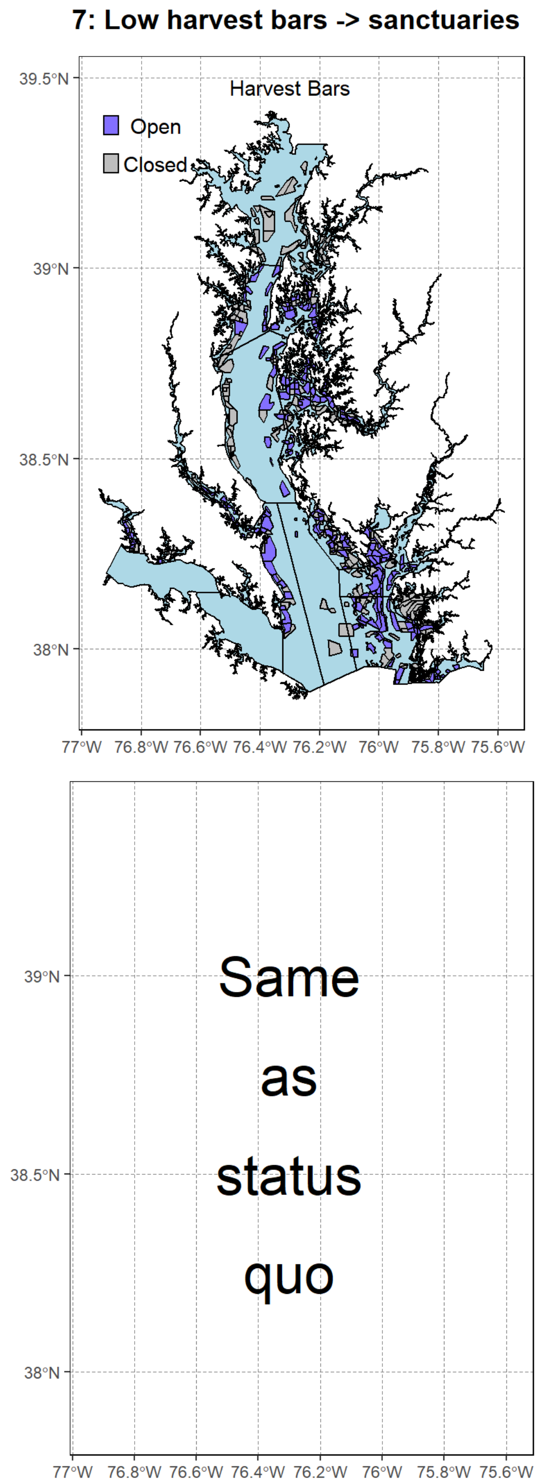

Fig. A14. Bars open to harvest, seed bars, bars open to rotational harvest, and shell dredging bars for option 7.

Fig. A15. Locations of shell, hatchery spat, alternate substrate, and wild seed plantings for option 8.

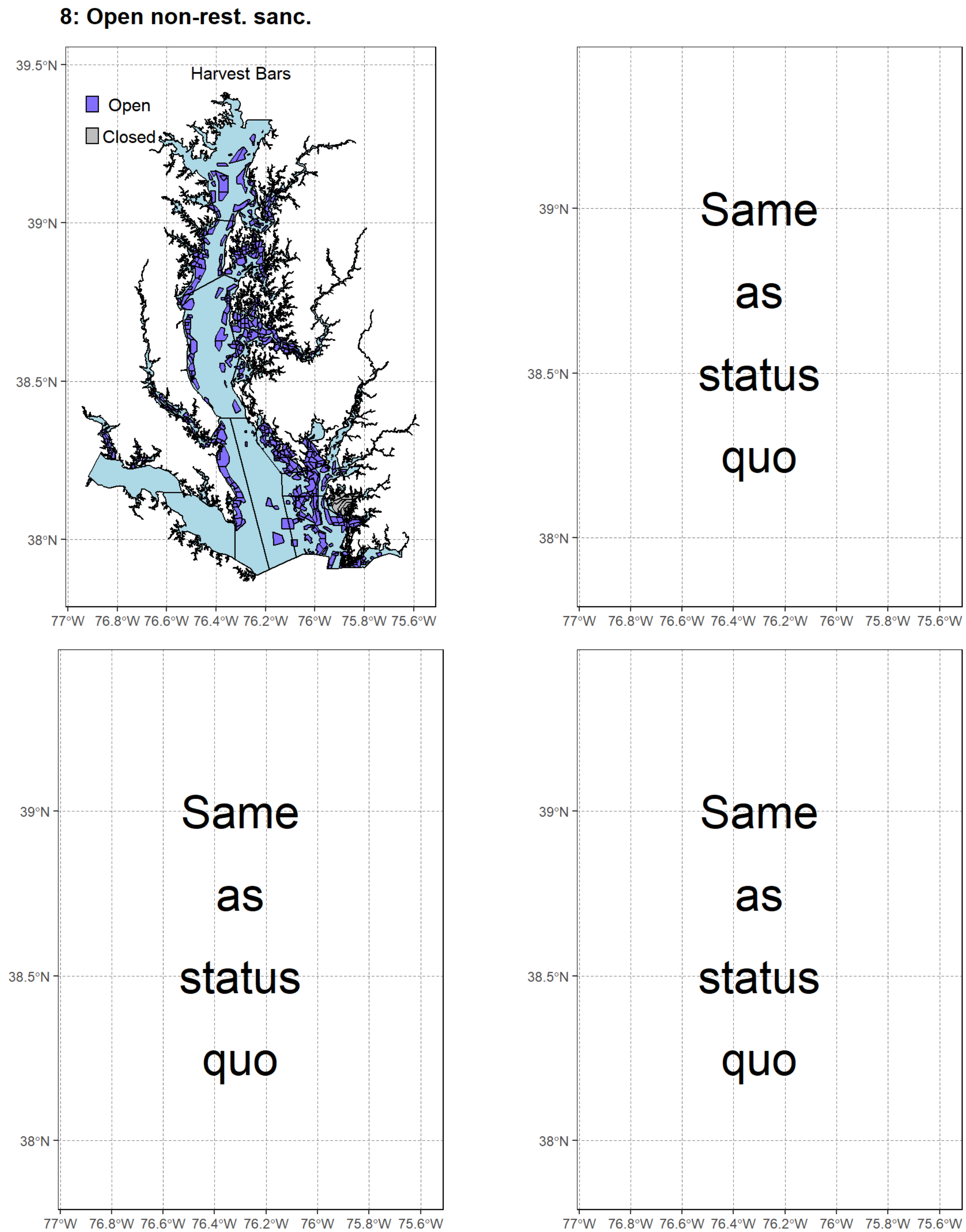

Fig. A16. Bars open to harvest, seed bars, bars open to rotational harvest, and shell dredging bars for option 8.

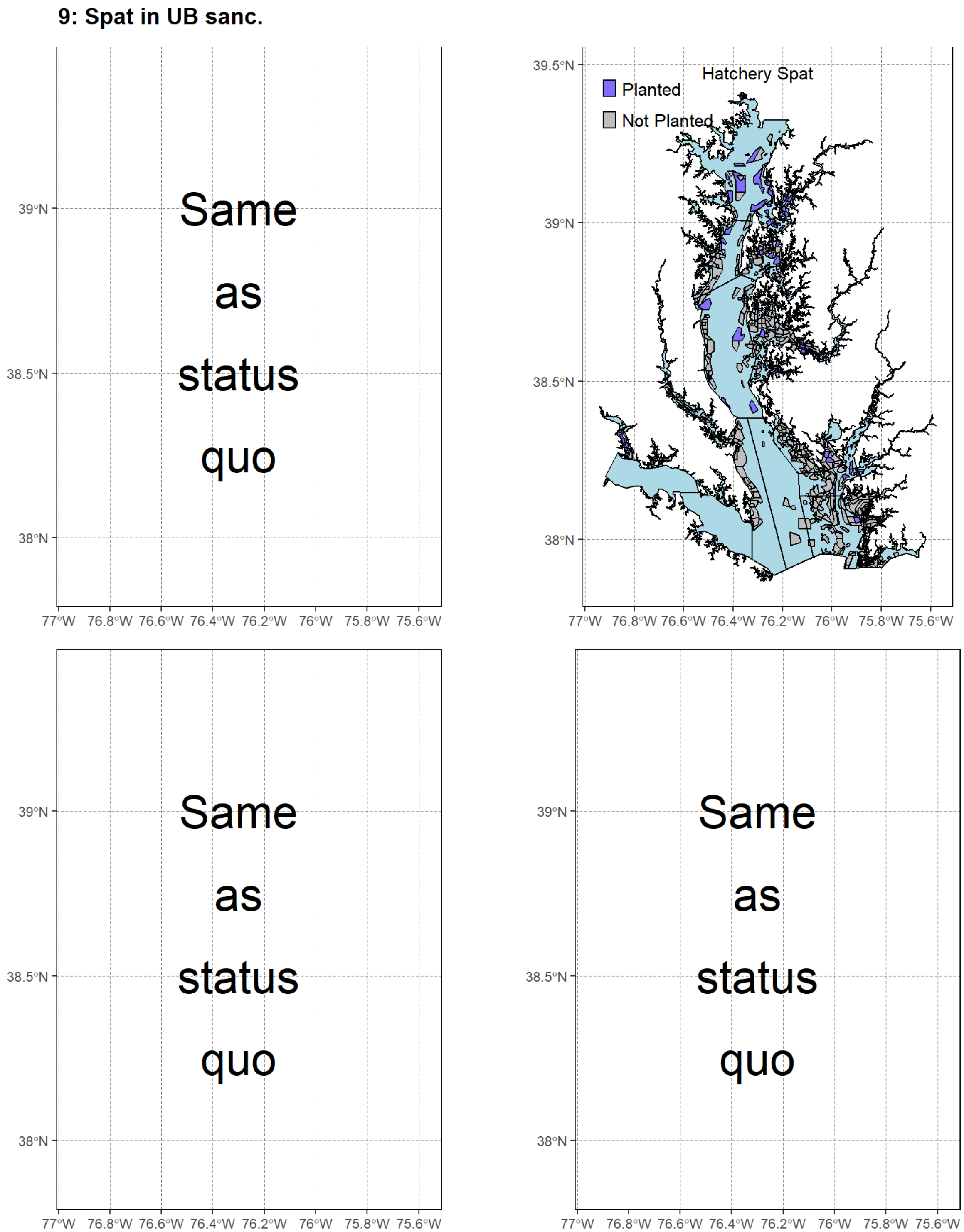

Fig. A17. Locations of shell, hatchery spat, alternate substrate, and wild seed plantings for option 9.

Fig. A18. Bars open to harvest, seed bars, bars open to rotational harvest, and shell dredging bars for option 9.

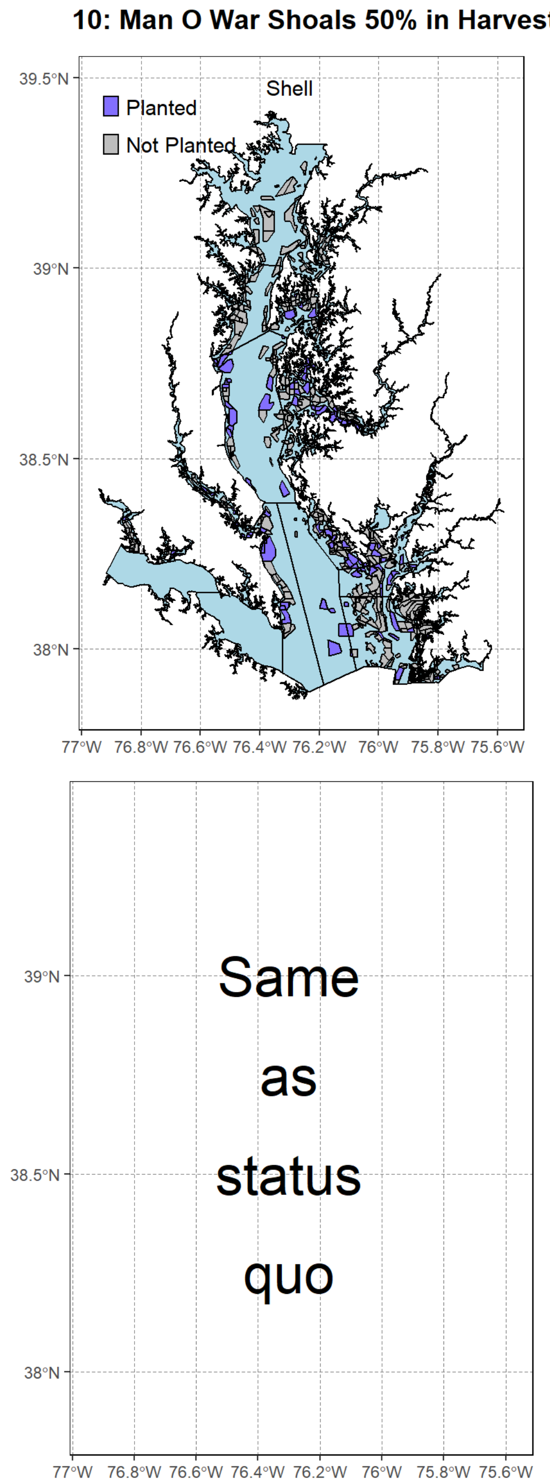

Fig. A19. Locations of shell, hatchery spat, alternate substrate, and wild seed plantings for option 10.

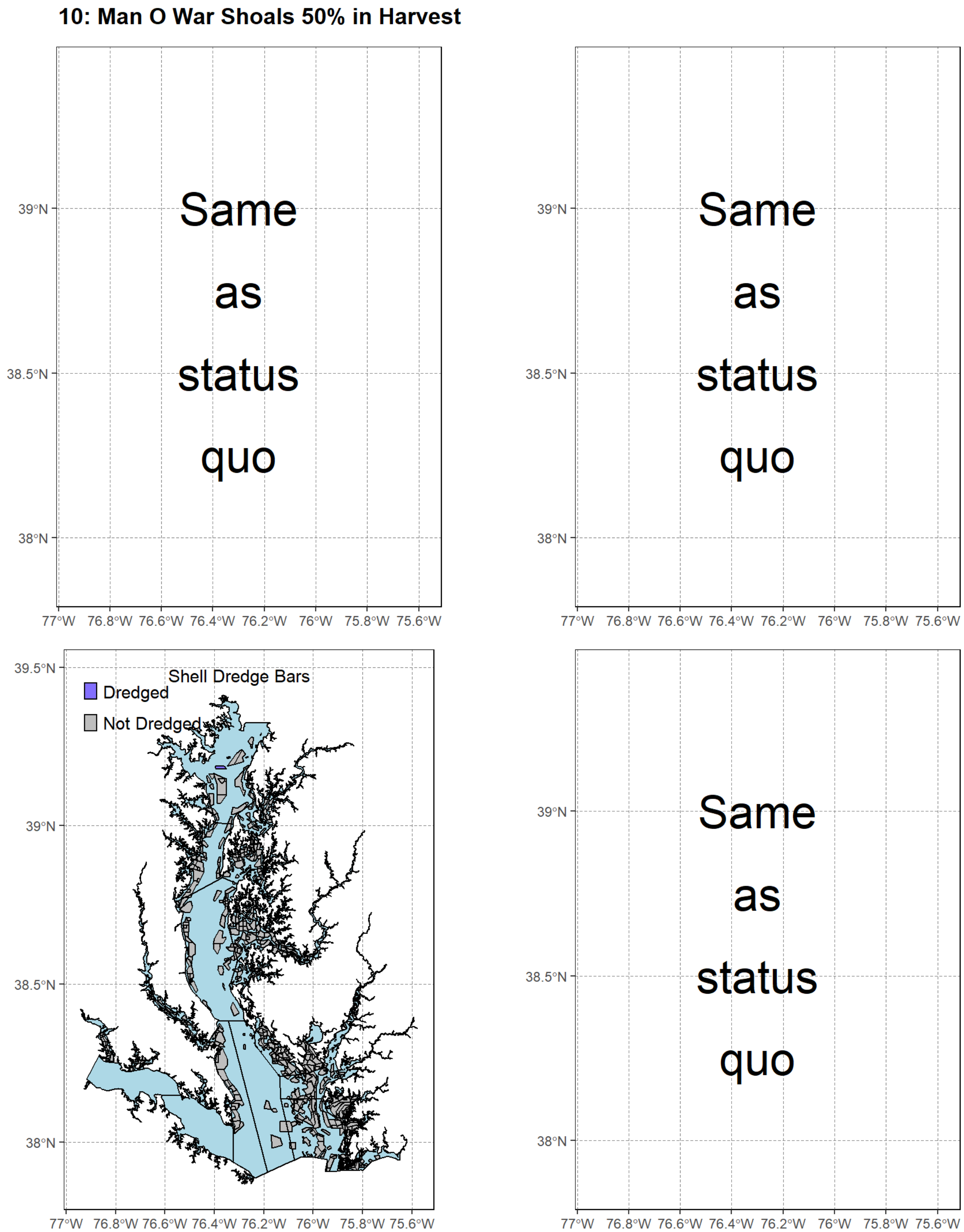

Fig. A20. Bars open to harvest, seed bars, bars open to rotational harvest, and shell dredging bars for option 10.

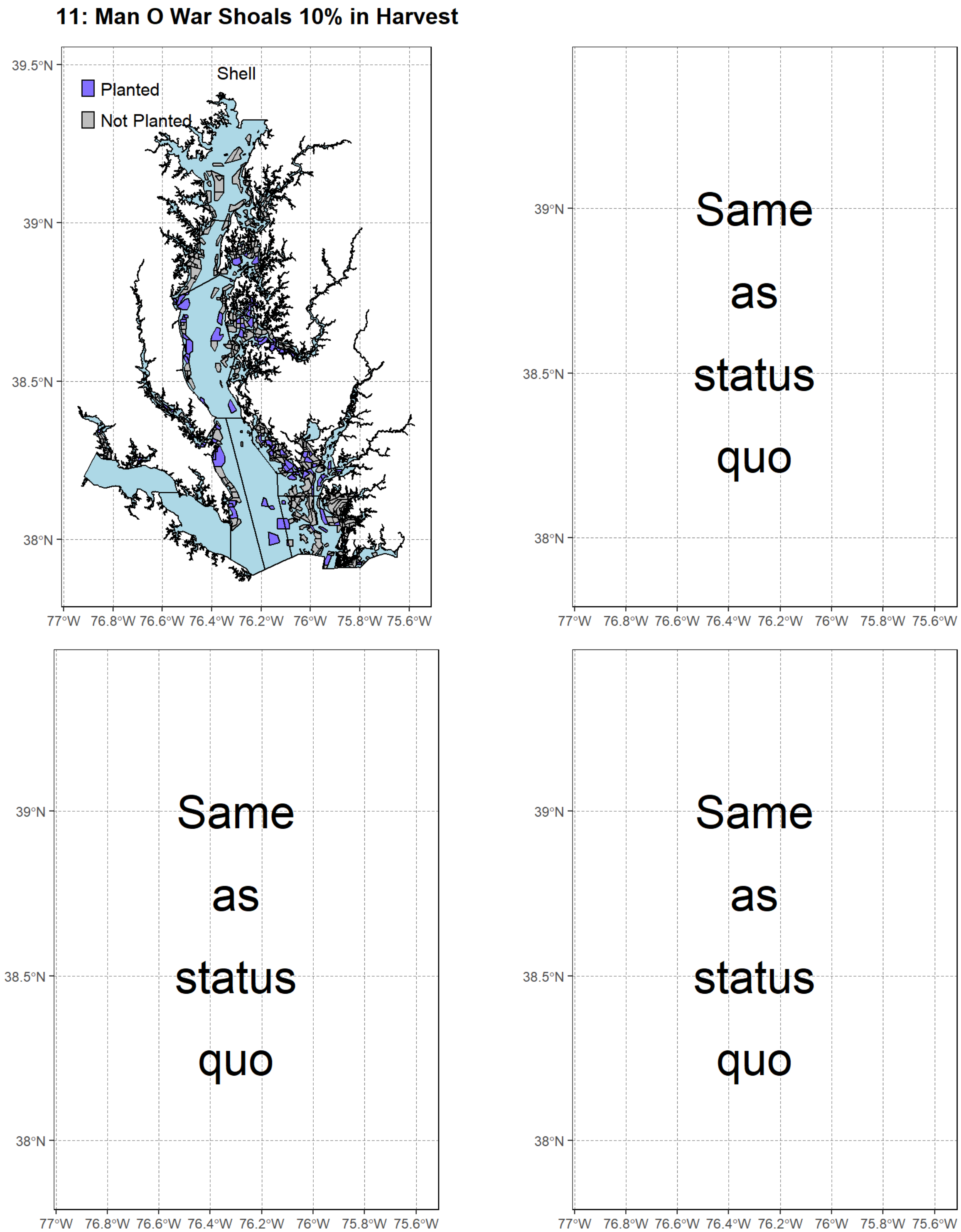

Fig. A21. Locations of shell, hatchery spat, alternate substrate, and wild seed plantings for option 11.

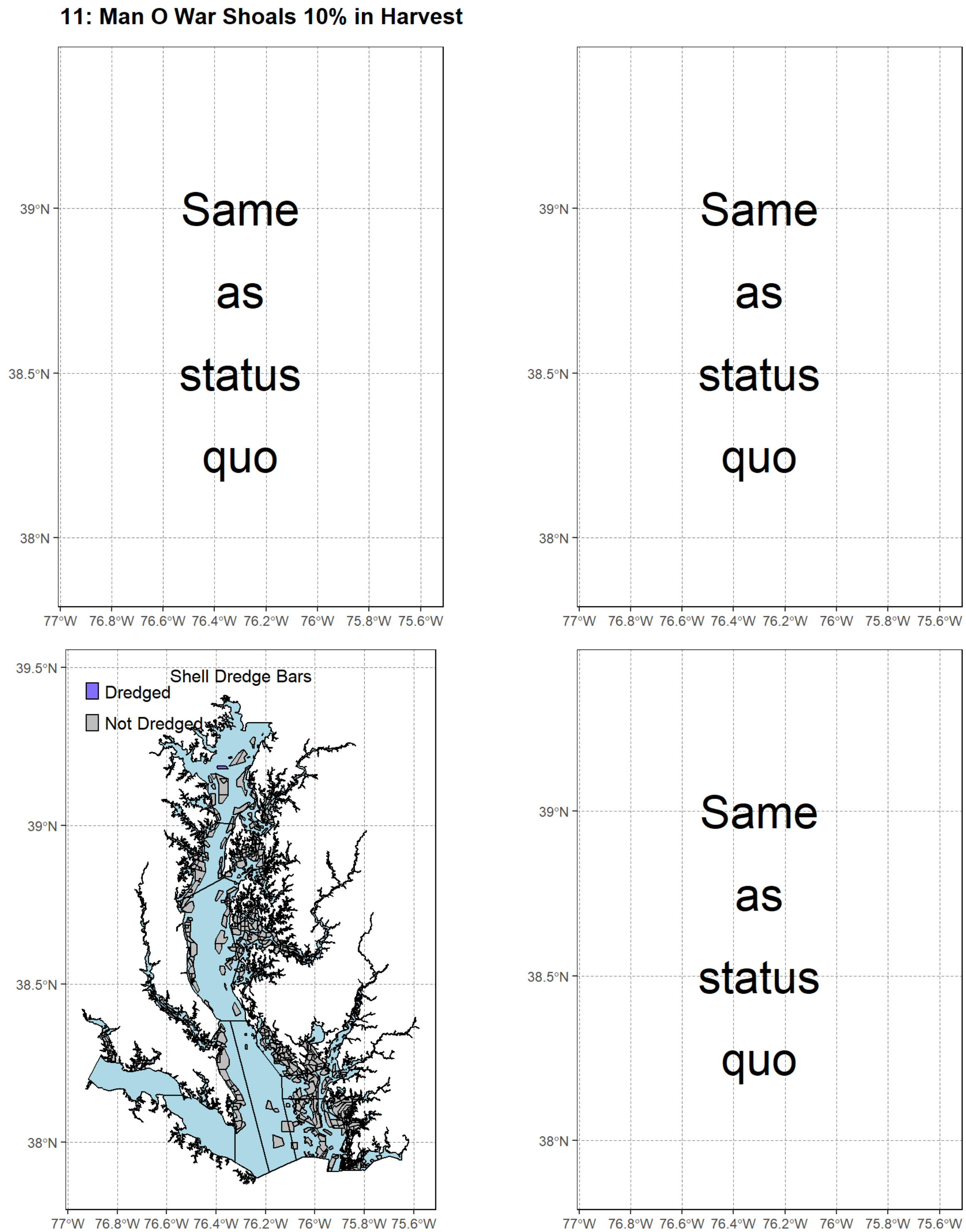

Fig. A22. Bars open to harvest, seed bars, bars open to rotational harvest, and shell dredging bars for option 11.

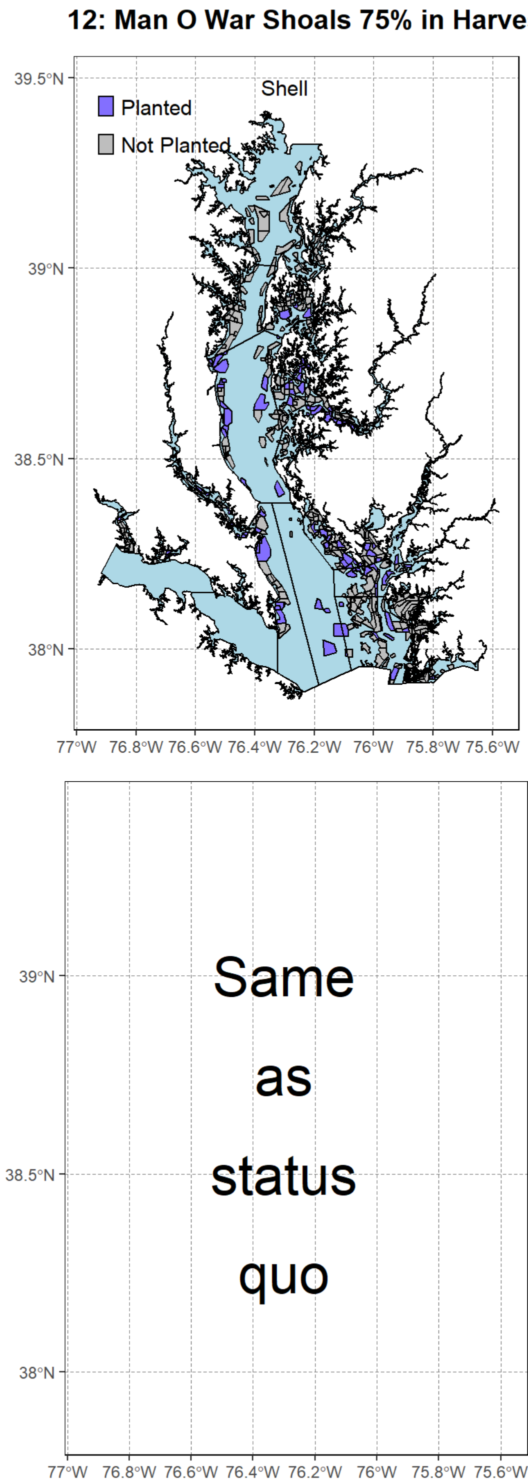

Fig. A23. Locations of shell, hatchery spat, alternate substrate, and wild seed plantings for option 12.

12: Man O War Shoals 75% in Harvest

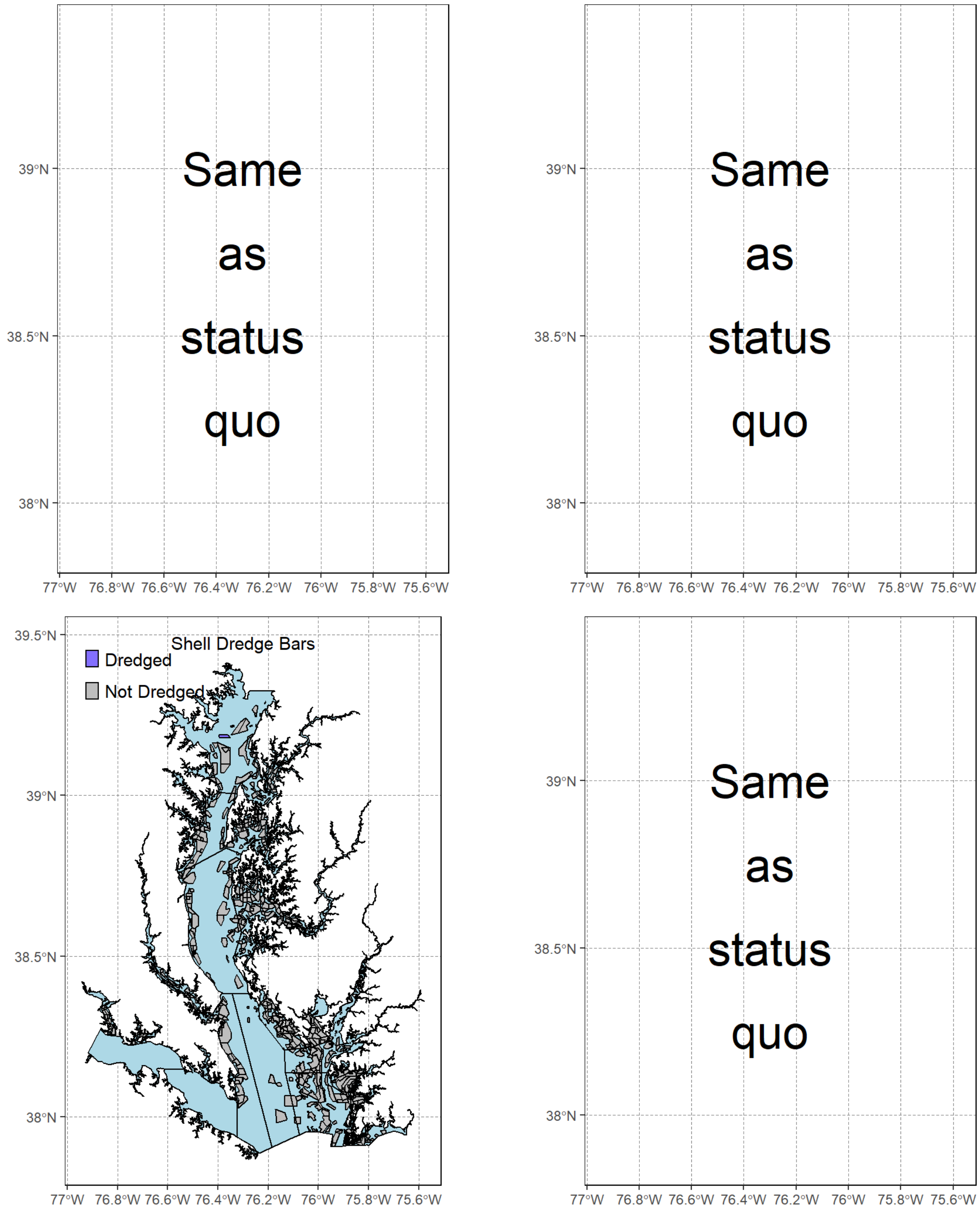

Fig. A24. Bars open to harvest, seed bars, bars open to rotational harvest, and shell dredging bars for option 12.

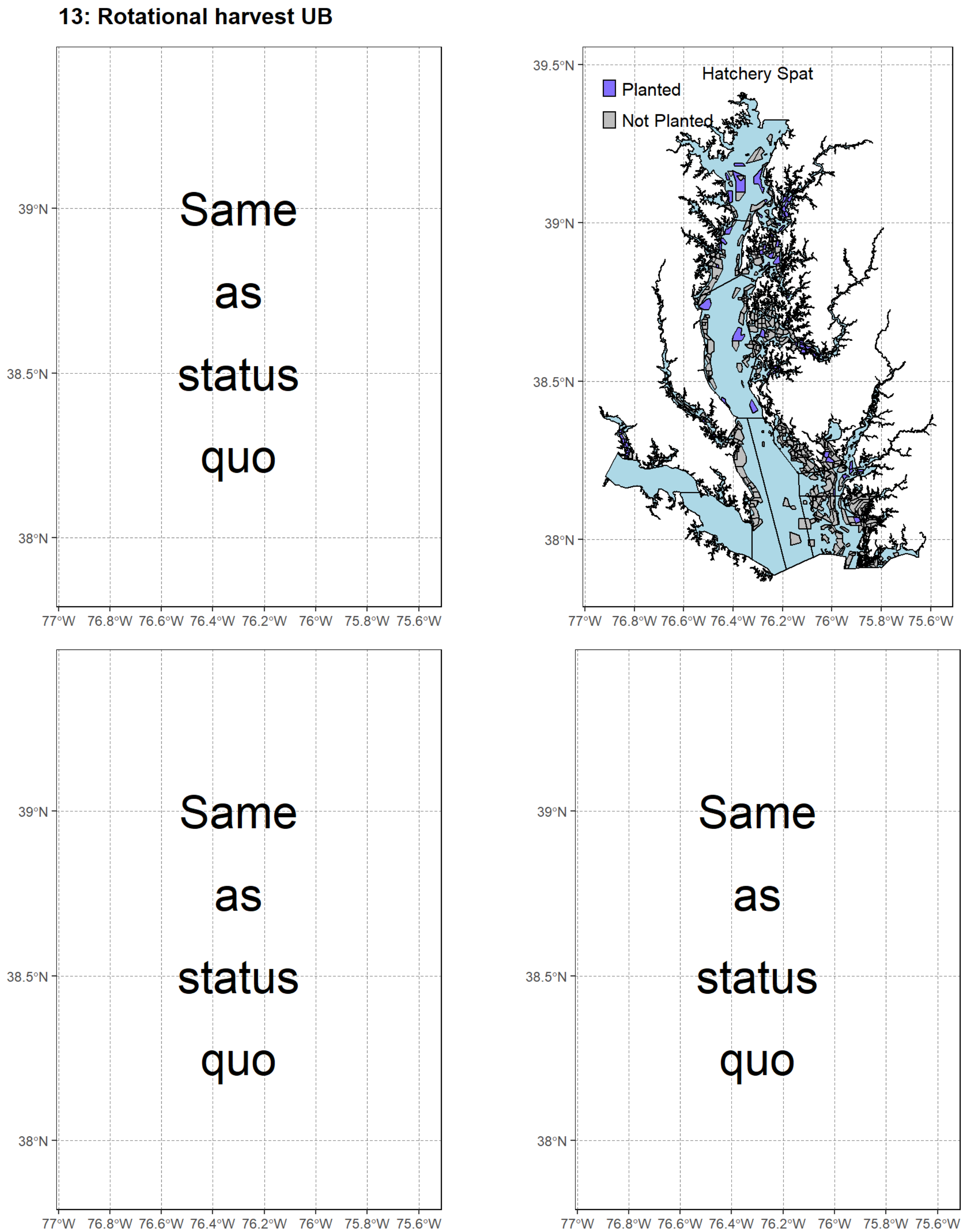

Fig. A25. Locations of shell, hatchery spat, alternate substrate, and wild seed plantings for option 13.

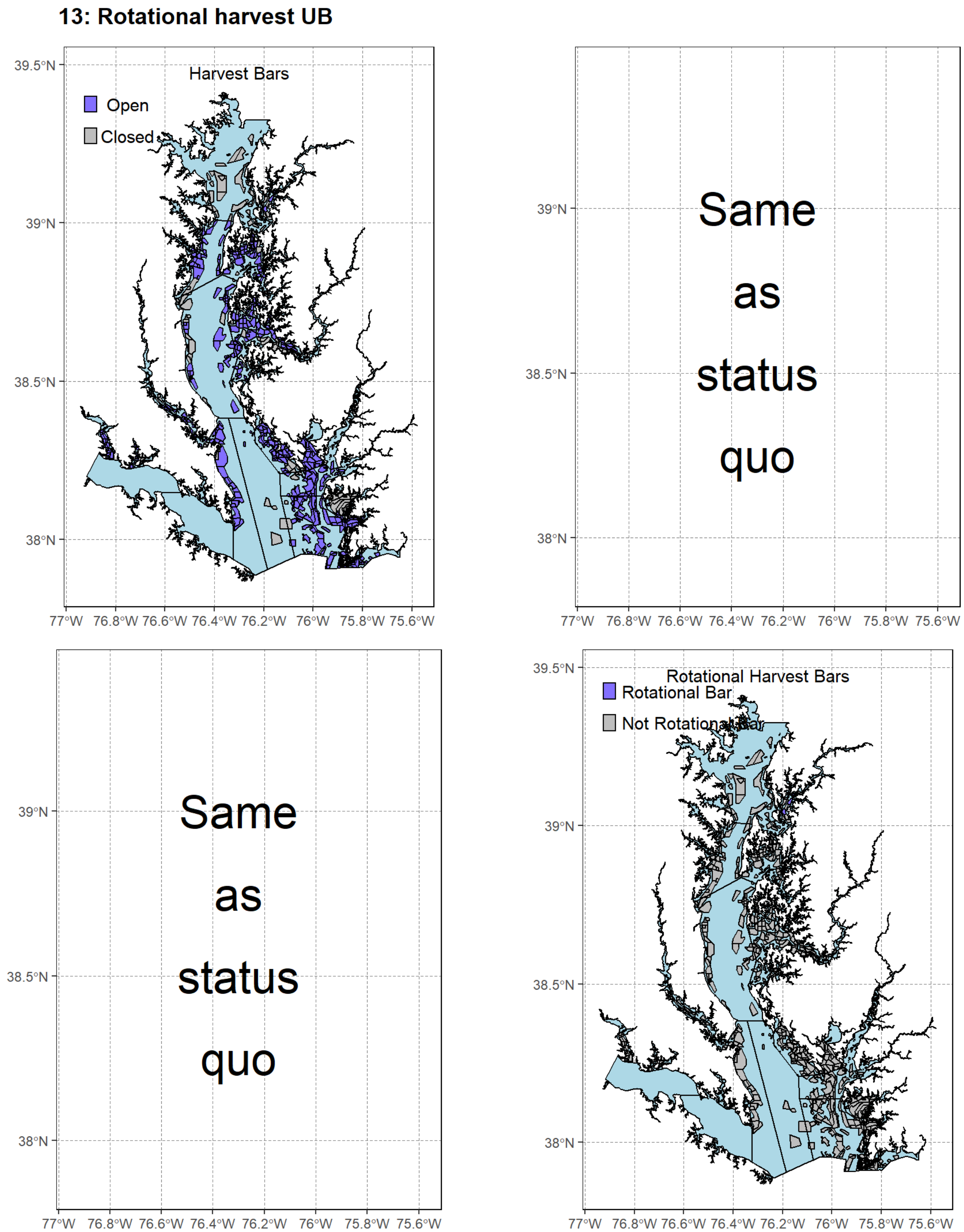

Fig. A26. Bars open to harvest, seed bars, bars open to rotational harvest, and shell dredging bars for option 13.

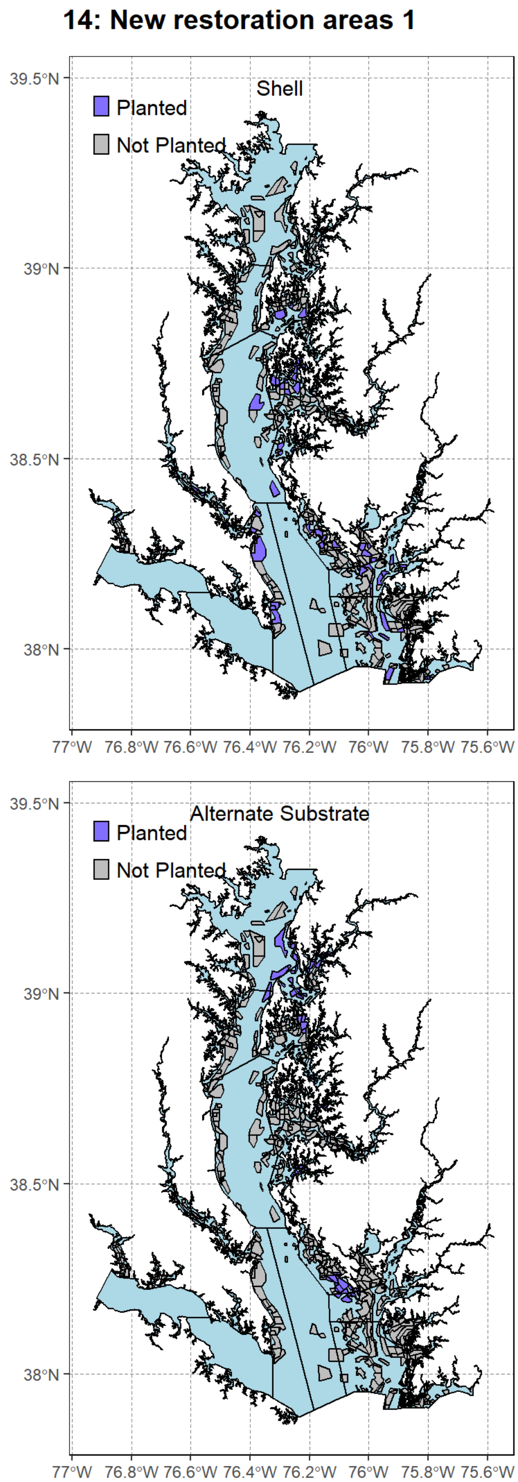

Fig. A27. Locations of shell, hatchery spat, alternate substrate, and wild seed plantings for option 14.

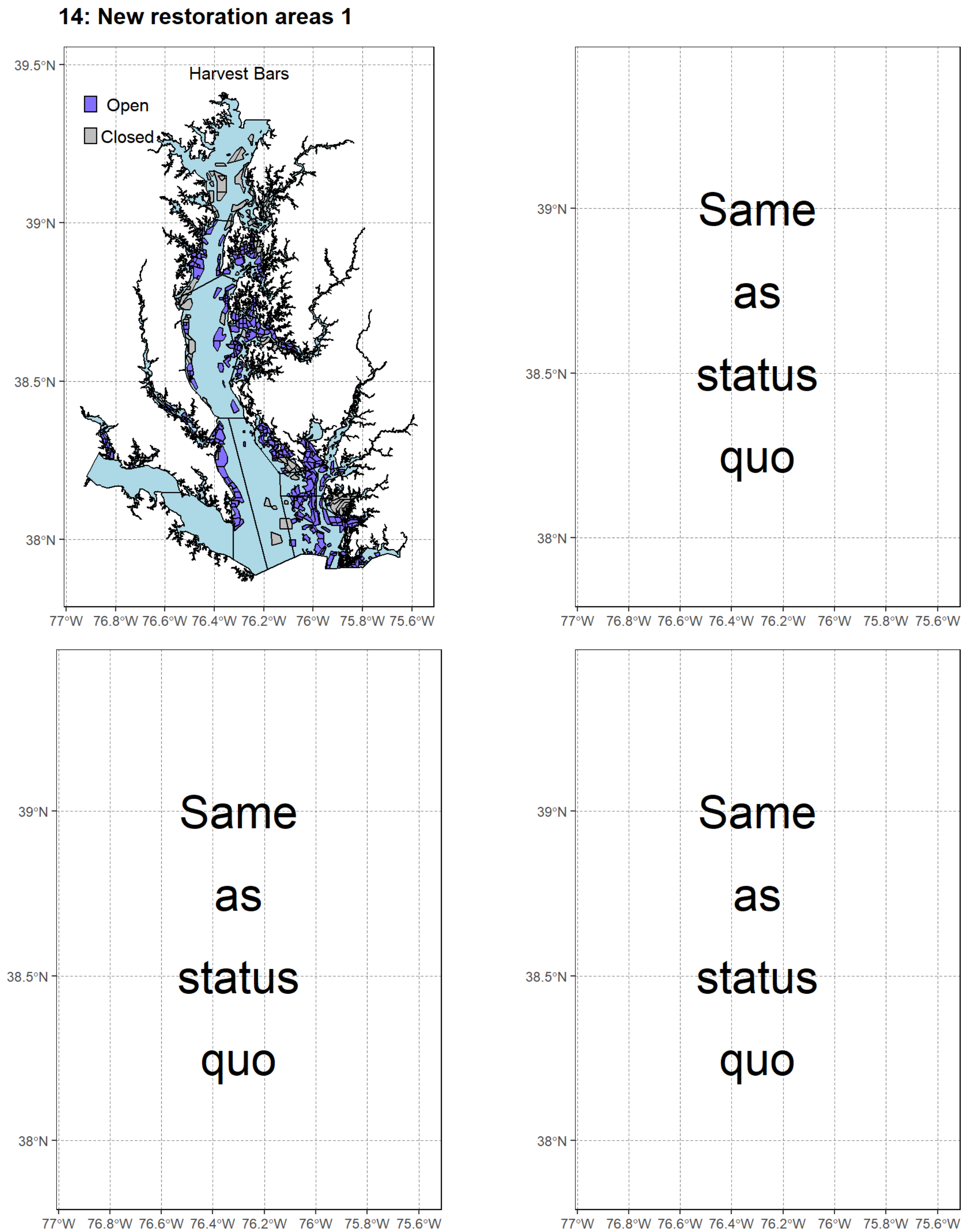

Fig. A28. Bars open to harvest, seed bars, bars open to rotational harvest, and shell dredging bars for option 14.

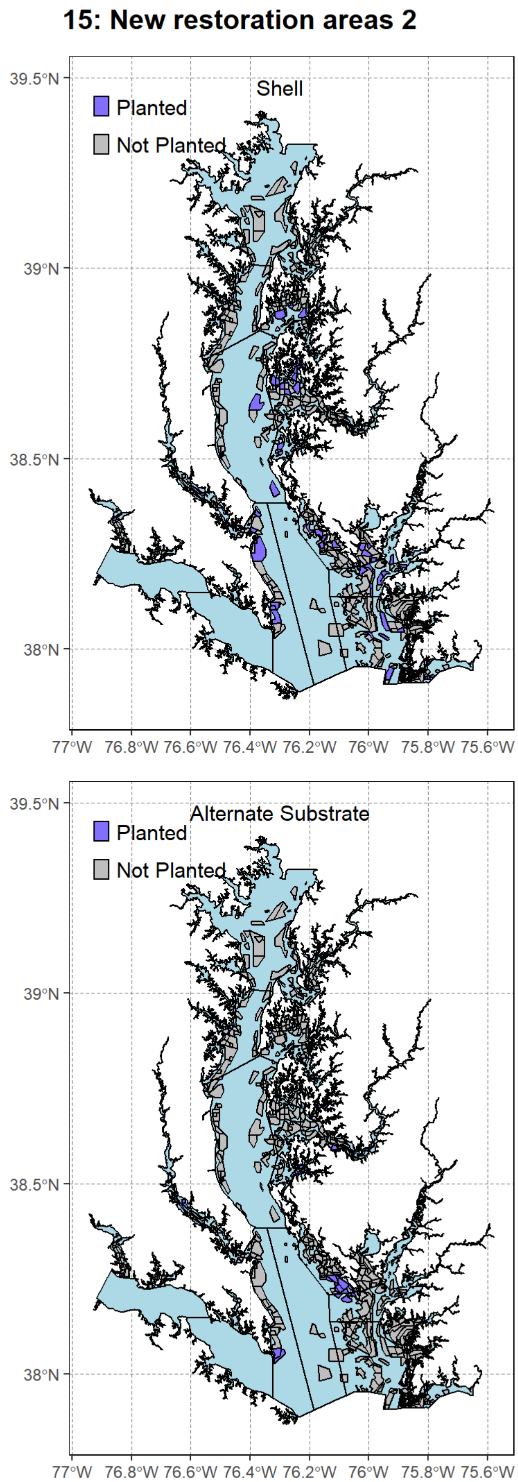

Fig. A29. Locations of shell, hatchery spat, alternate substrate, and wild seed plantings for option 15.

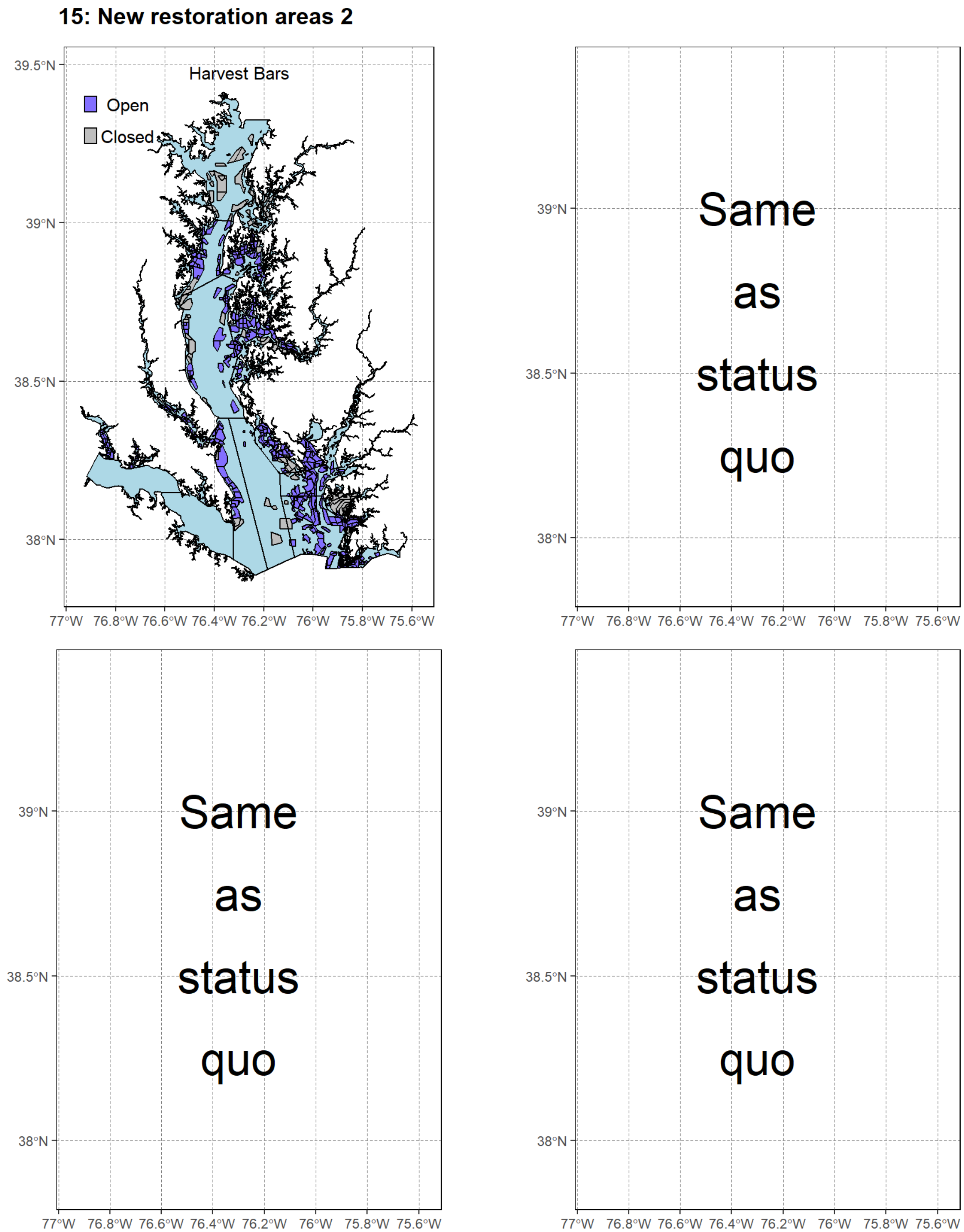

Fig. A30. Bars open to harvest, seed bars, bars open to rotational harvest, and shell dredging bars for option 15.

16: New restoration areas 3

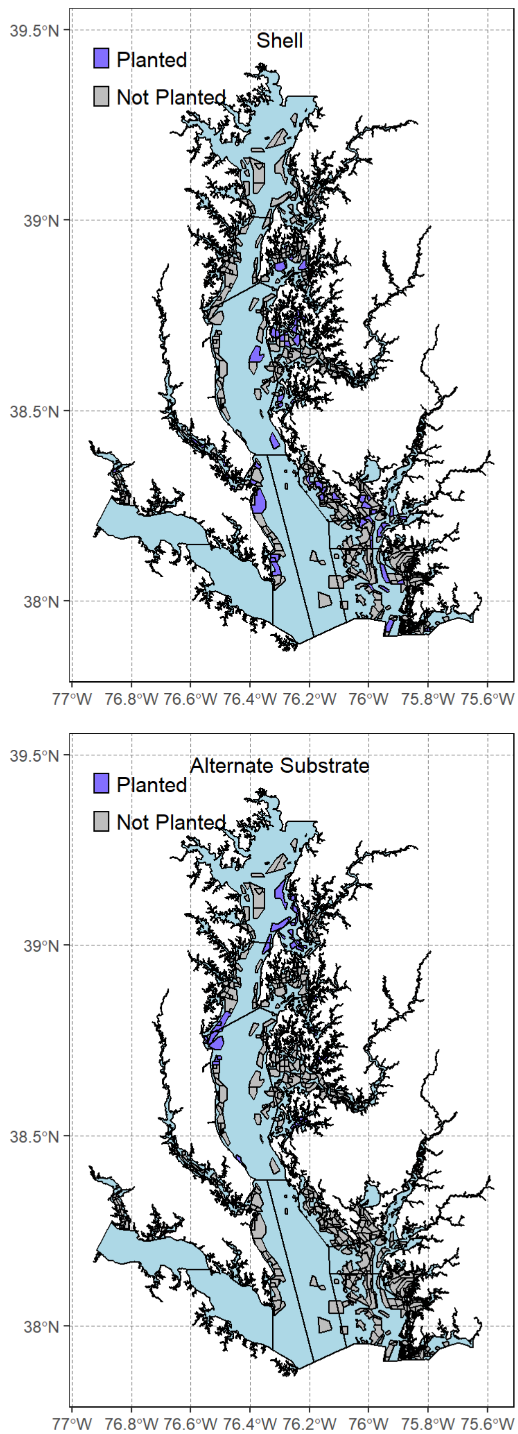

Fig. A31. Locations of shell, hatchery spat, alternate substrate, and wild seed plantings for option 16.

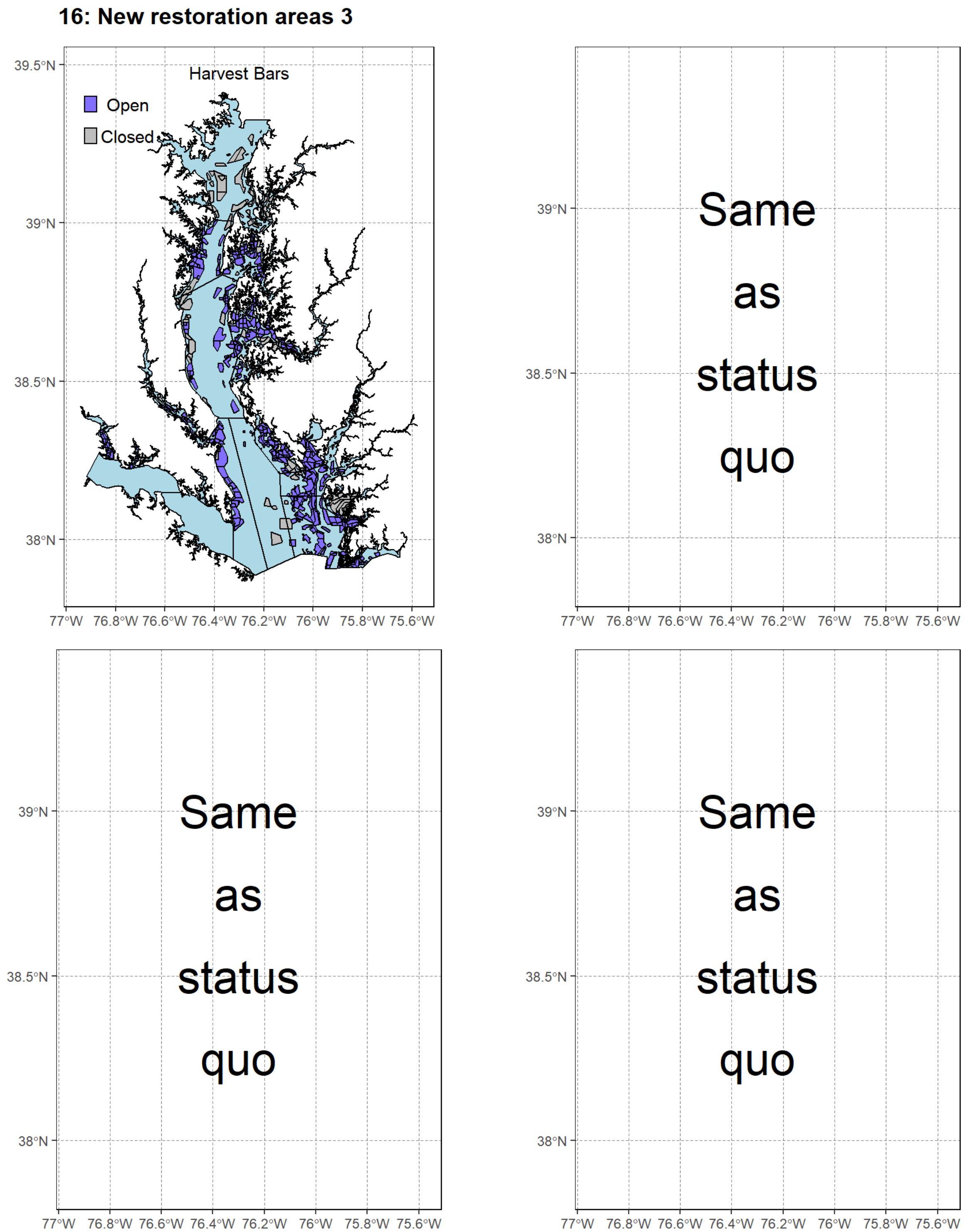

Fig. A32. Bars open to harvest, seed bars, bars open to rotational harvest, and shell dredging bars for option 16.

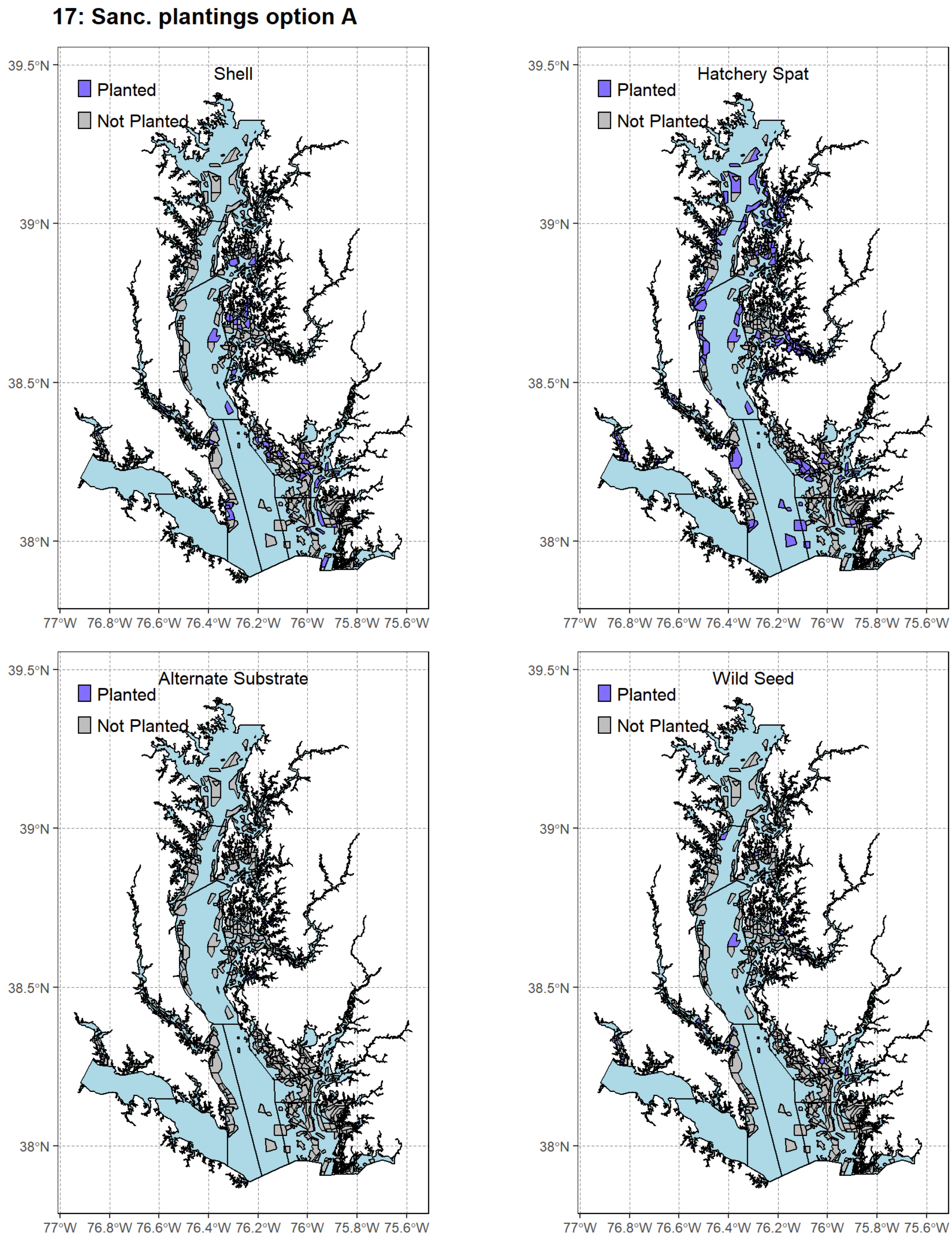

Fig. A33. Locations of shell, hatchery spat, alternate substrate, and wild seed plantings for option 17.

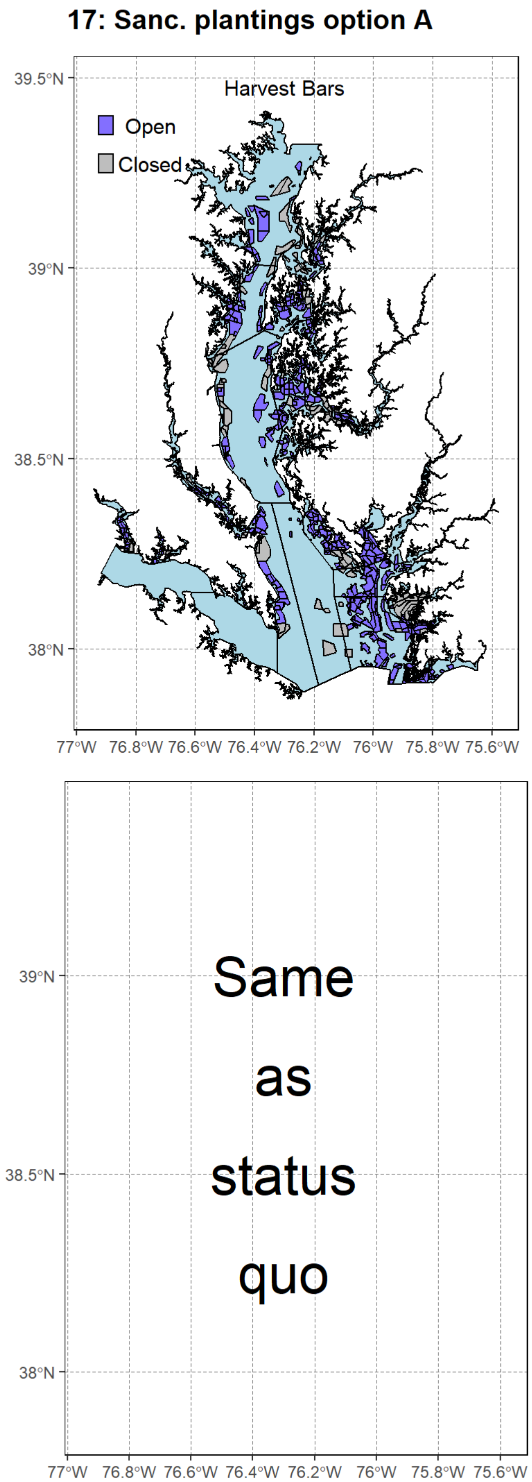

Fig. A34. Bars open to harvest, seed bars, bars open to rotational harvest, and shell dredging bars for option 17.

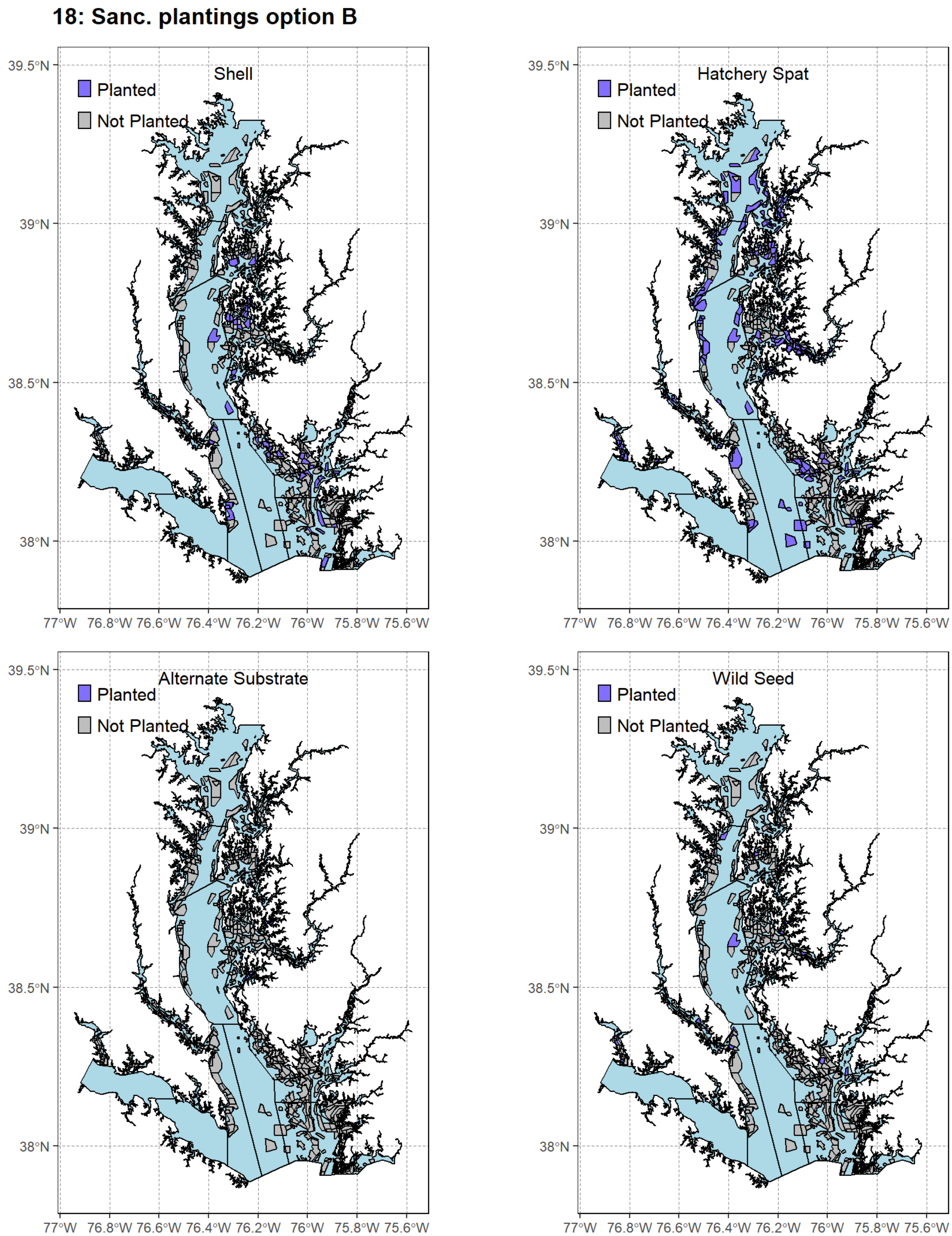

Fig. A35. Locations of shell, hatchery spat, alternate substrate, and wild seed plantings for option 18.

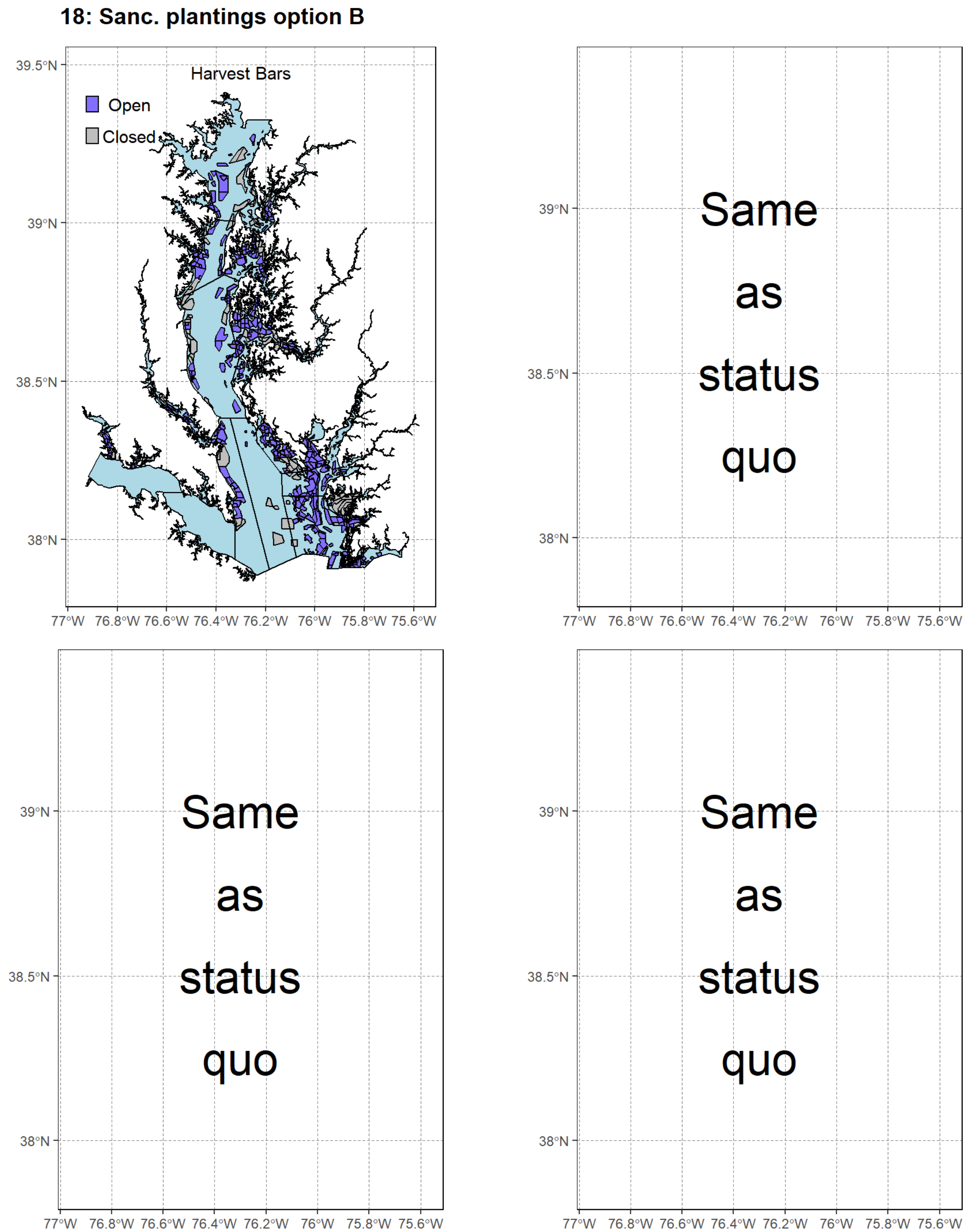

Fig. A36. Bars open to harvest, seed bars, bars open to rotational harvest, and shell dredging bars for option 18.

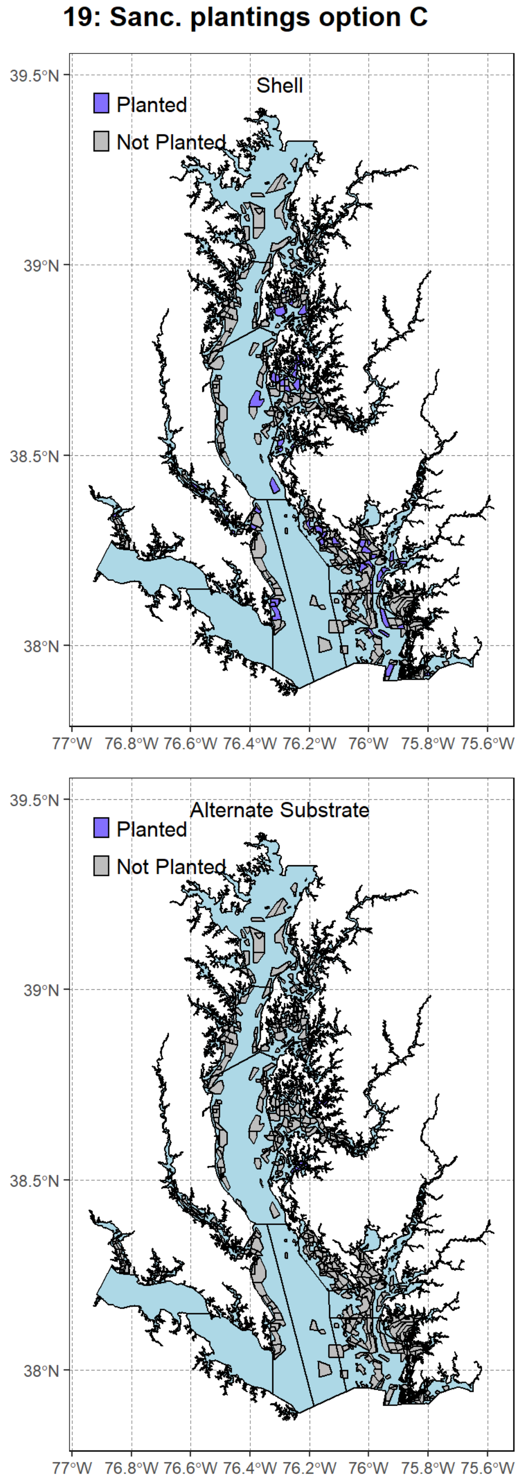

Fig. A37. Locations of shell, hatchery spat, alternate substrate, and wild seed plantings for option 19.

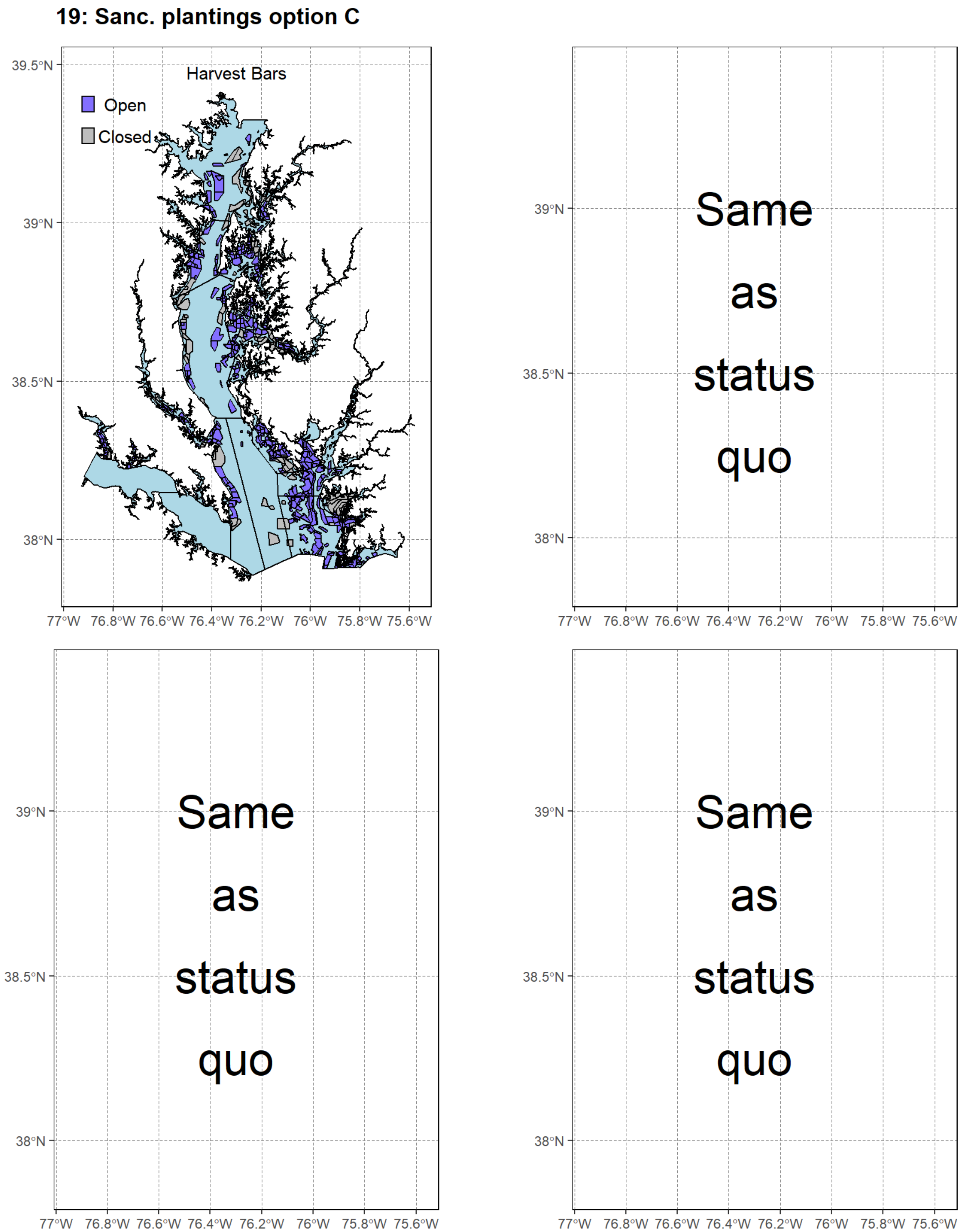

Fig. A38. Bars open to harvest, seed bars, bars open to rotational harvest, and shell dredging bars for option 19.

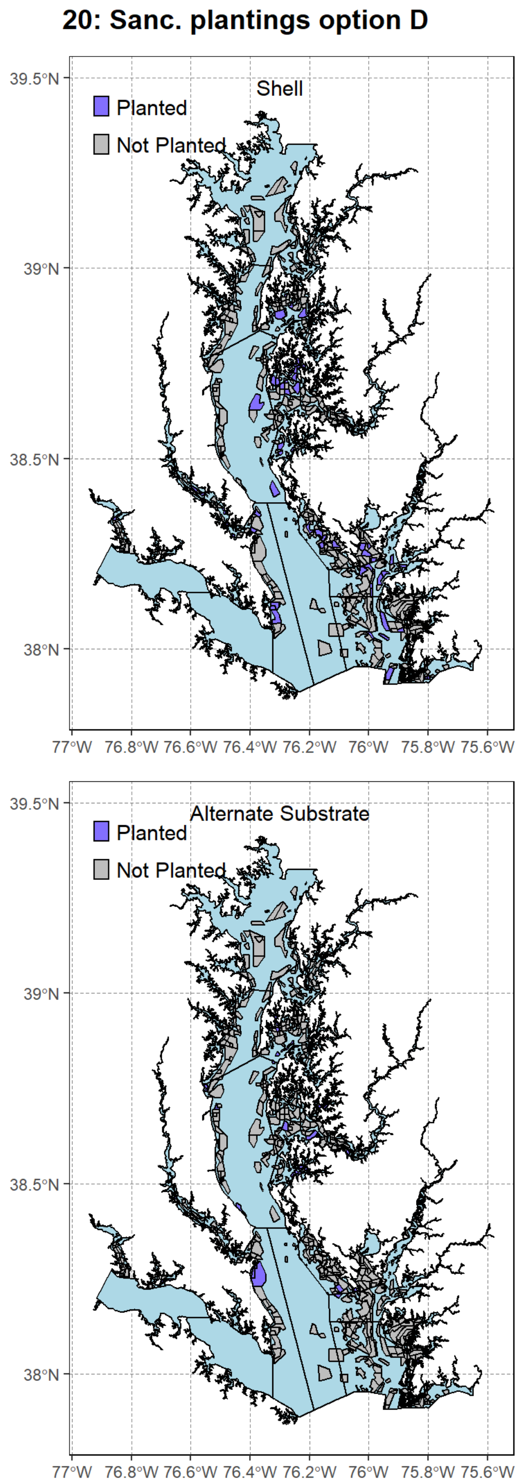

Fig. A39. Locations of shell, hatchery spat, alternate substrate, and wild seed plantings for option 20.

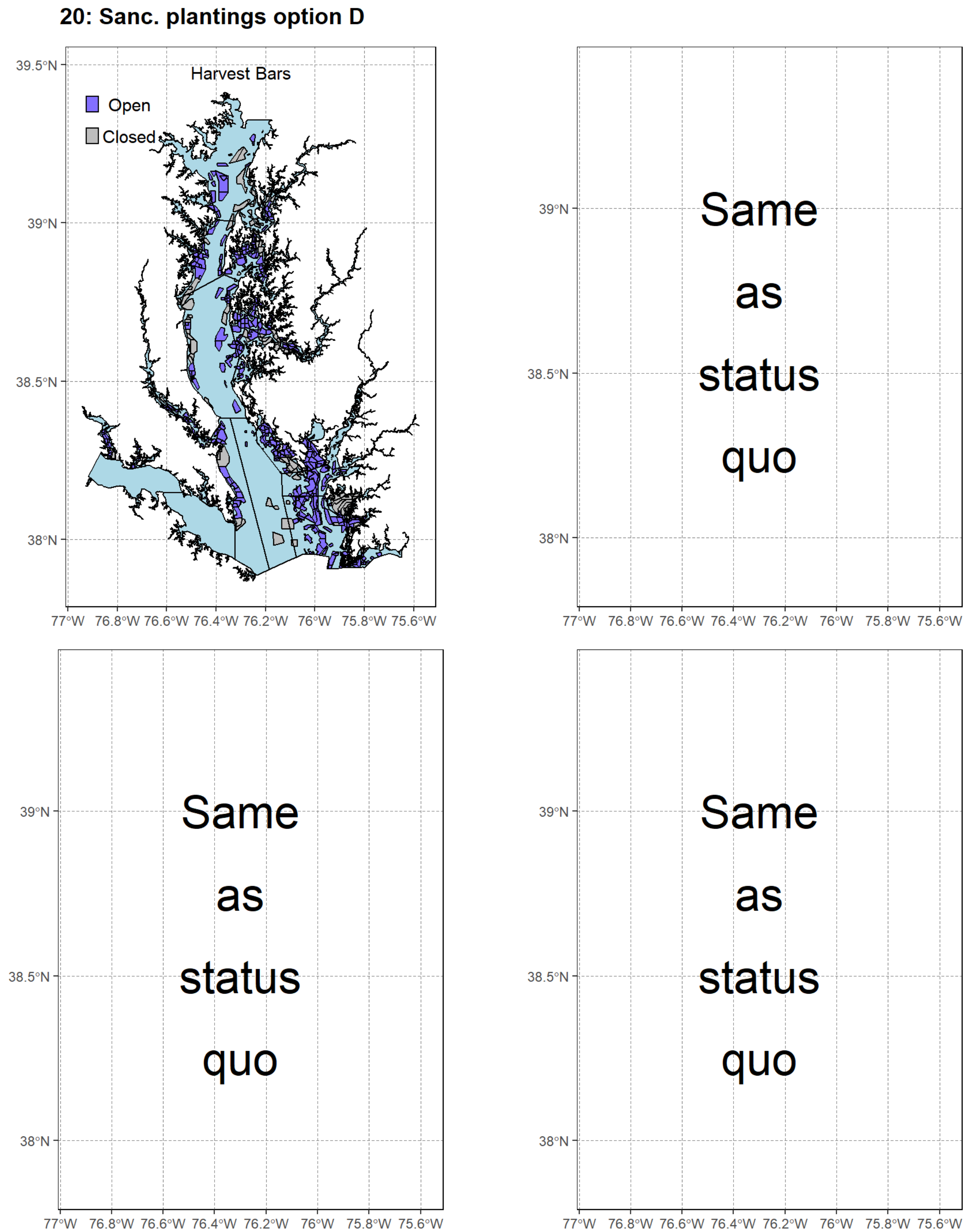

Fig. A40. Bars open to harvest, seed bars, bars open to rotational harvest, and shell dredging bars for option 20.

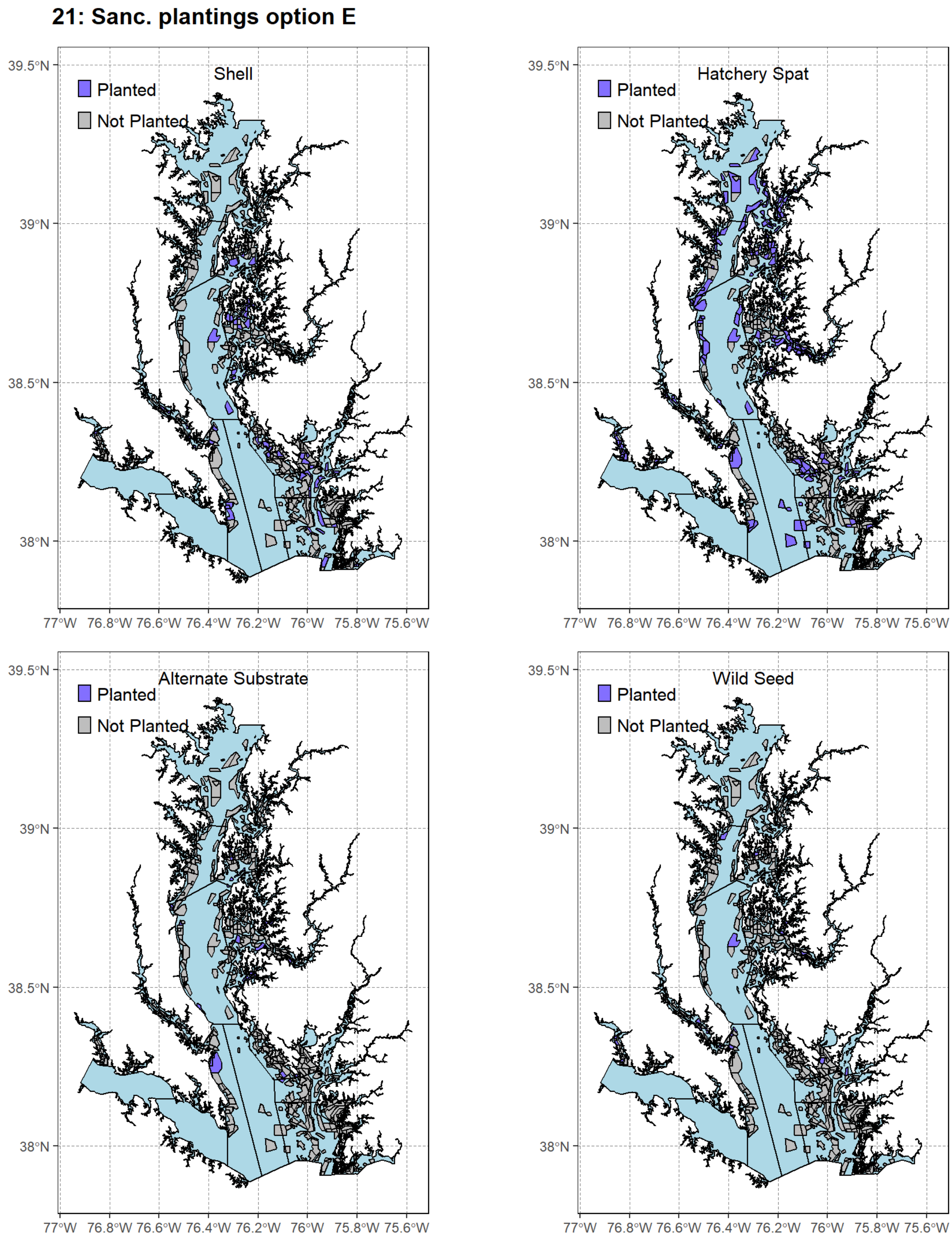

Fig. A41. Locations of shell, hatchery spat, alternate substrate, and wild seed plantings for option 21.

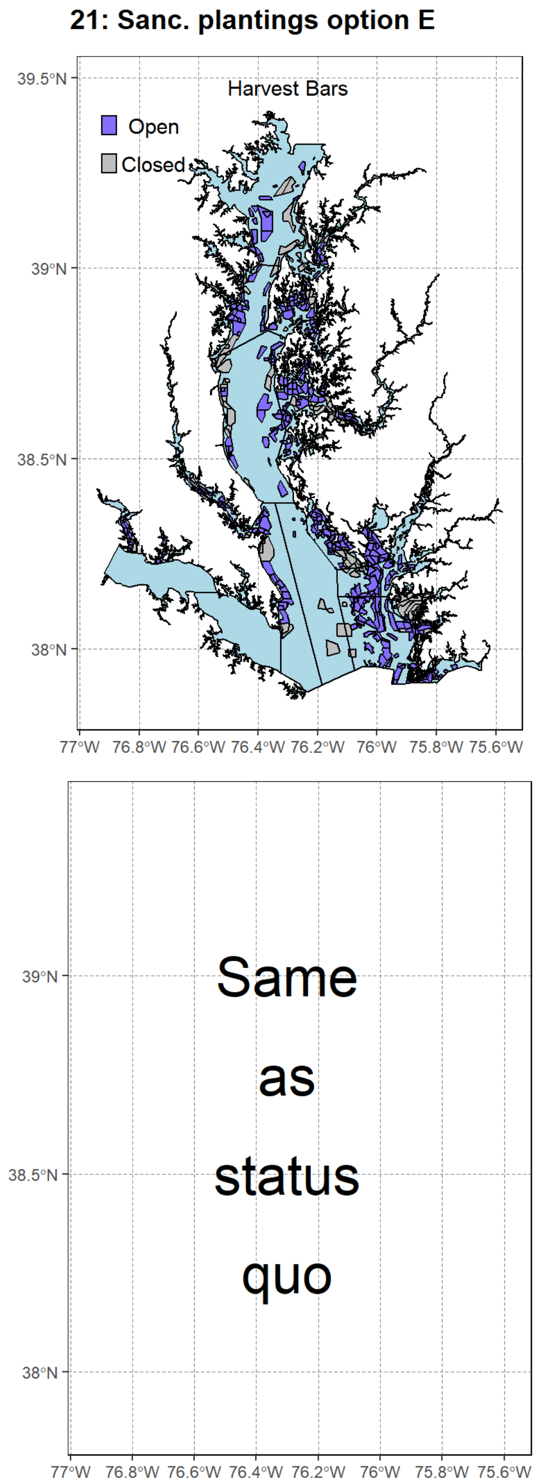

Fig. A42. Bars open to harvest, seed bars, bars open to rotational harvest, and shell dredging bars for option 21.

22: Sanc. plantings option F

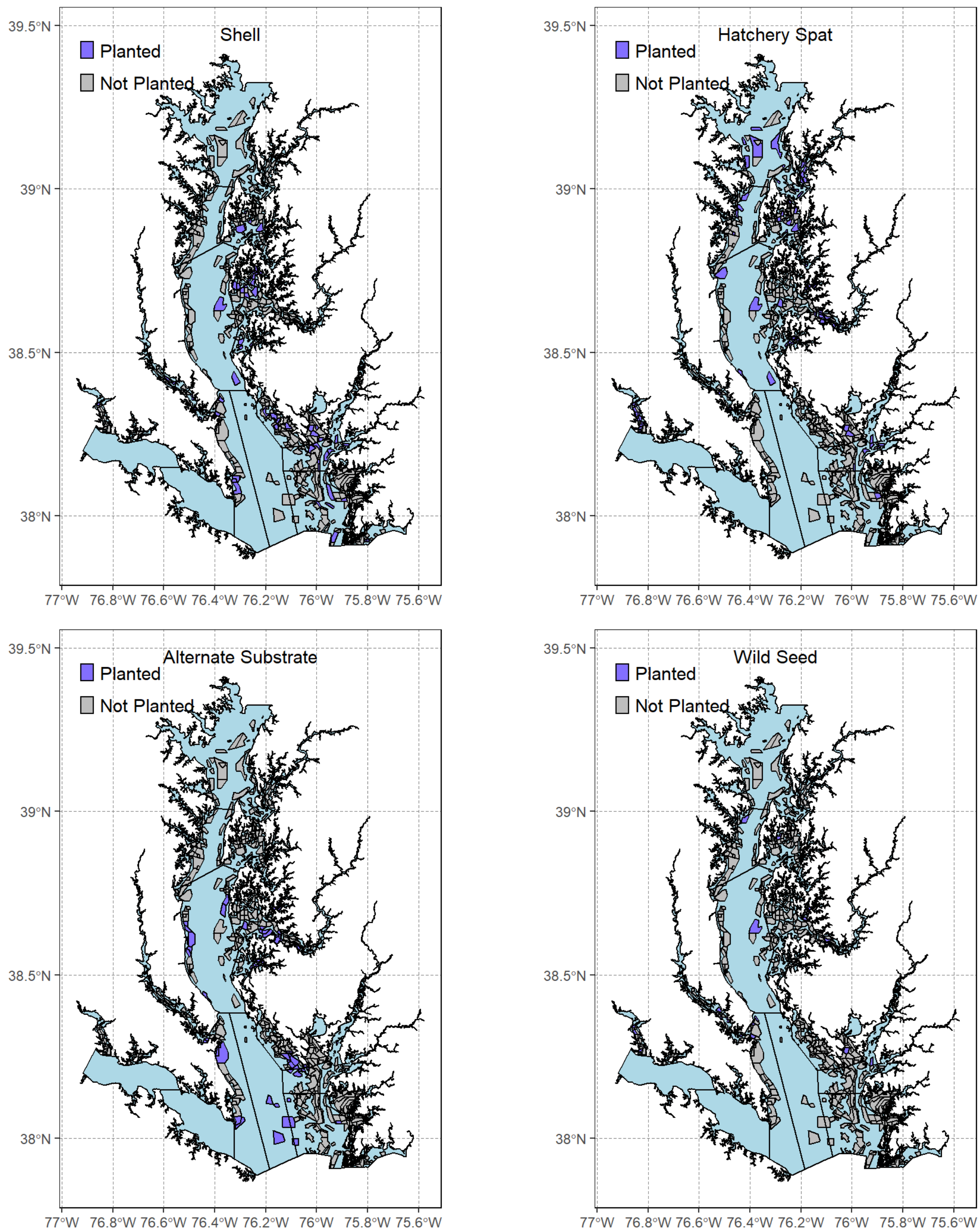

Fig. A43. Locations of shell, hatchery spat, alternate substrate, and wild seed plantings for option 22.

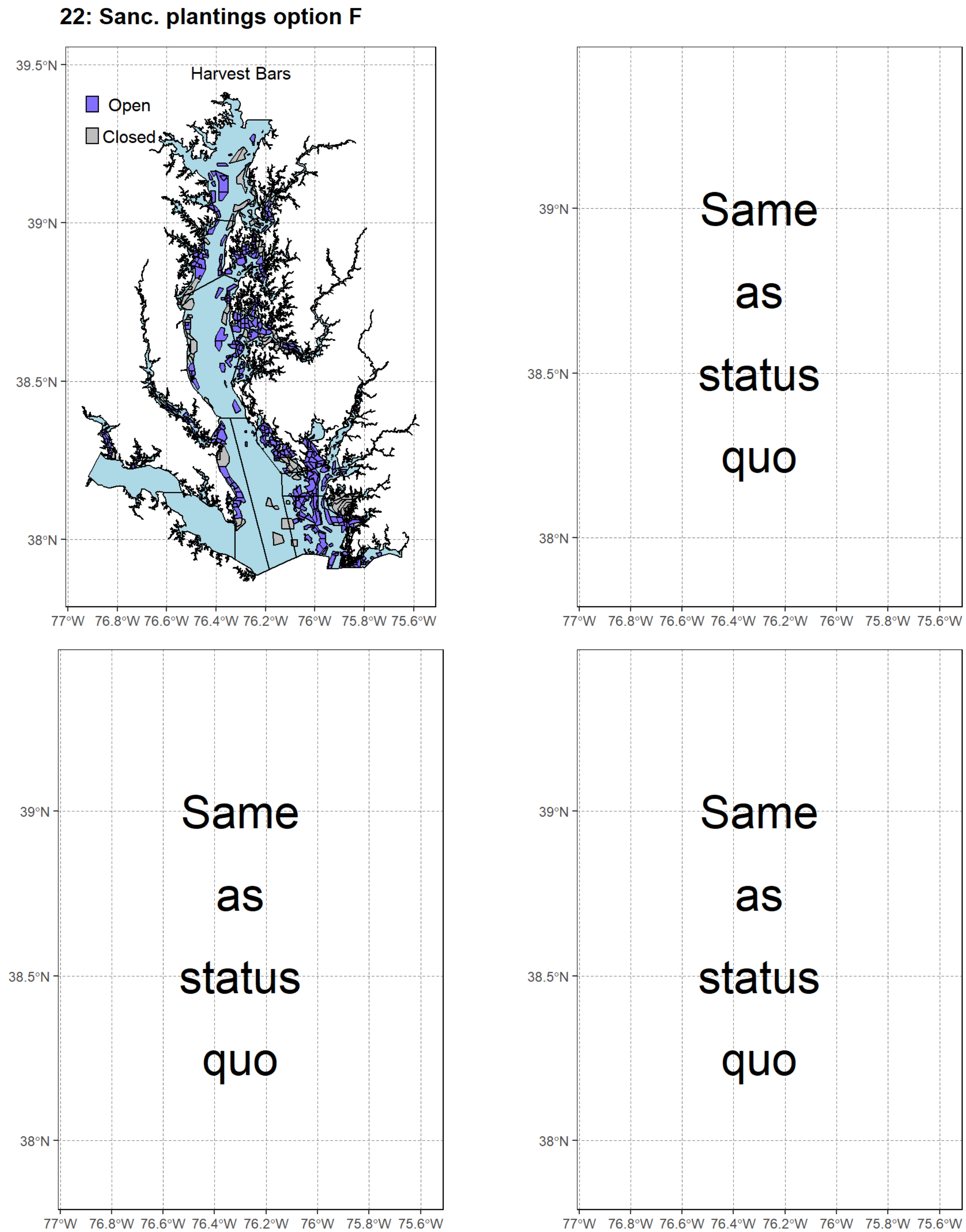

Fig. A44. Bars open to harvest, seed bars, bars open to rotational harvest, and shell dredging bars for option 22.

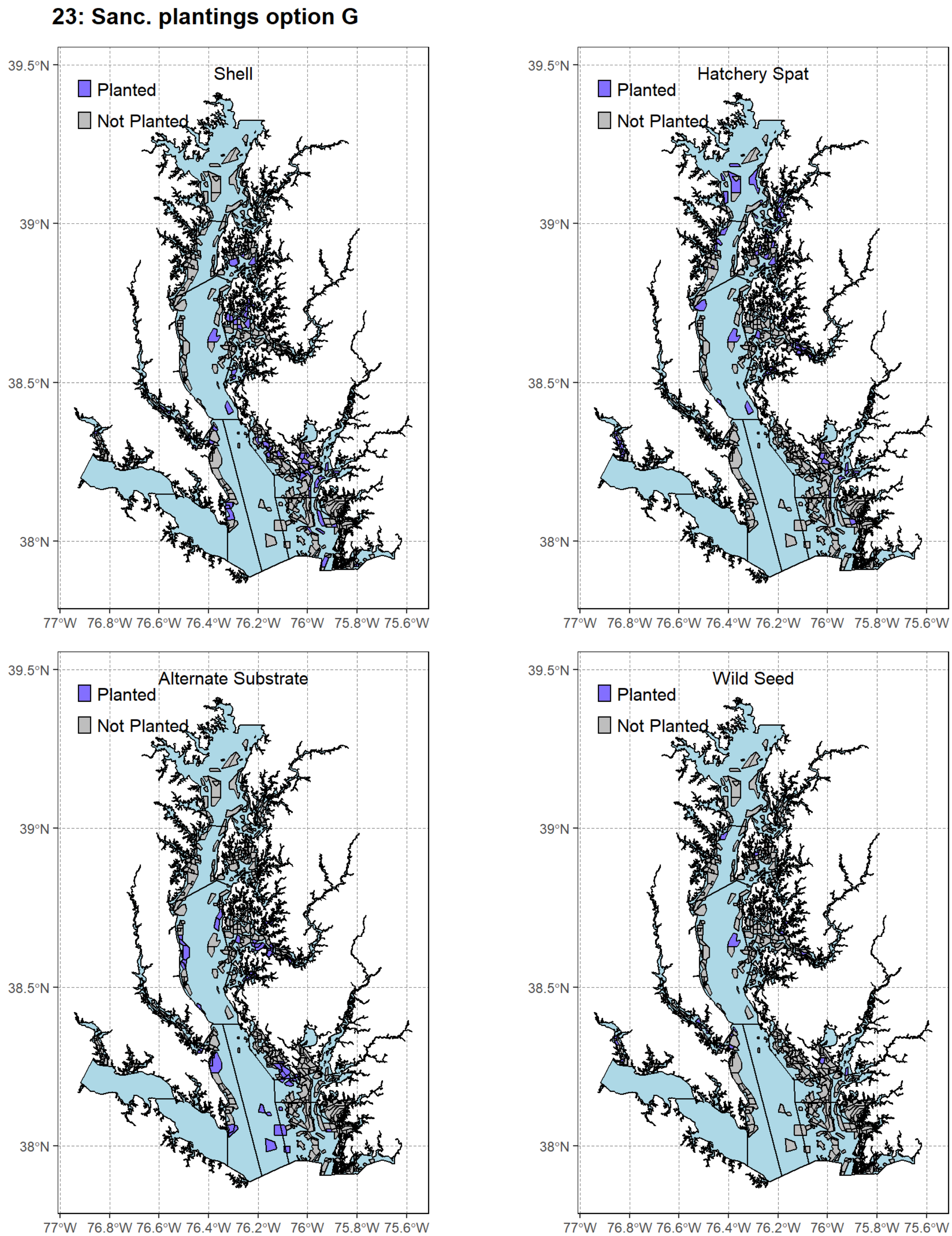

Fig. A45. Locations of shell, hatchery spat, alternate substrate, and wild seed plantings for option 23.

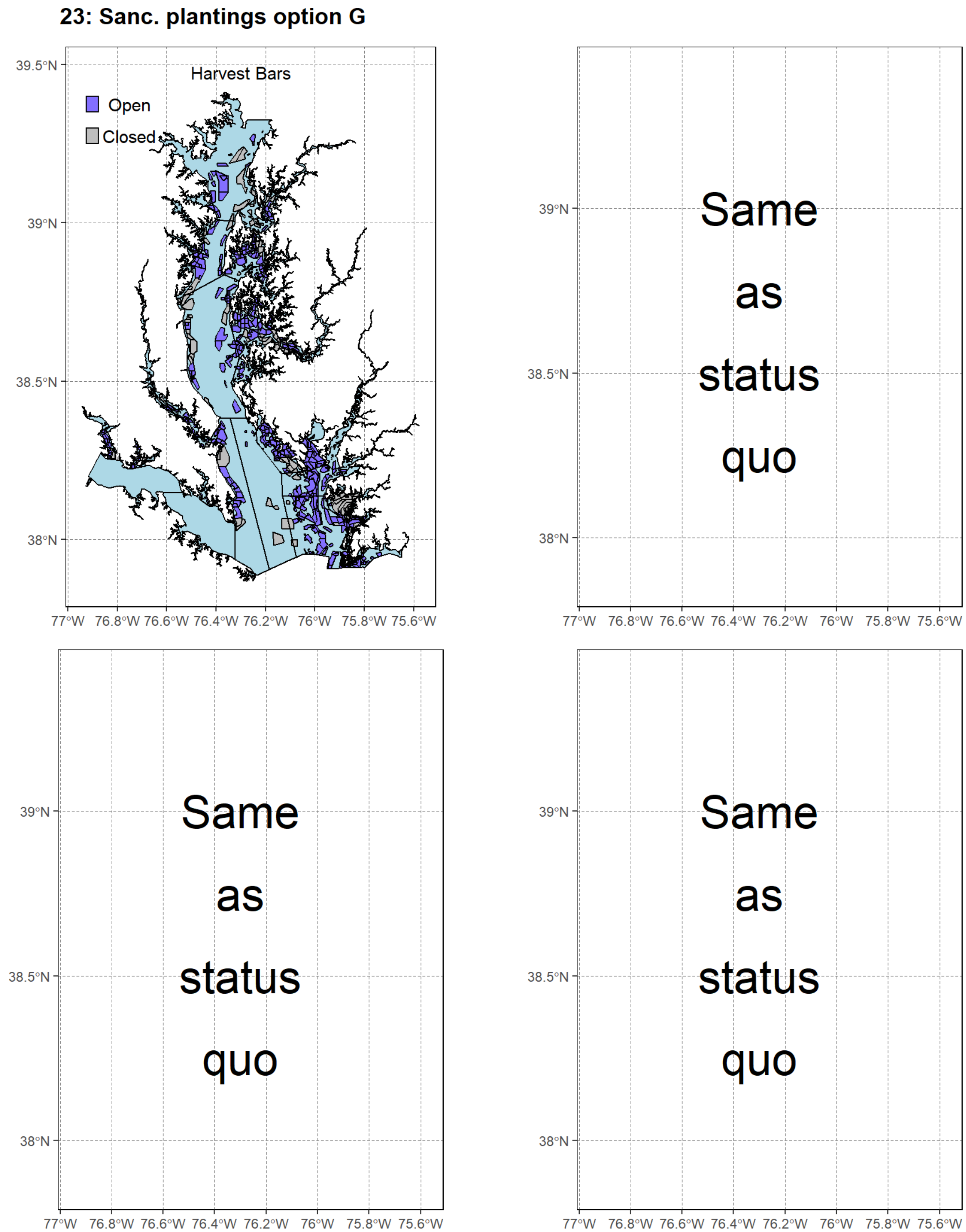

Fig. A46. Bars open to harvest, seed bars, bars open to rotational harvest, and shell dredging bars for option 23.

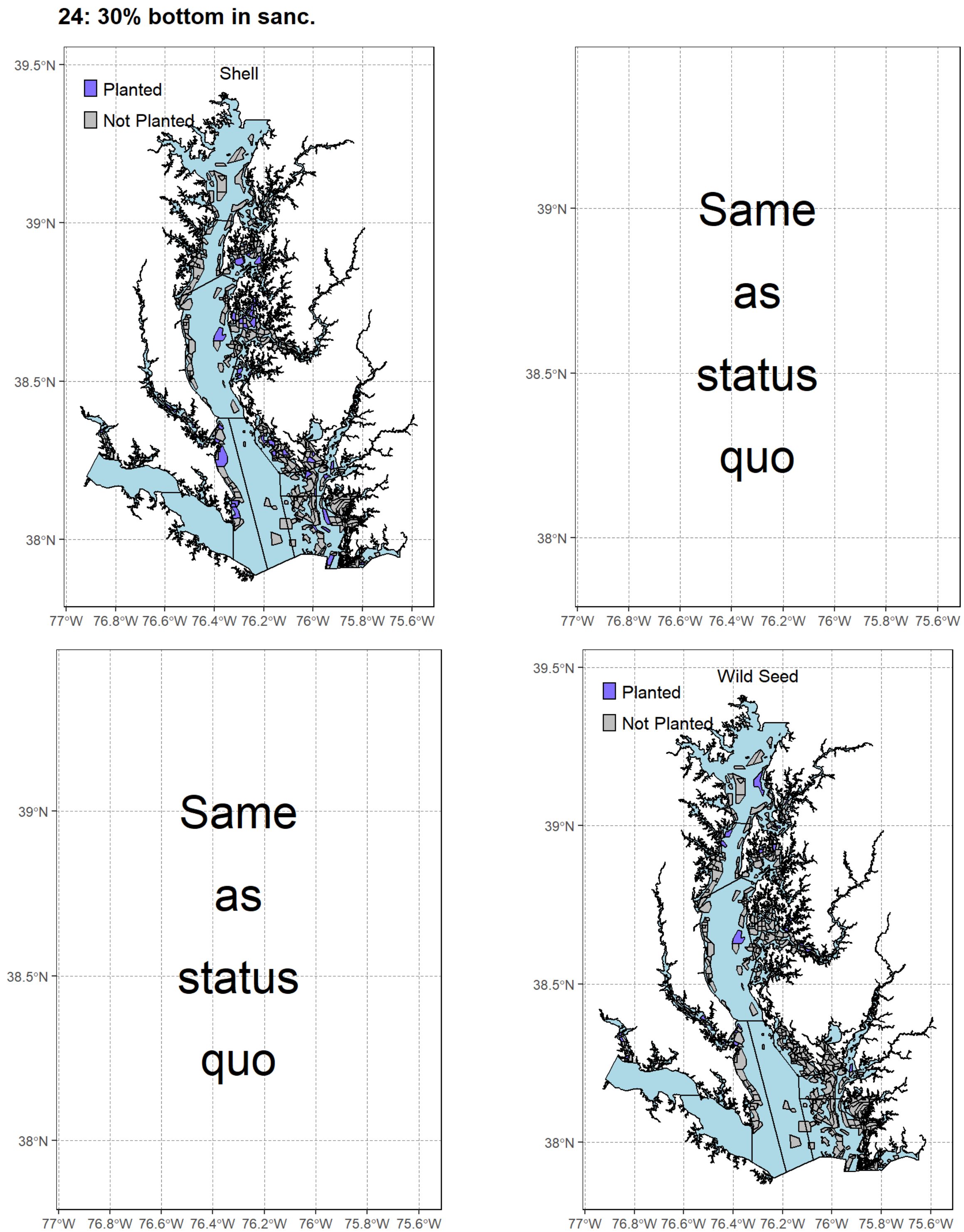

Fig. A47. Locations of shell, hatchery spat, alternate substrate, and wild seed plantings for option 24.

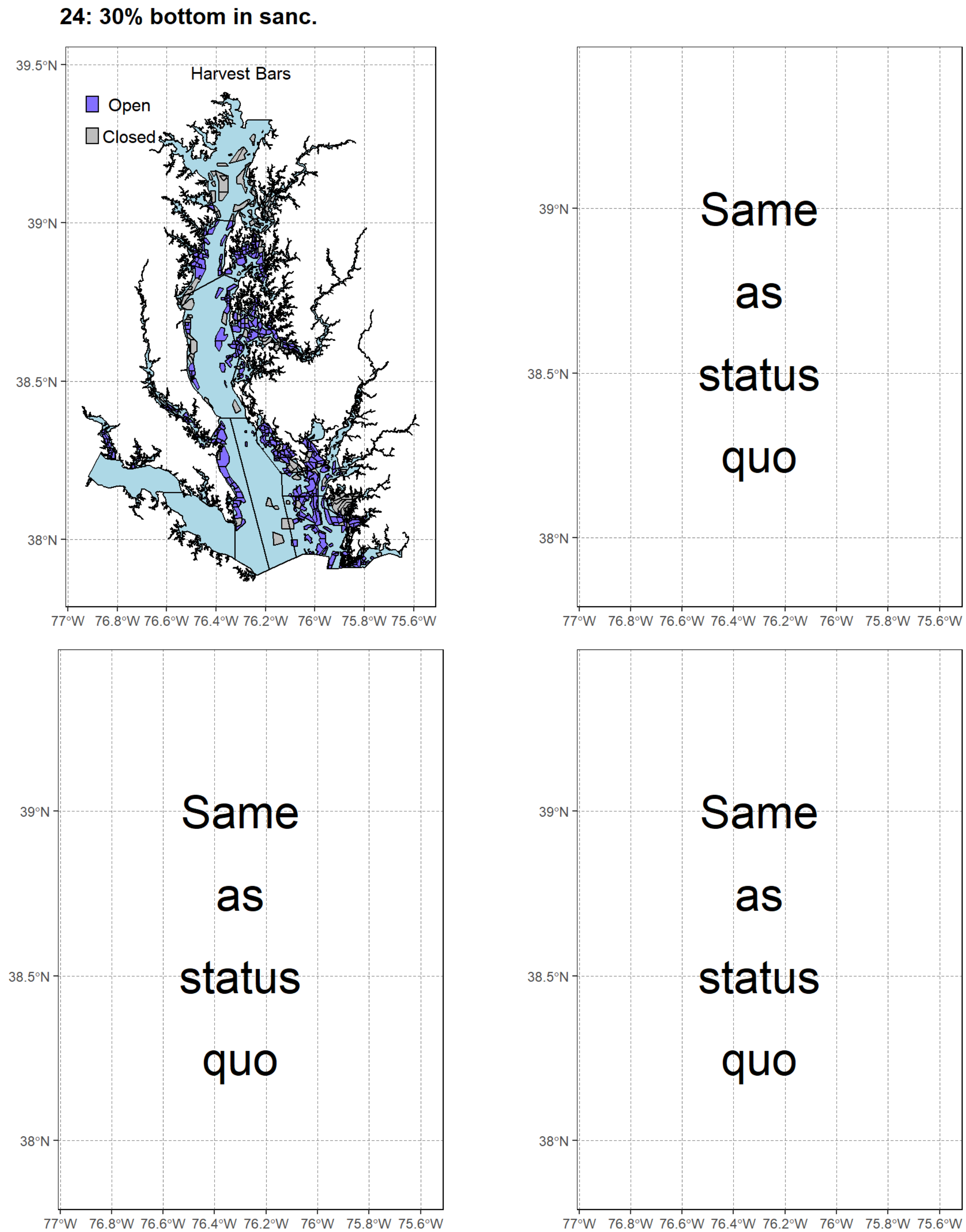

Fig. A48. Bars open to harvest, seed bars, bars open to rotational harvest, and shell dredging bars for option 24.

25: No fishing (no plantings)

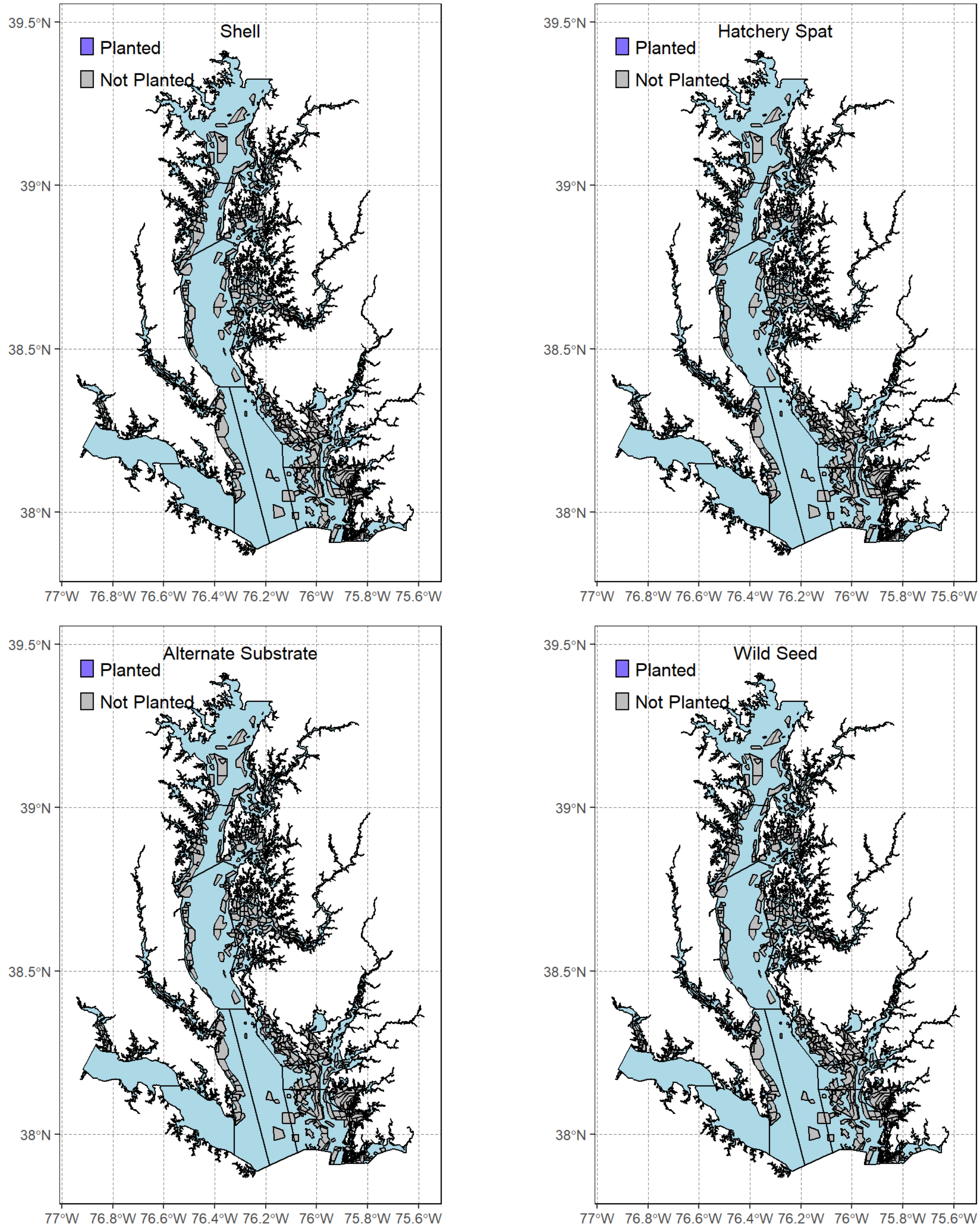

Fig. A49. Locations of shell, hatchery spat, alternate substrate, and wild seed plantings for option 25.

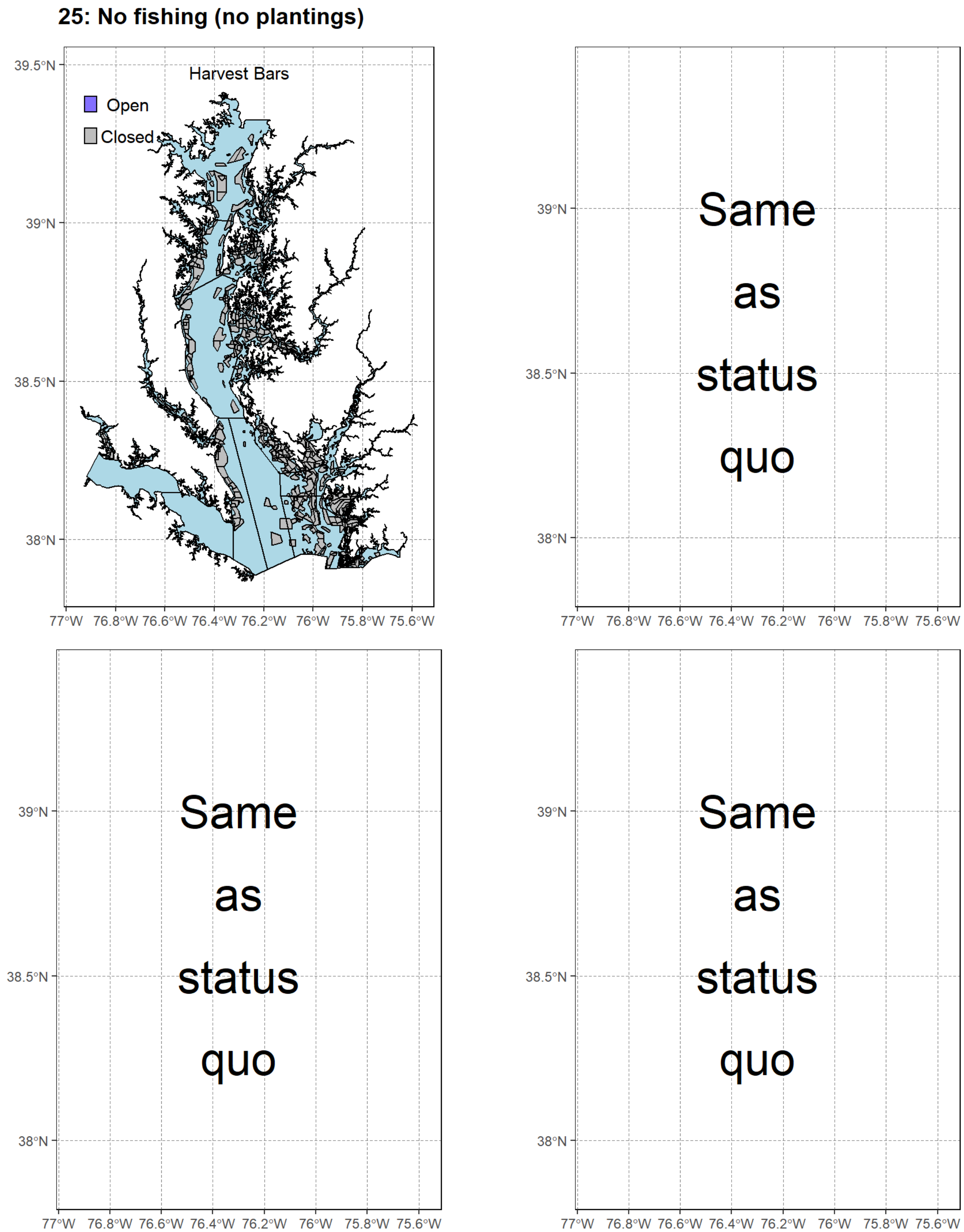

Fig. A50. Bars open to harvest, seed bars, bars open to rotational harvest, and shell dredging bars for option 25.

Fig. A51. Locations of shell, hatchery spat, alternate substrate, and wild seed plantings for option 26.

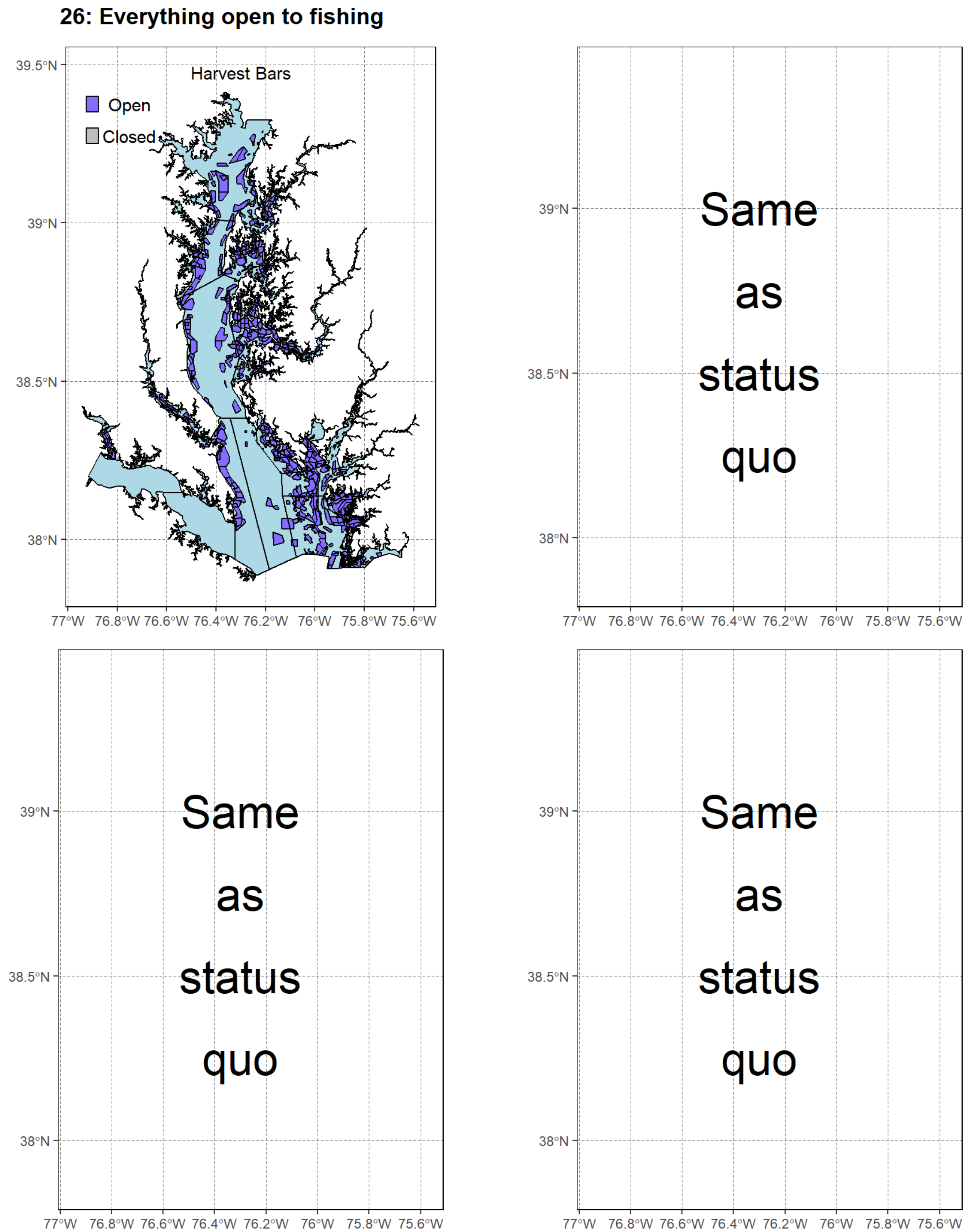

Fig. A52. Bars open to harvest, seed bars, bars open to rotational harvest, and shell dredging bars for option 26.

27: 4-yr rotational harvest by region

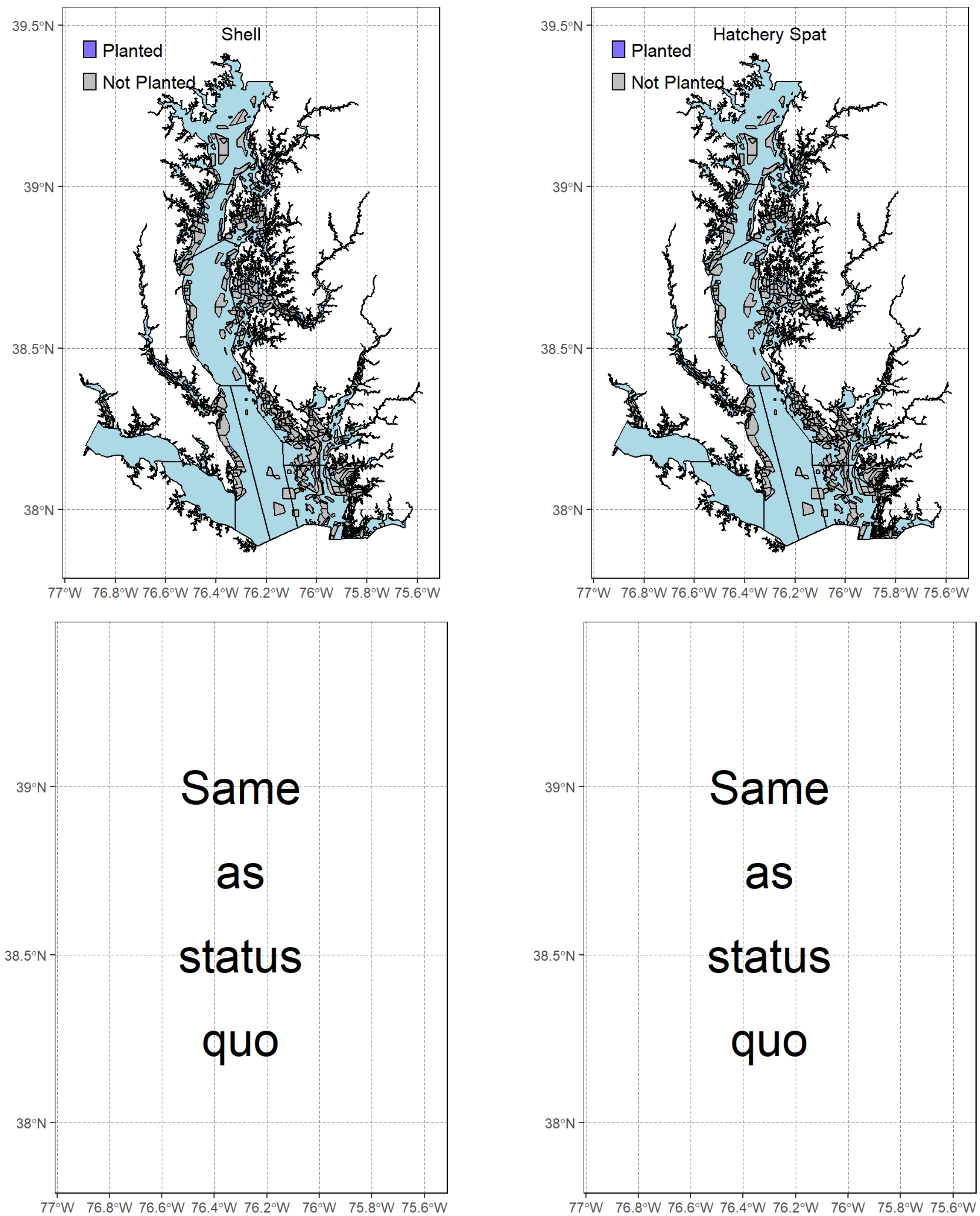

Fig. A53. Locations of shell, hatchery spat, alternate substrate, and wild seed plantings for option 27.

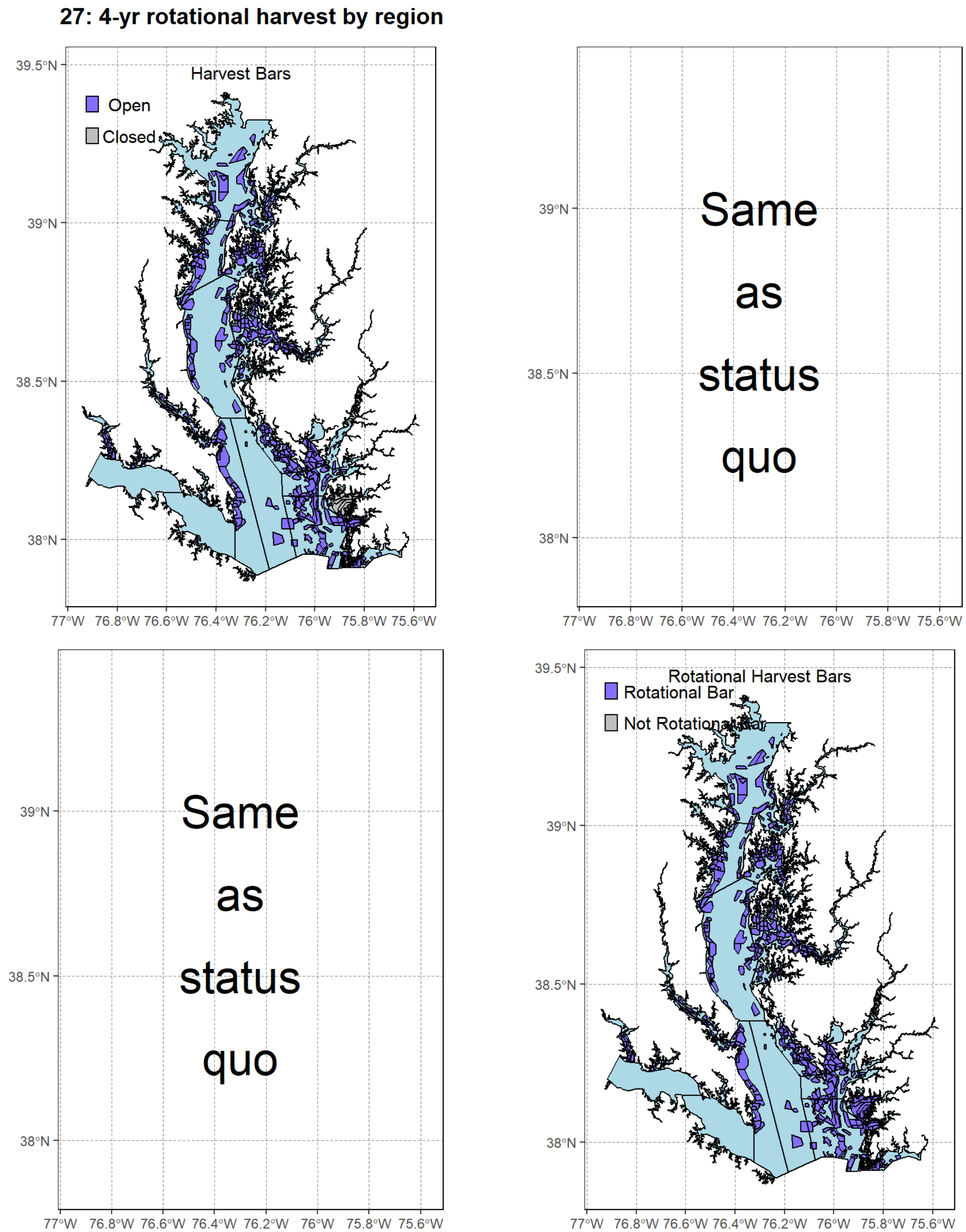

Fig. A54. Bars open to harvest, seed bars, bars open to rotational harvest, and shell dredging bars for option 27.

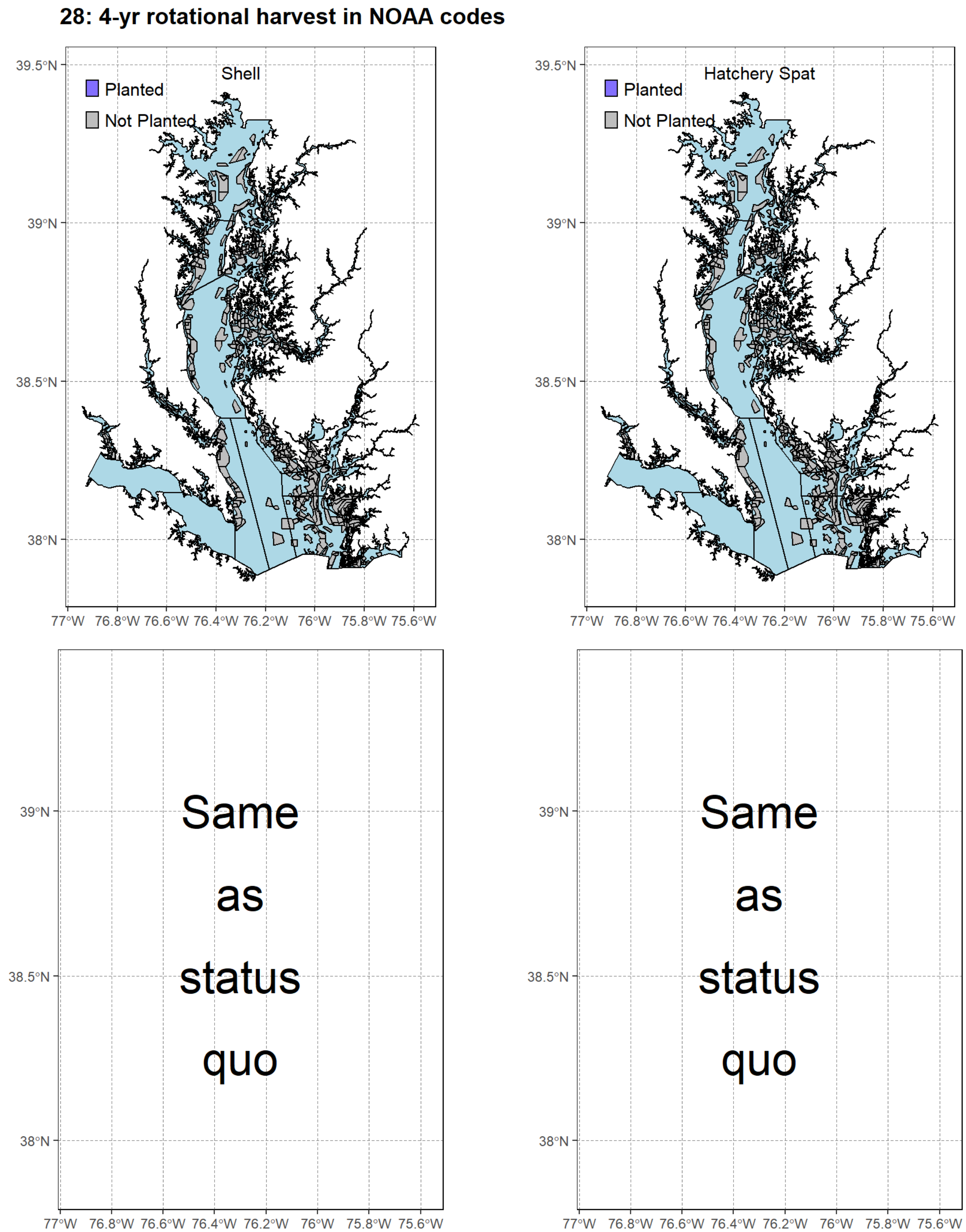

Fig. A55. Locations of shell, hatchery spat, alternate substrate, and wild seed plantings for option 28.

28: 4-yr rotational harvest in NOAA codes

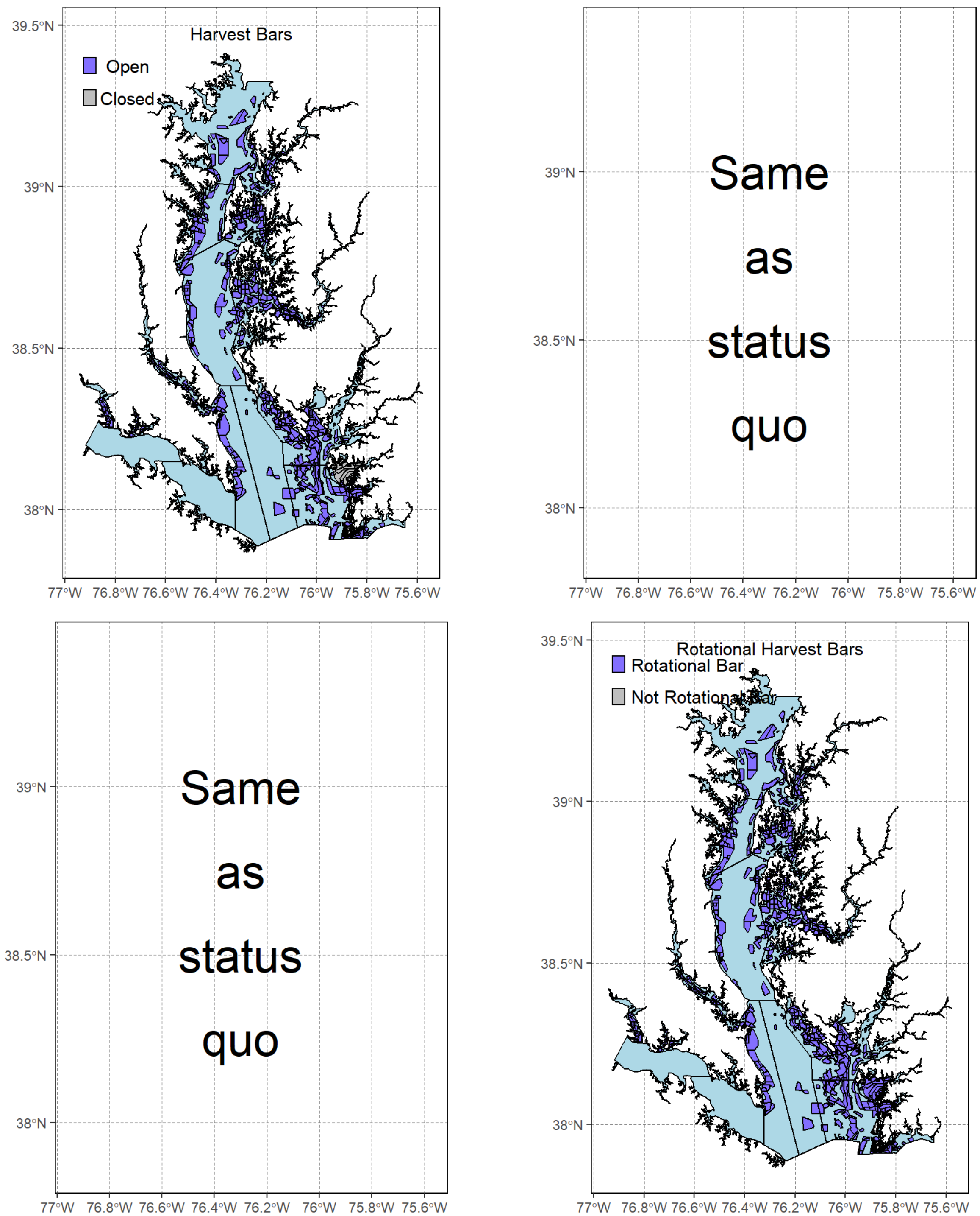

Fig. A56. Bars open to harvest, seed bars, bars open to rotational harvest, and shell dredging bars for option 28.

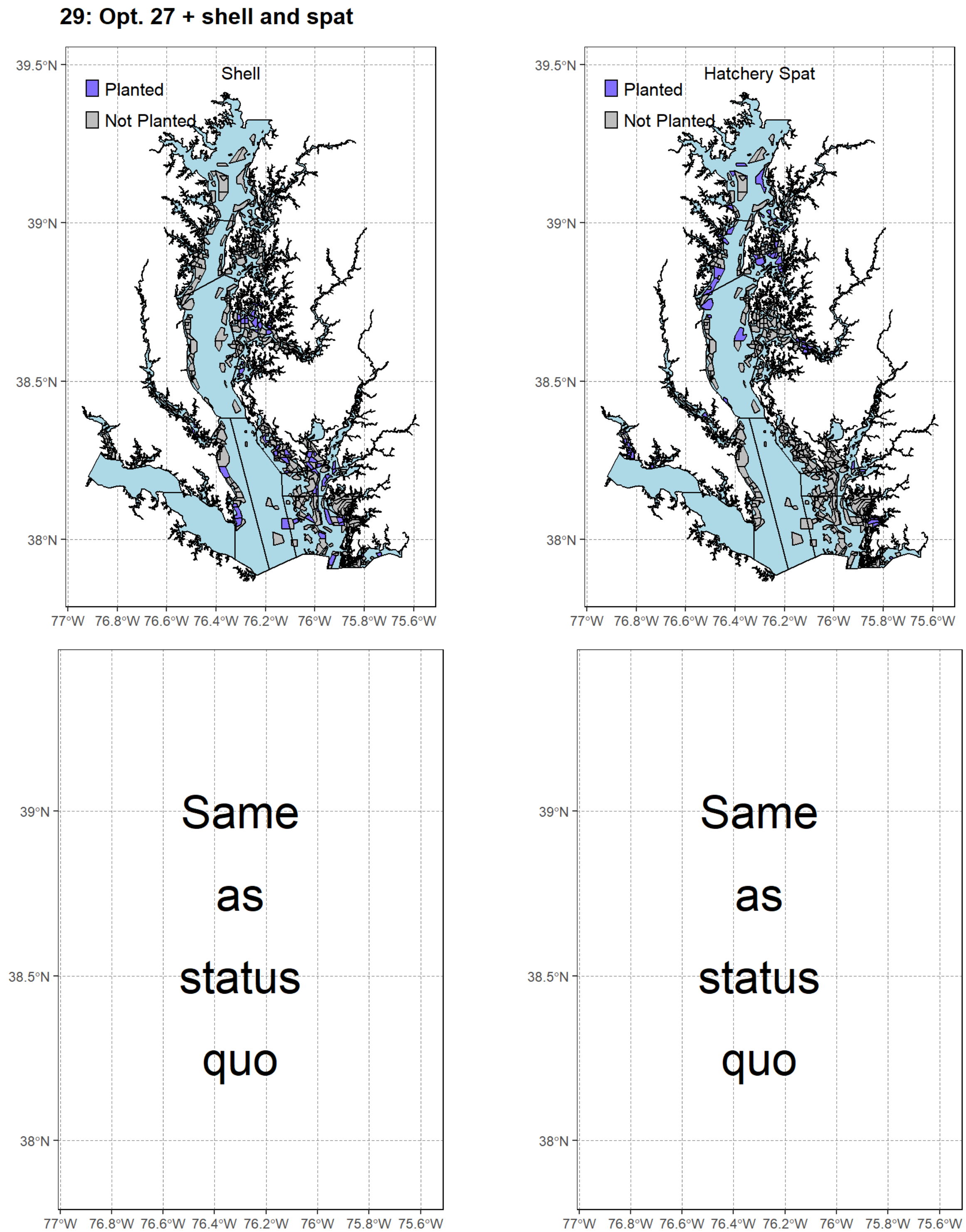

Fig. A57. Locations of shell, hatchery spat, alternate substrate, and wild seed plantings for option 29.

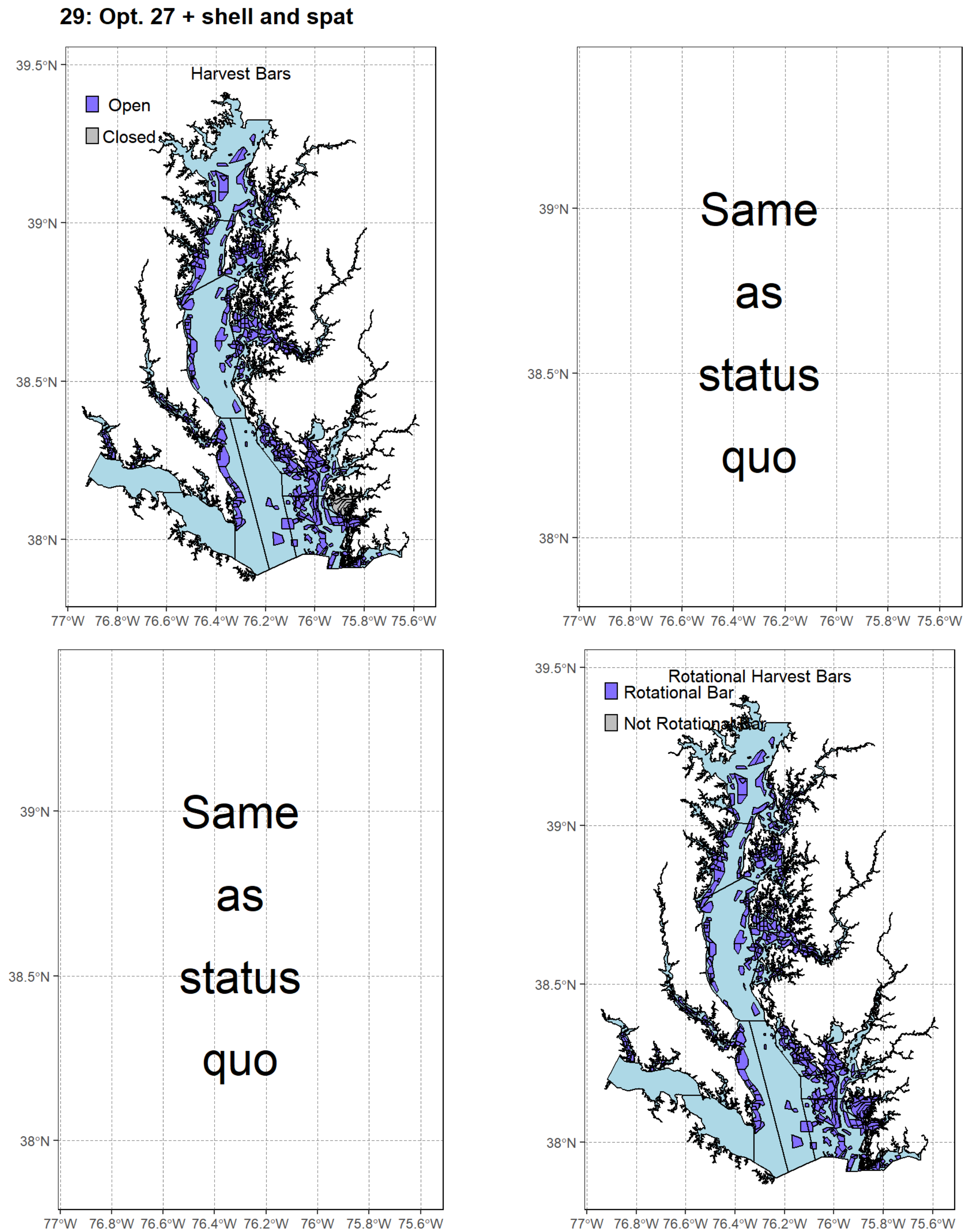

Fig. A58. Bars open to harvest, seed bars, bars open to rotational harvest, and shell dredging bars for option 29.

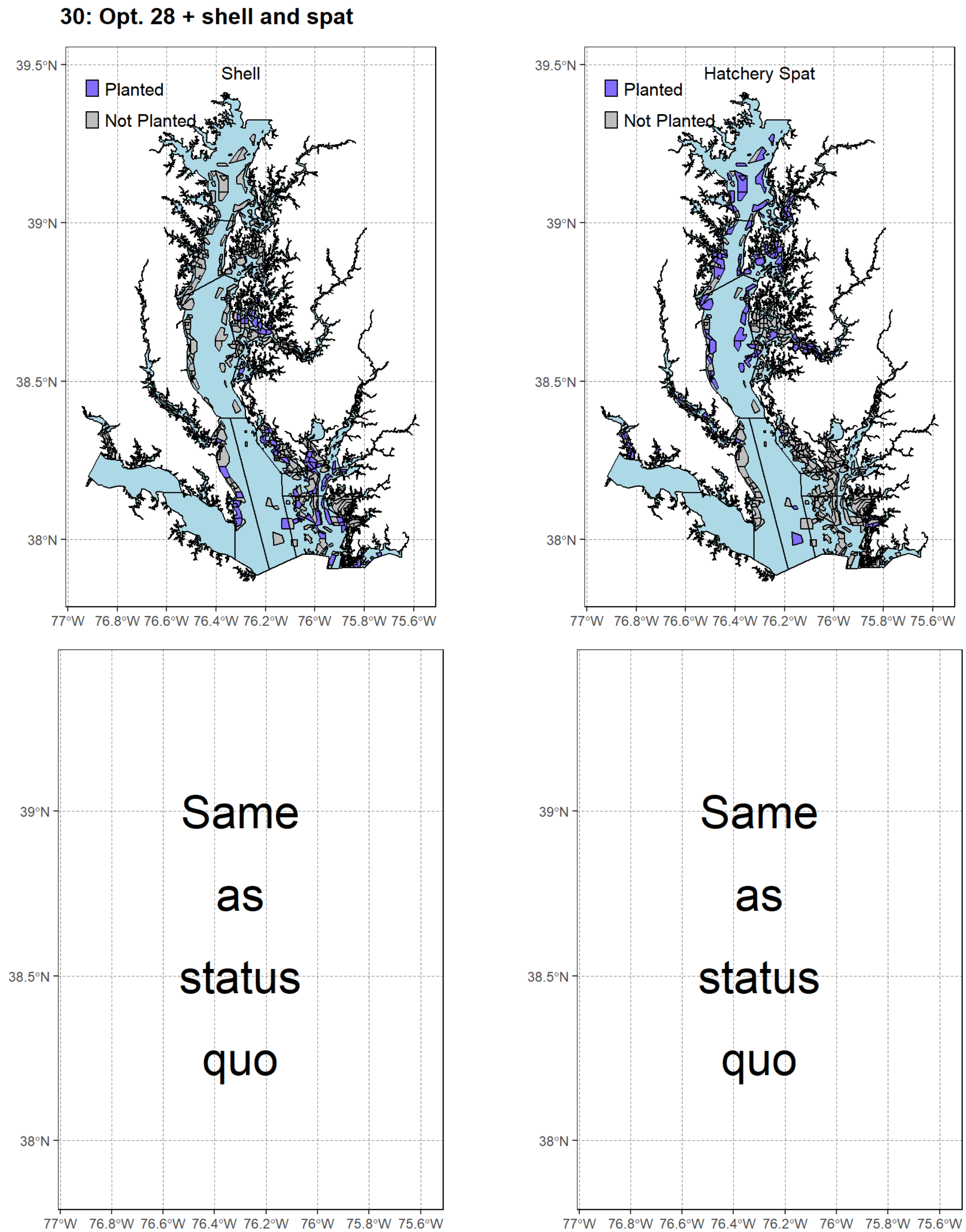

Fig. A59. Locations of shell, hatchery spat, alternate substrate, and wild seed plantings for option 30.

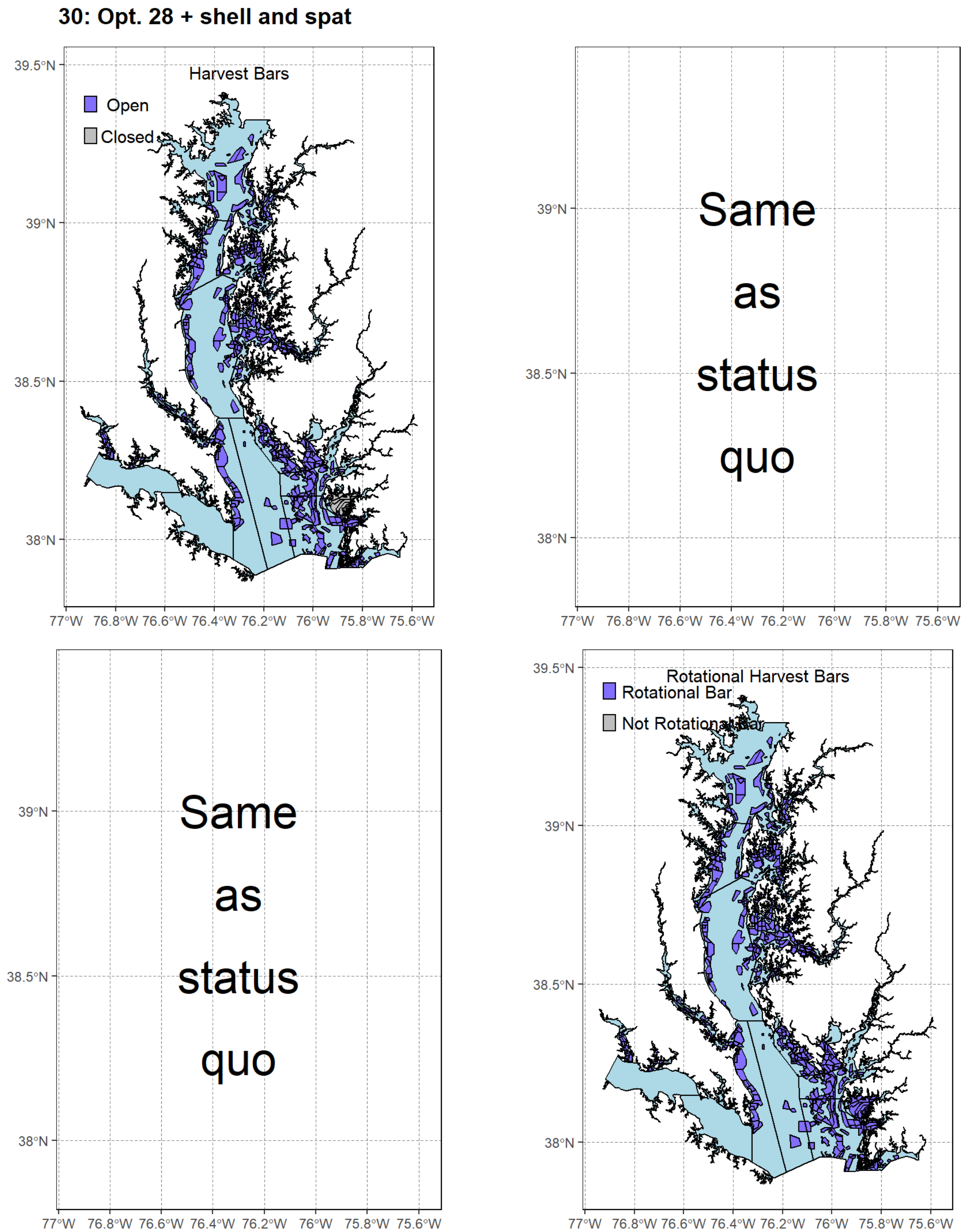

Fig. A60. Bars open to harvest, seed bars, bars open to rotational harvest, and shell dredging bars for option 30.

Fig. A61. Locations of shell, hatchery spat, alternate substrate, and wild seed plantings for option 31.

Fig. A62. Bars open to harvest, seed bars, bars open to rotational harvest, and shell dredging bars for option 31.

Fig. A63. Locations of shell, hatchery spat, alternate substrate, and wild seed plantings for option 32.

Fig. A64. Bars open to harvest, seed bars, bars open to rotational harvest, and shell dredging bars for option 32.

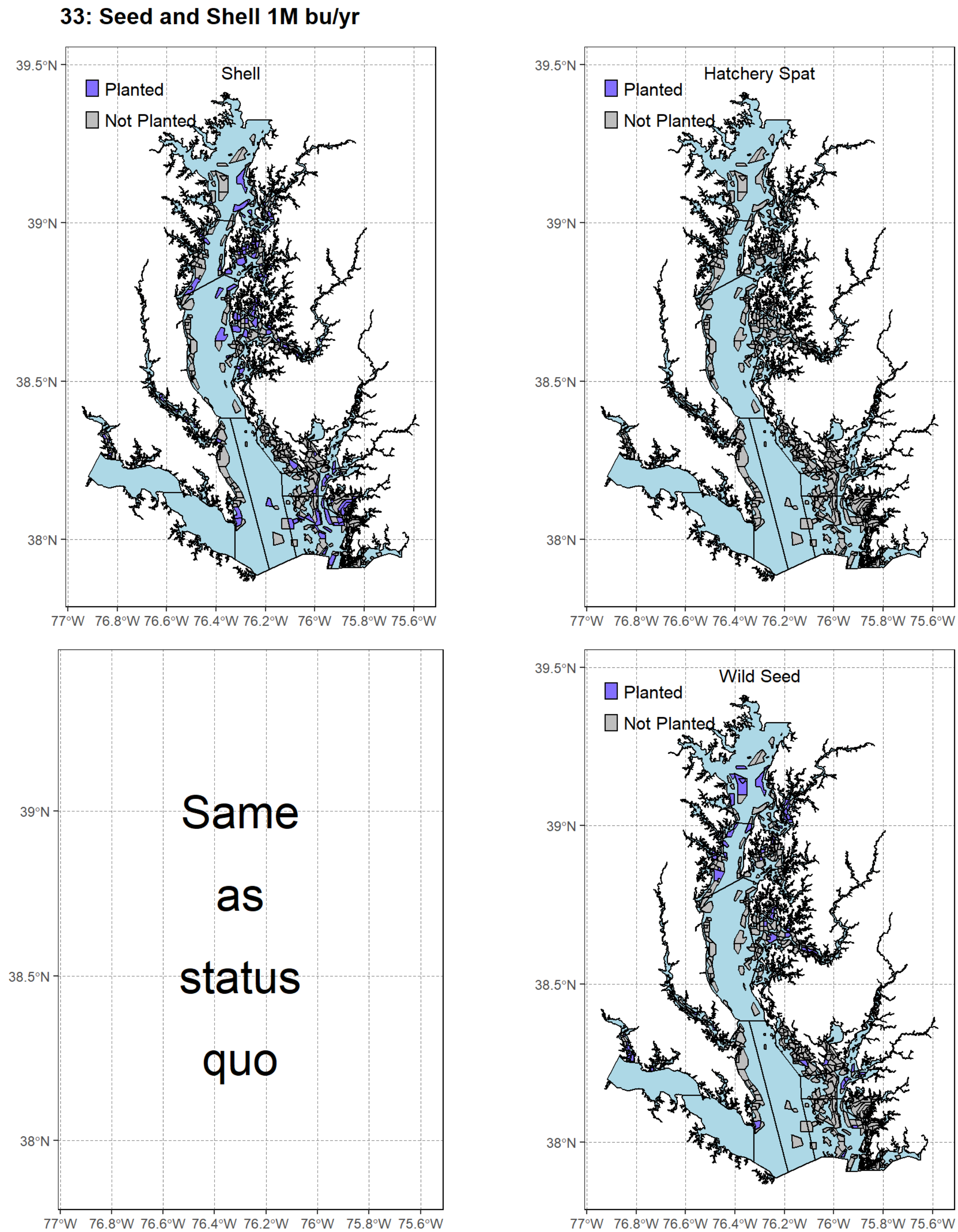

Fig. A65. Locations of shell, hatchery spat, alternate substrate, and wild seed plantings for option 33.

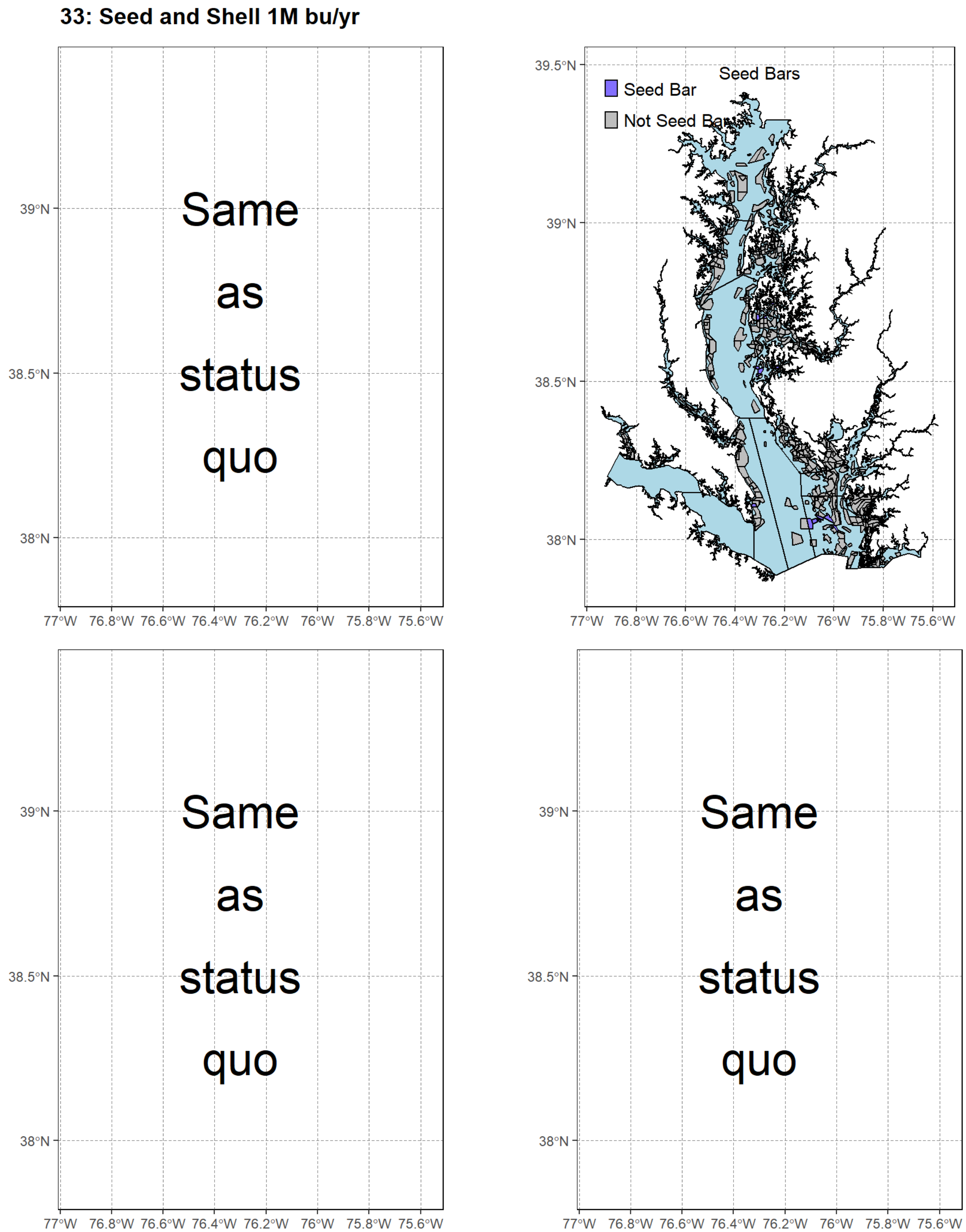

Fig. A66. Bars open to harvest, seed bars, bars open to rotational harvest, and shell dredging bars for option 33.

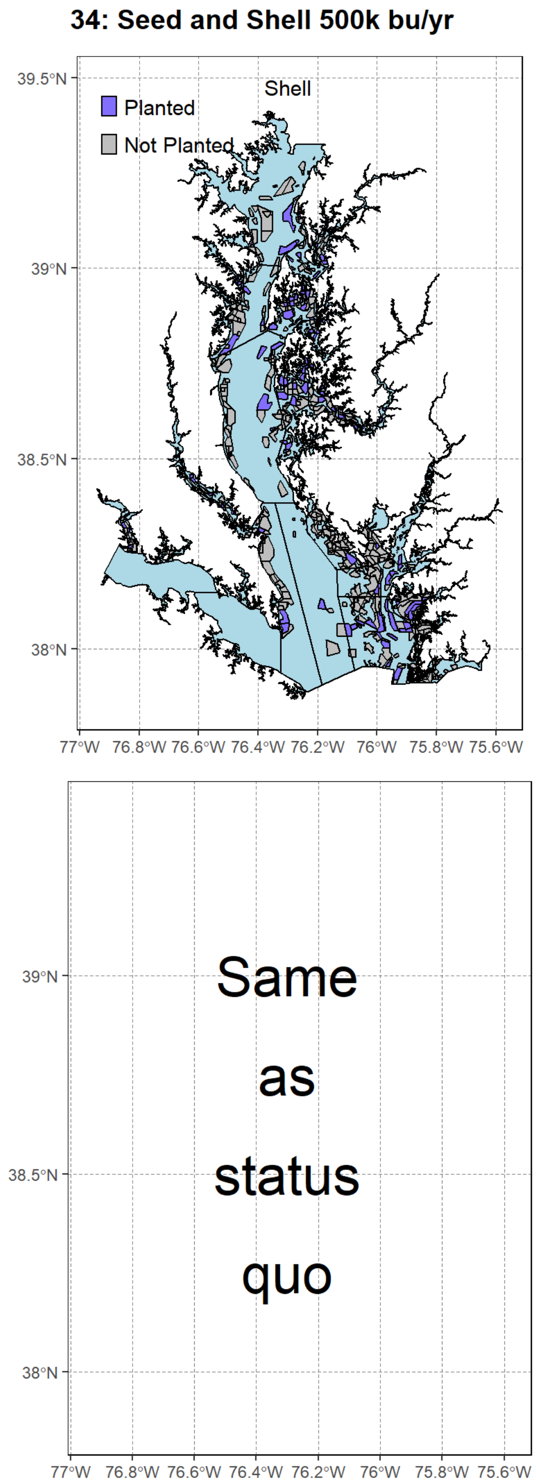

Fig. A67. Locations of shell, hatchery spat, alternate substrate, and wild seed plantings for option 34.

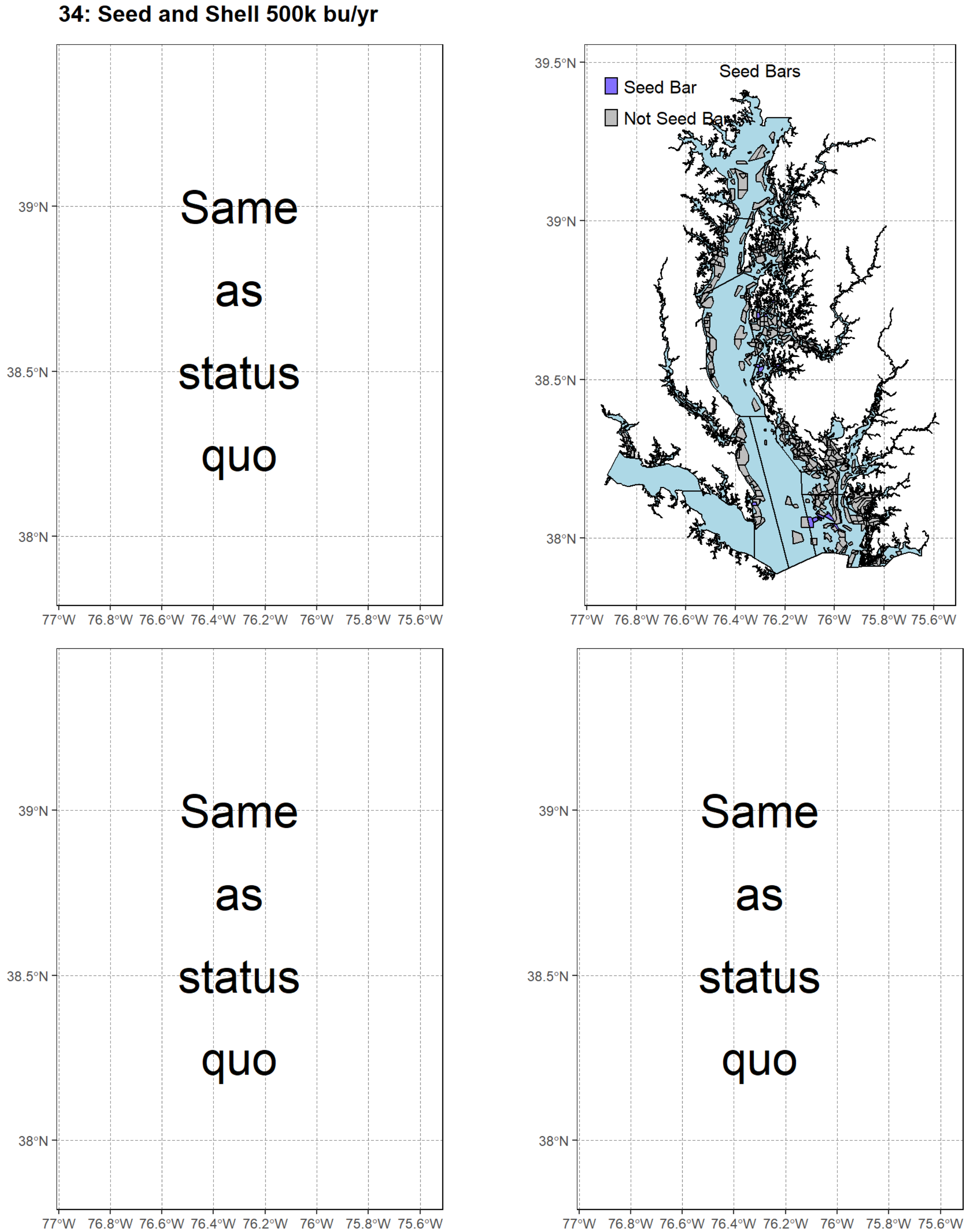

Fig. A68. Bars open to harvest, seed bars, bars open to rotational harvest, and shell dredging bars for option 34.

35: 14.a - 14 except using shell as substrate

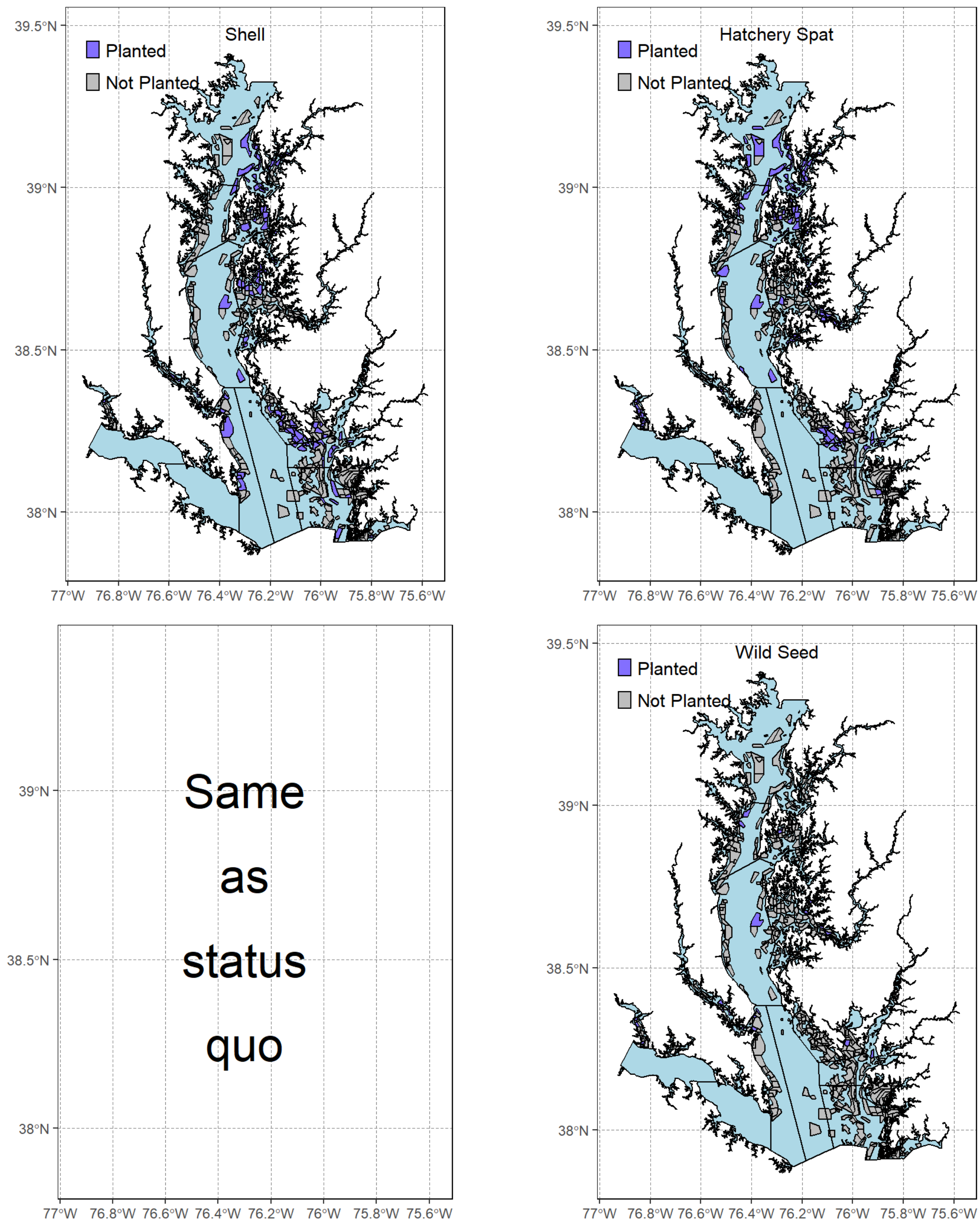

Fig. A69. Locations of shell, hatchery spat, alternate substrate, and wild seed plantings for option 35.

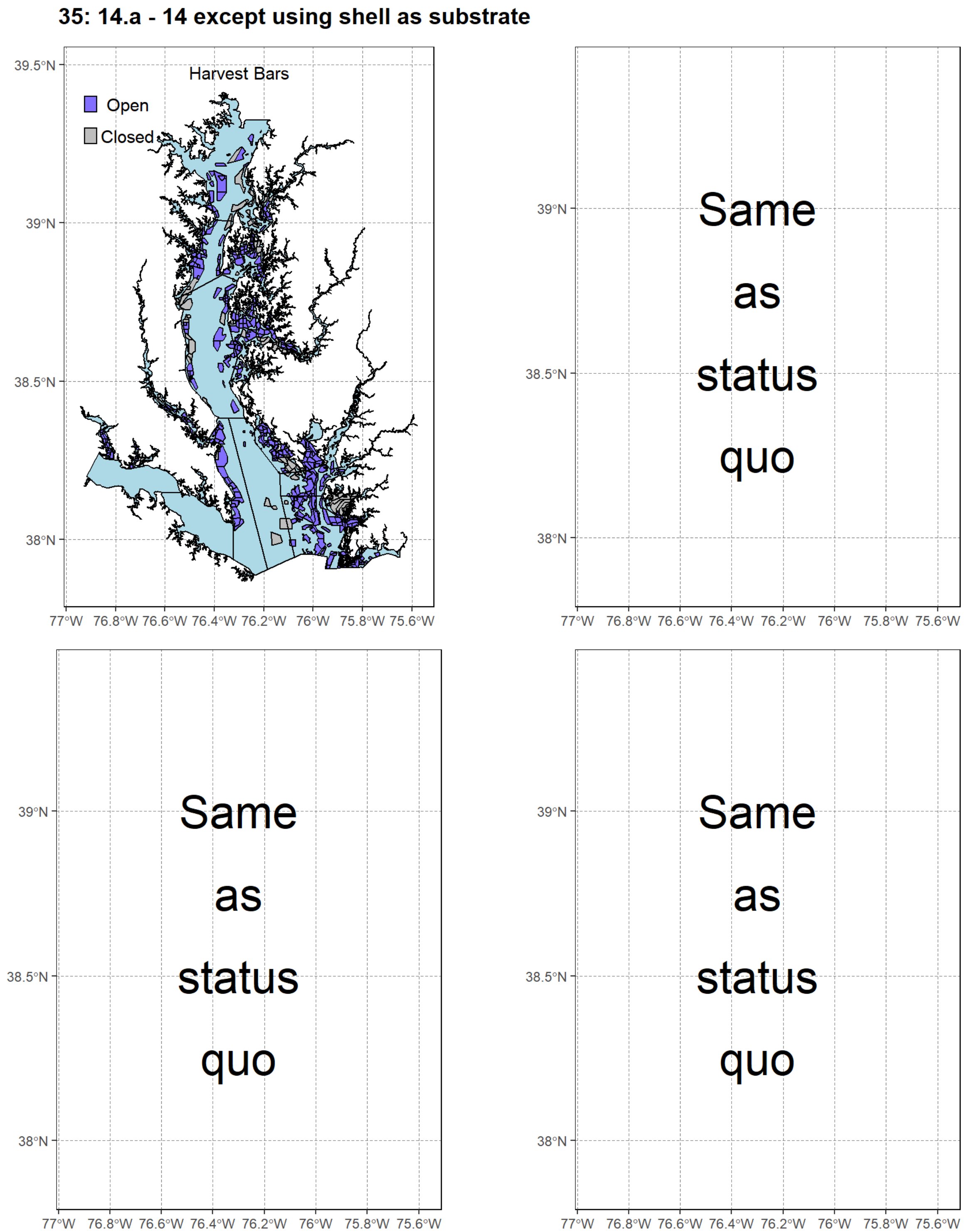

Fig. A70. Bars open to harvest, seed bars, bars open to rotational harvest, and shell dredging bars for option 35.

36: 15.a - 15 except using shell as substrate

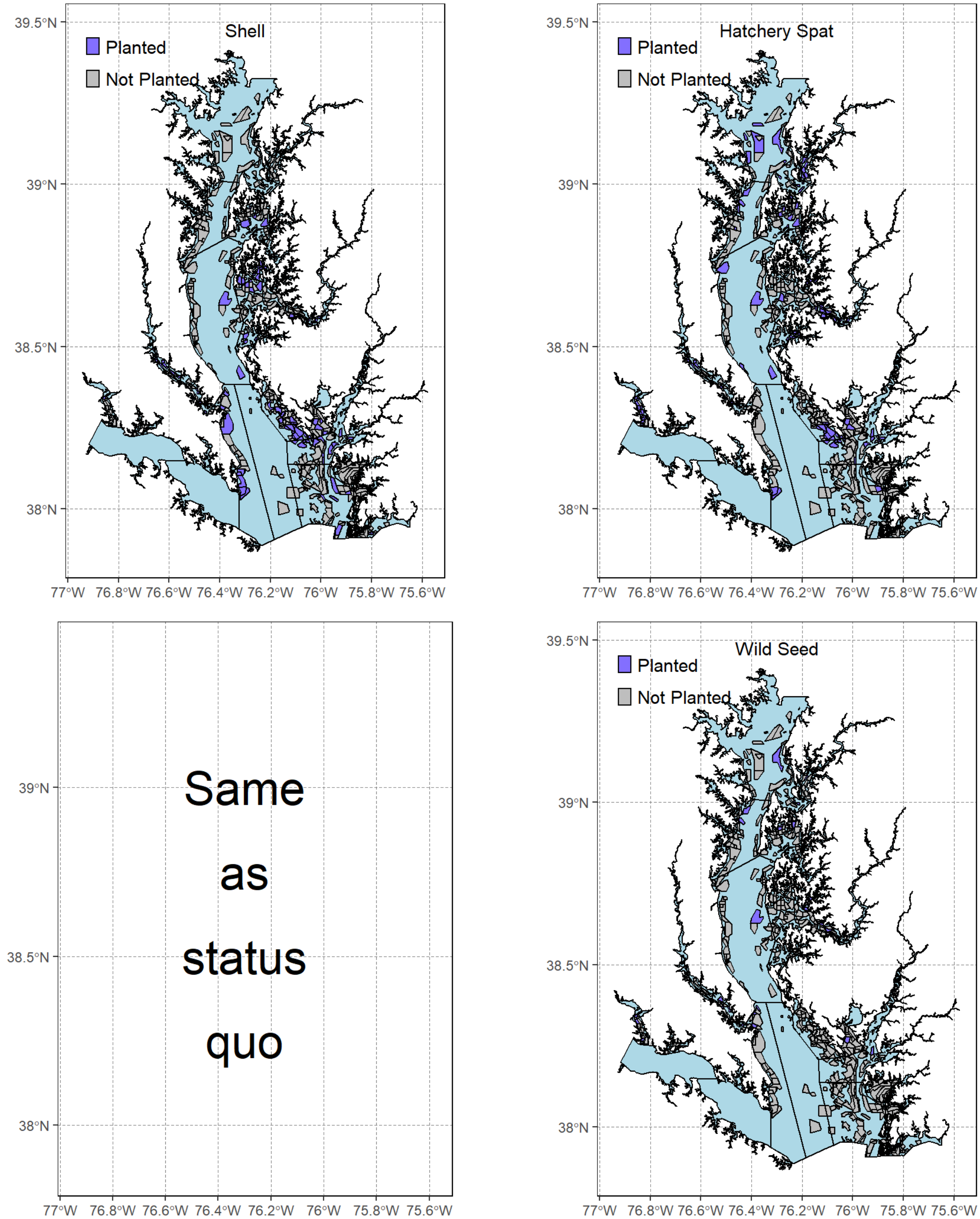

Fig. A71. Locations of shell, hatchery spat, alternate substrate, and wild seed plantings for option 36.

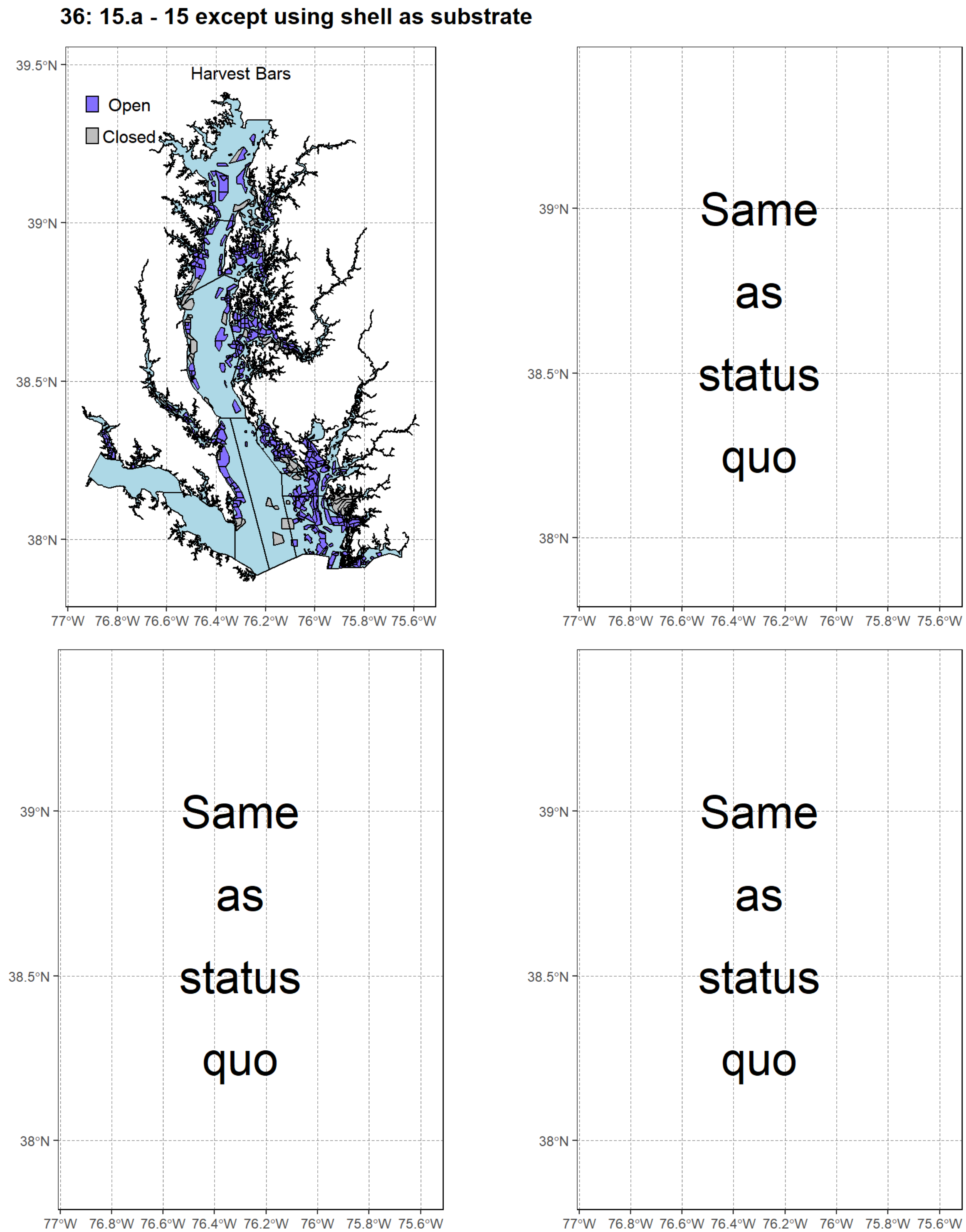

Fig. A72. Bars open to harvest, seed bars, bars open to rotational harvest, and shell dredging bars for option 36.

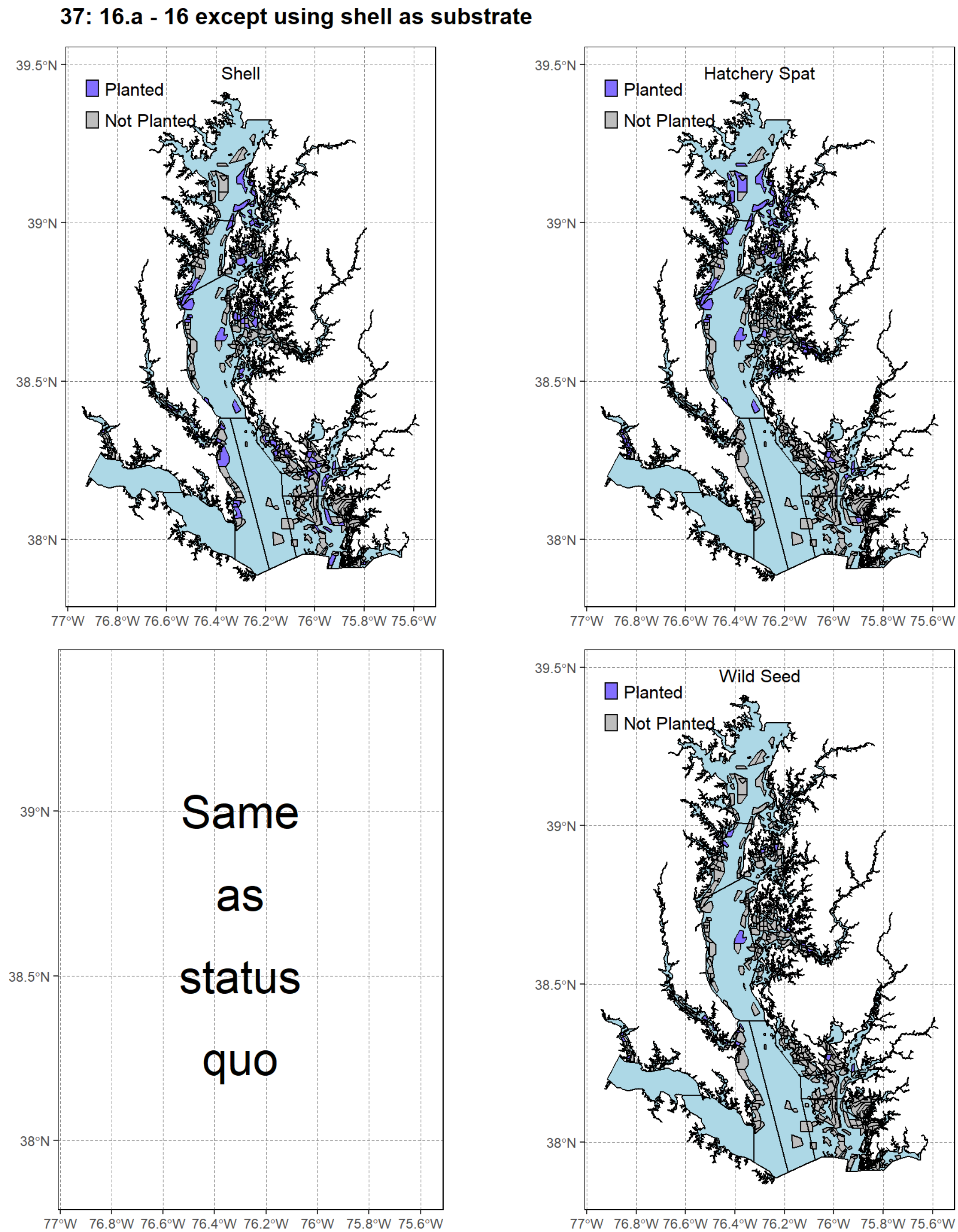

Fig. A73. Locations of shell, hatchery spat, alternate substrate, and wild seed plantings for option 37.

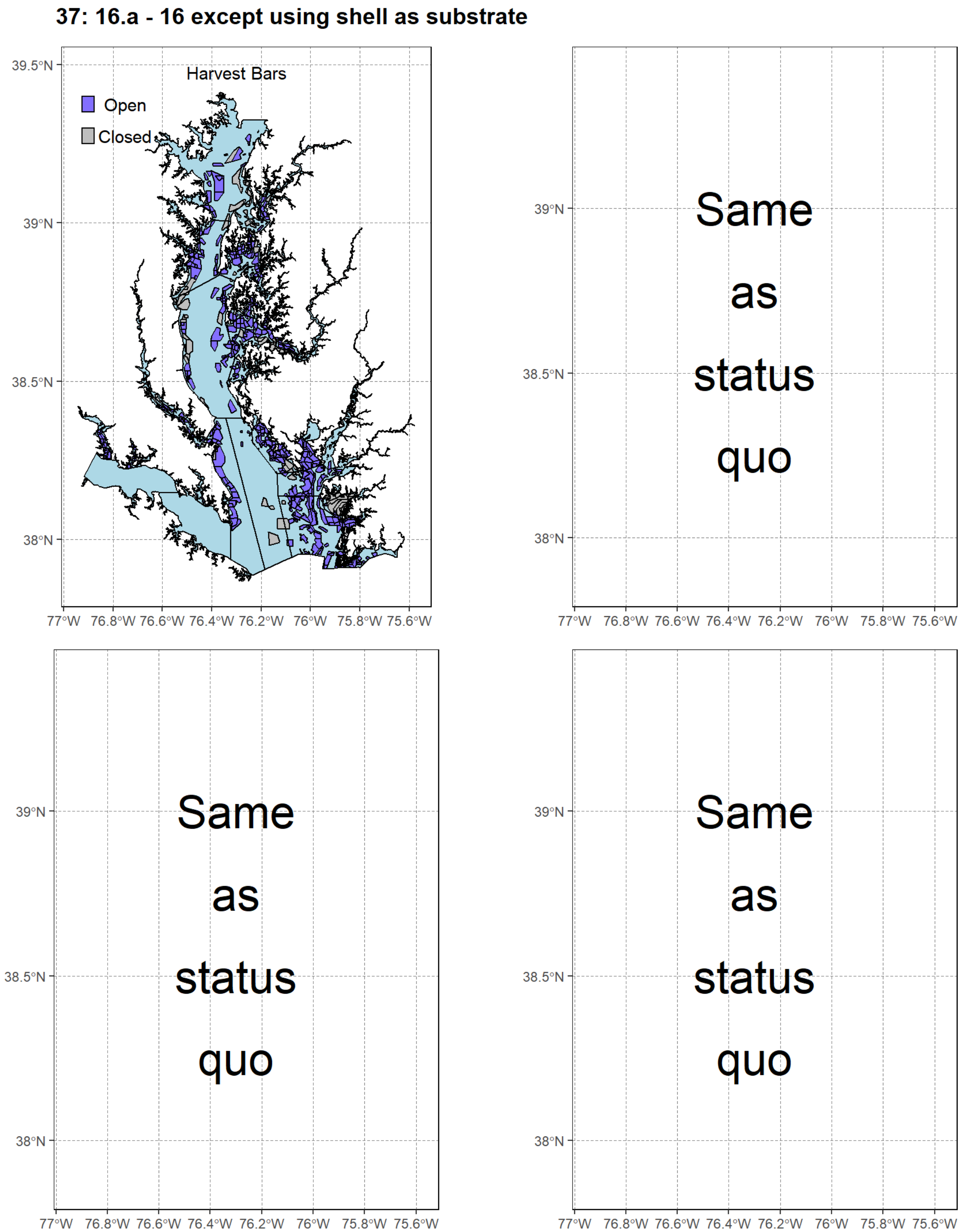

Fig. A74. Bars open to harvest, seed bars, bars open to rotational harvest, and shell dredging bars for option 37.

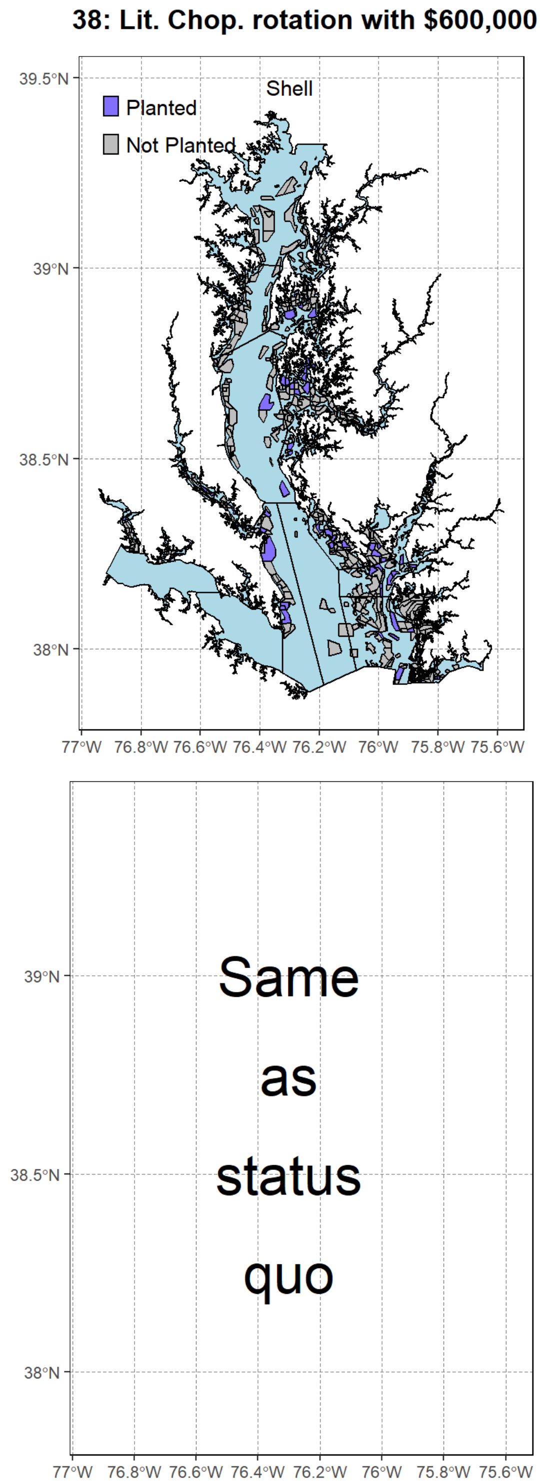

Fig. A75. Locations of shell, hatchery spat, alternate substrate, and wild seed plantings for option 38.

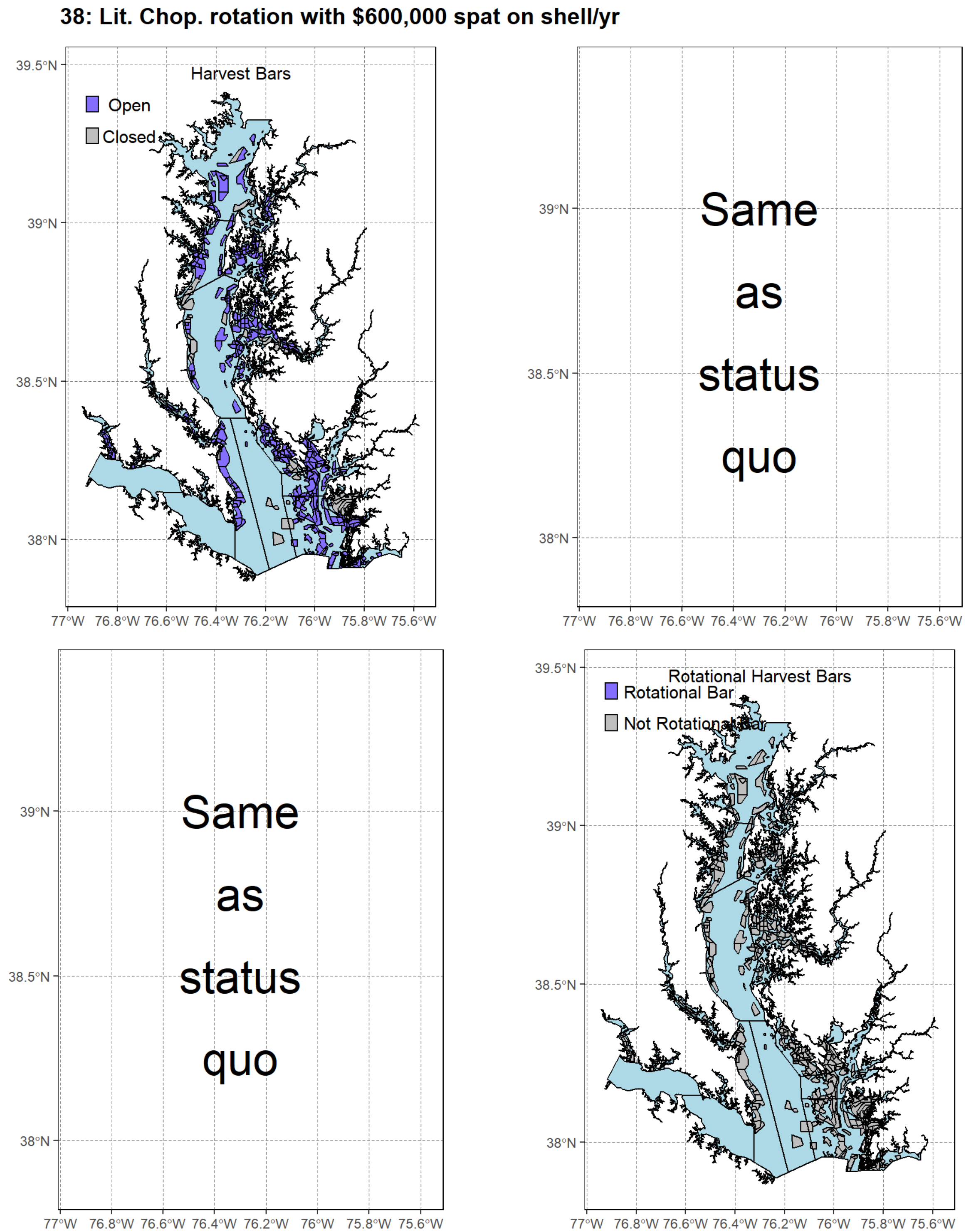

Fig. A76. Bars open to harvest, seed bars, bars open to rotational harvest, and shell dredging bars for option 38.

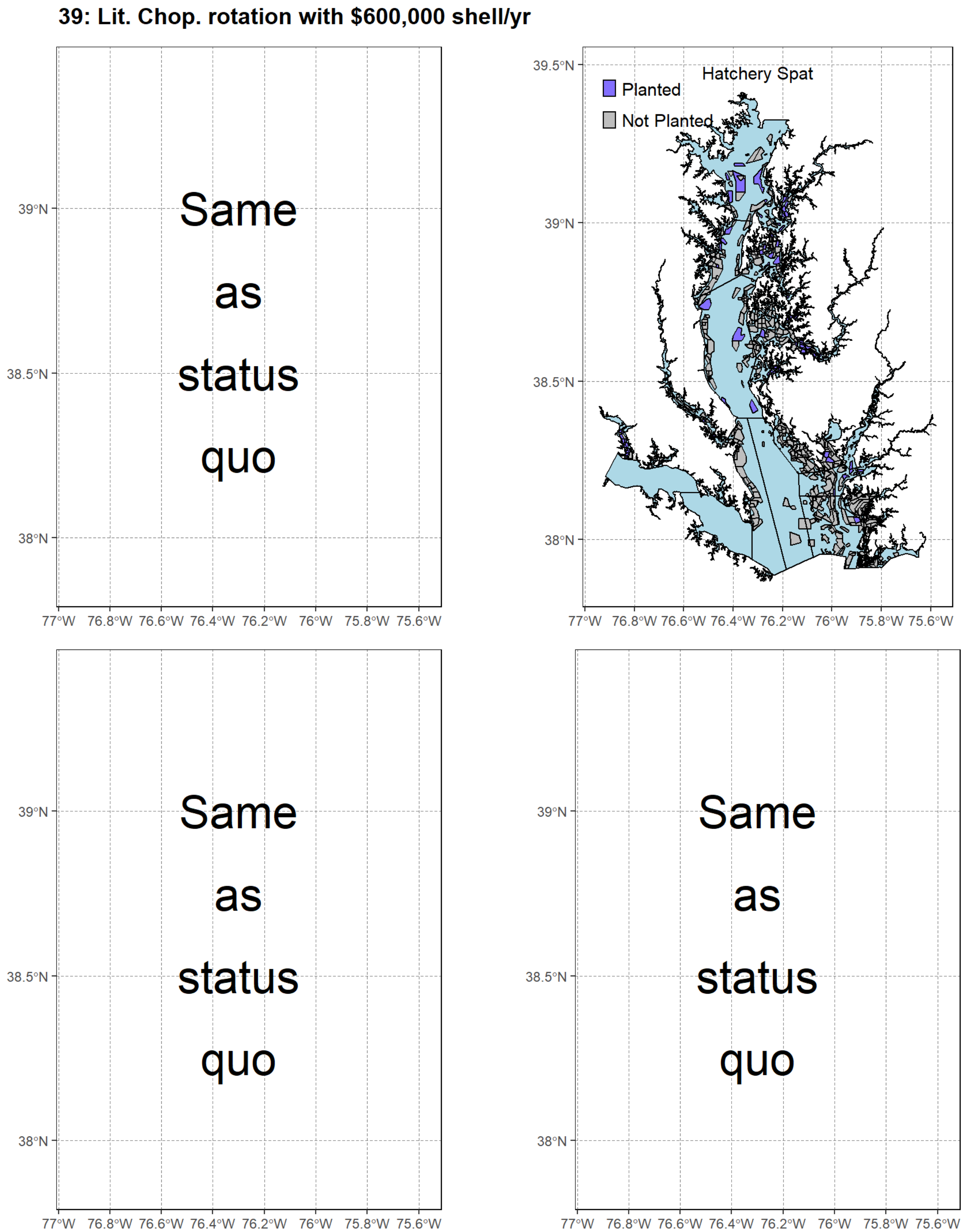

Fig. A77. Locations of shell, hatchery spat, alternate substrate, and wild seed plantings for option 39.

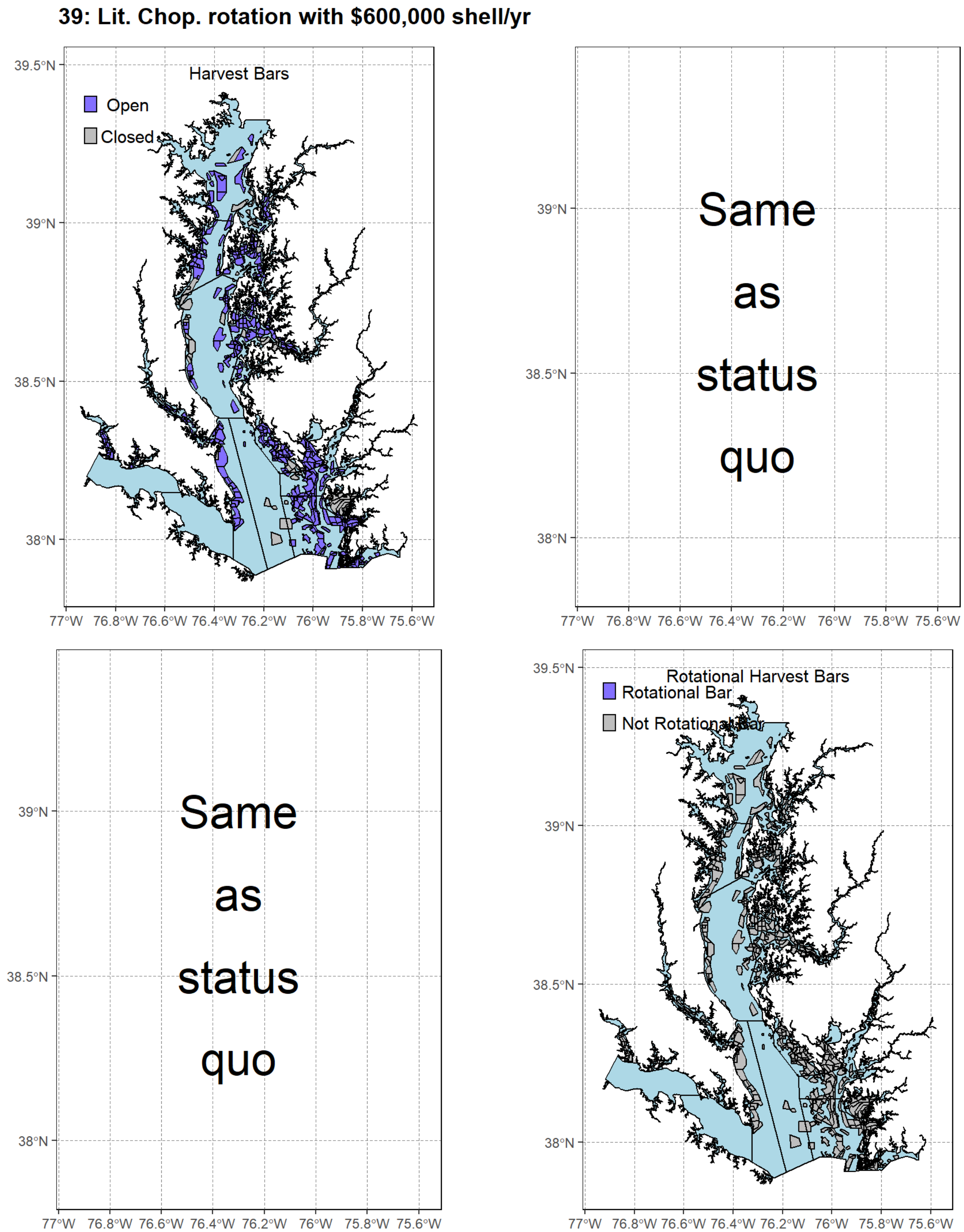

Fig. A78. Bars open to harvest, seed bars, bars open to rotational harvest, and shell dredging bars for option 39.

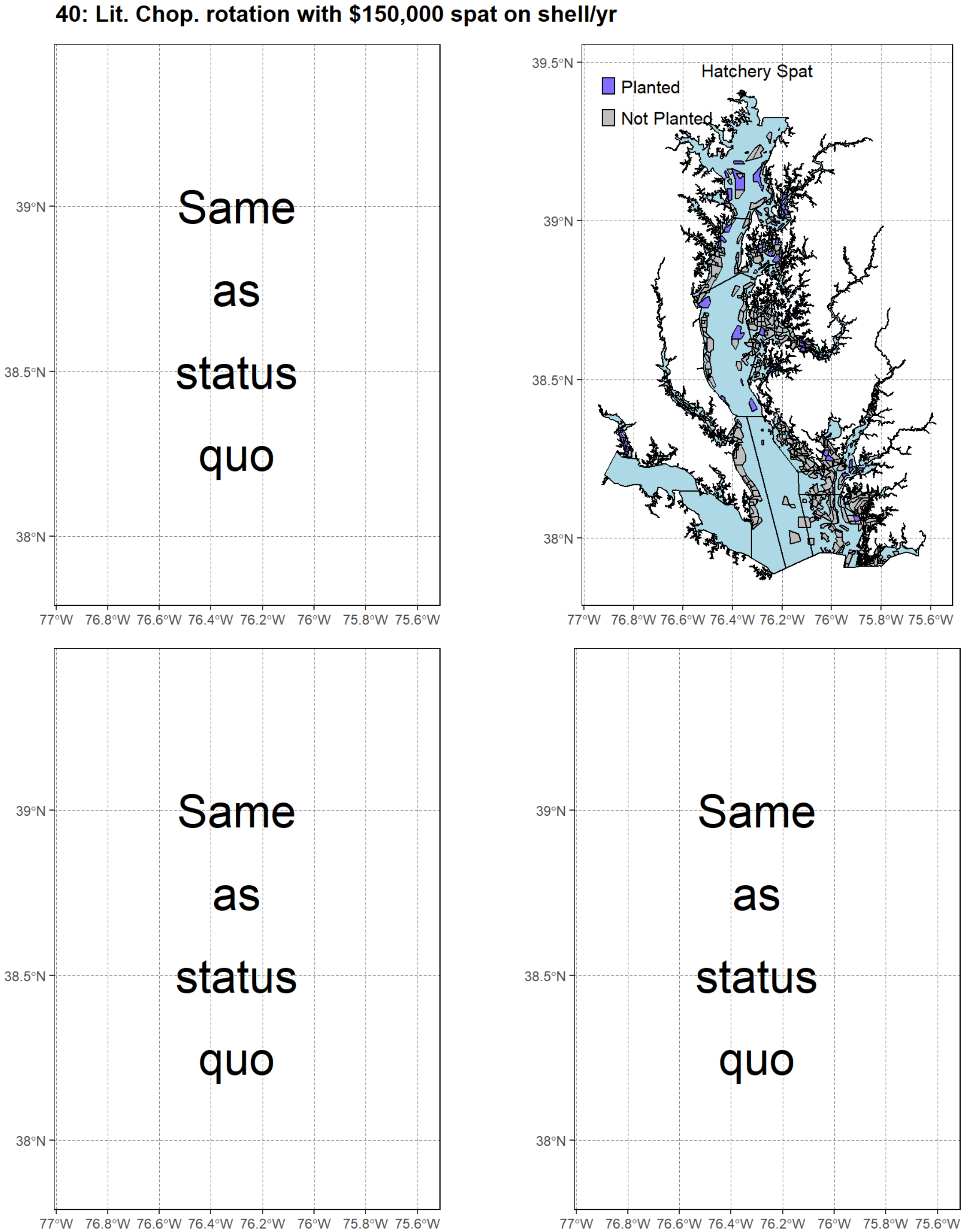

Fig. A79. Locations of shell, hatchery spat, alternate substrate, and wild seed plantings for option 40.

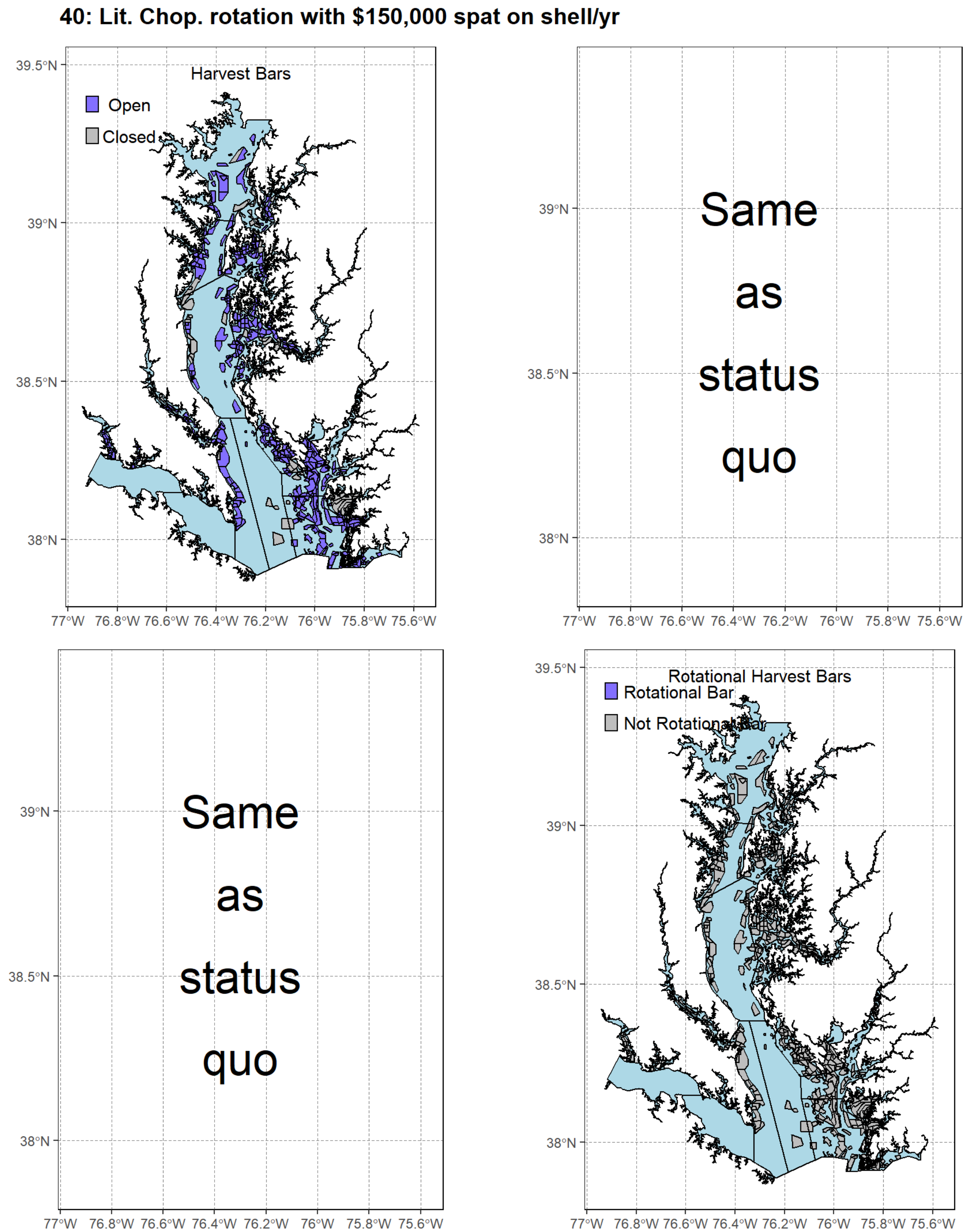

Fig. A80. Bars open to harvest, seed bars, bars open to rotational harvest, and shell dredging bars for option 40.

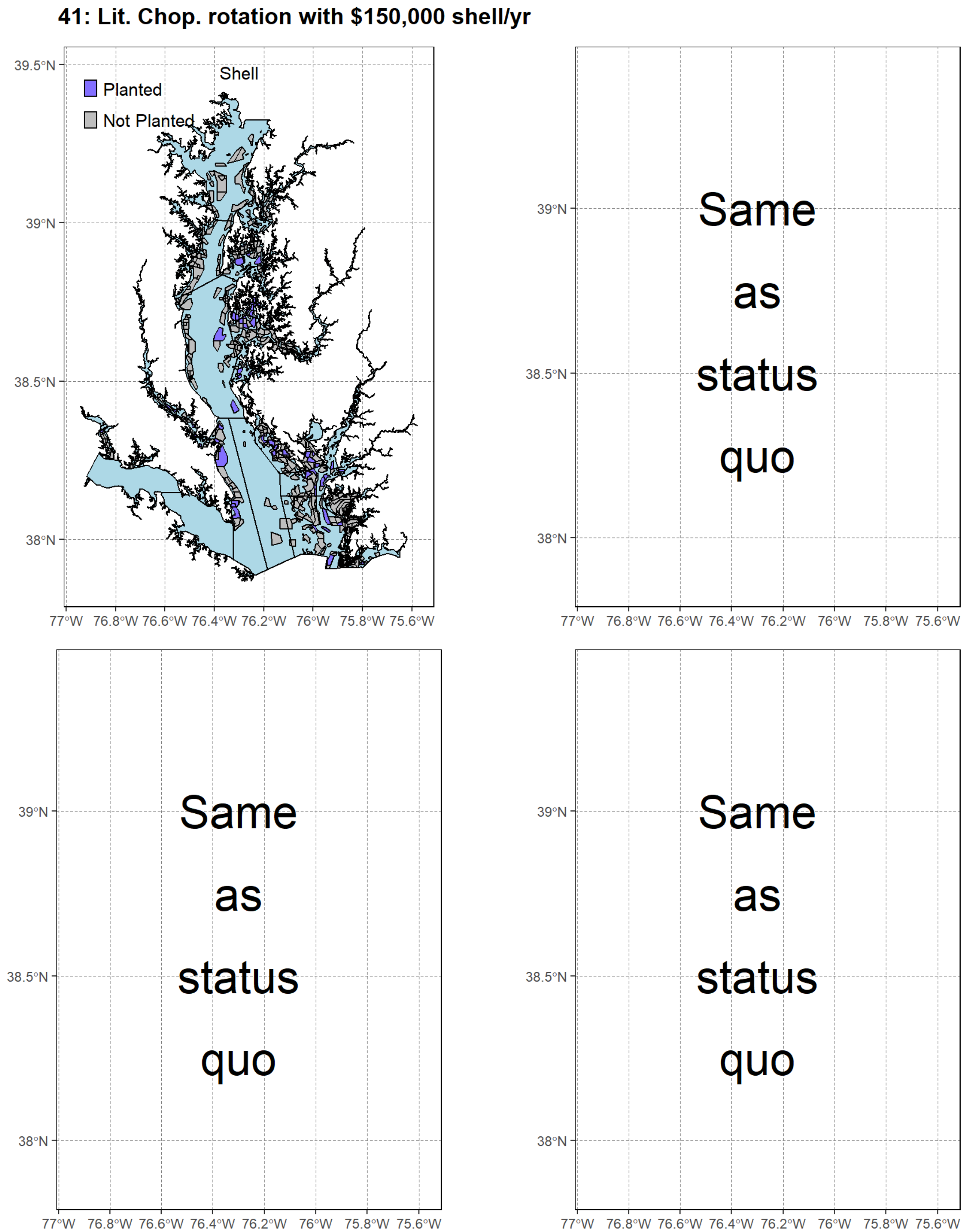

Fig. A81. Locations of shell, hatchery spat, alternate substrate, and wild seed plantings for option 41.

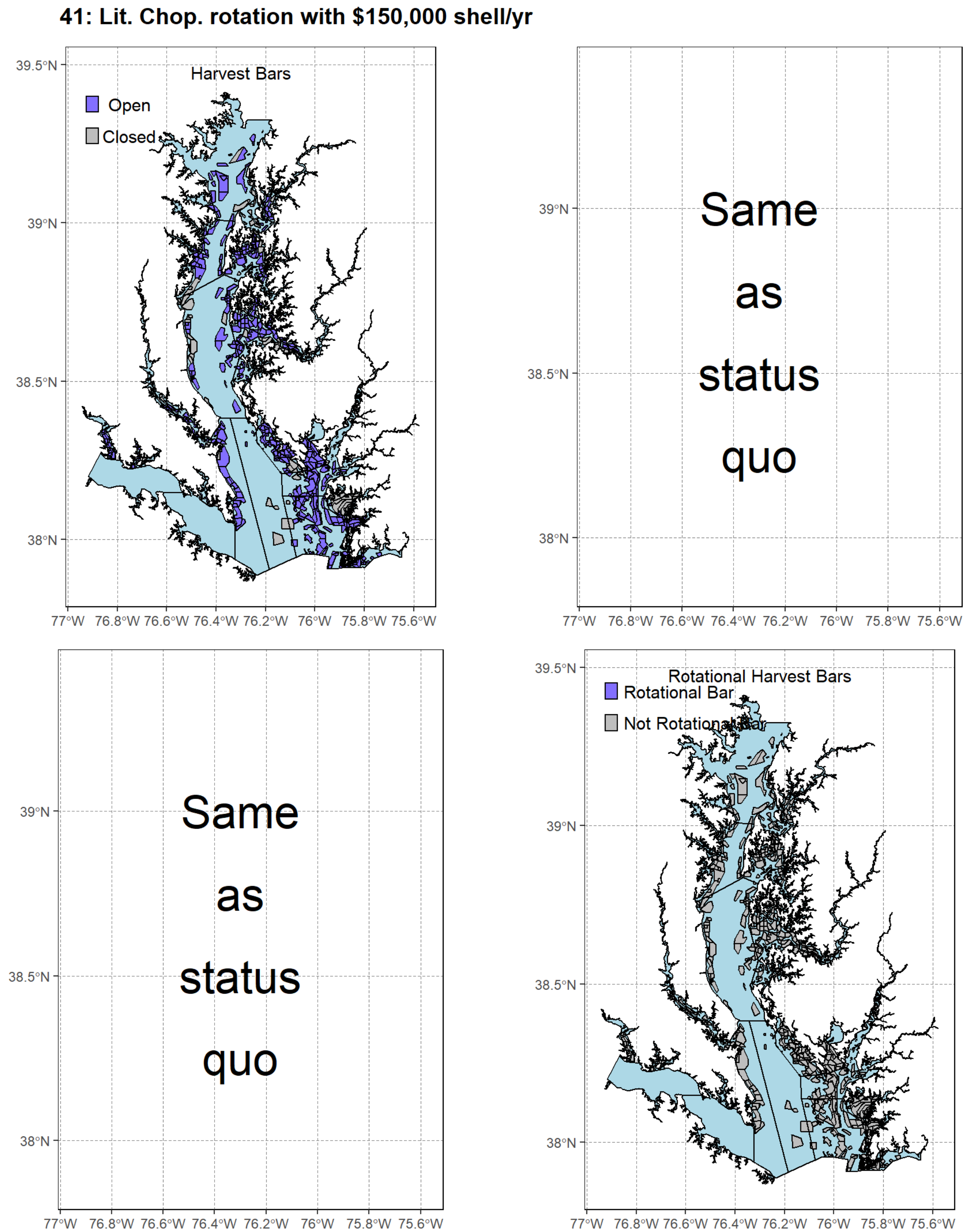

Fig. A82. Bars open to harvest, seed bars, bars open to rotational harvest, and shell dredging bars for option 41.

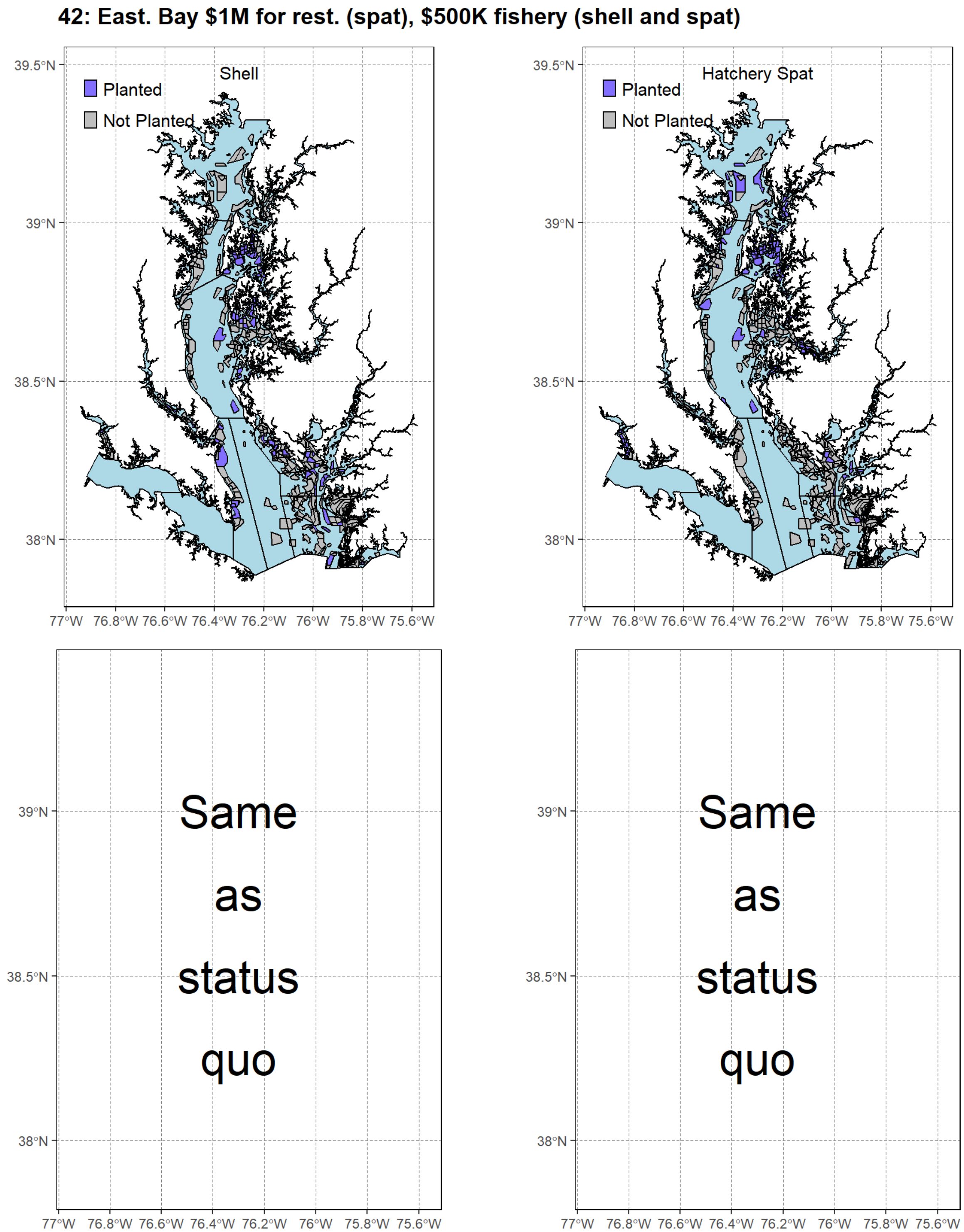

Fig. A83. Locations of shell, hatchery spat, alternate substrate, and wild seed plantings for option 42.

Fig. A84. Bars open to harvest, seed bars, bars open to rotational harvest, and shell dredging bars for option 42.

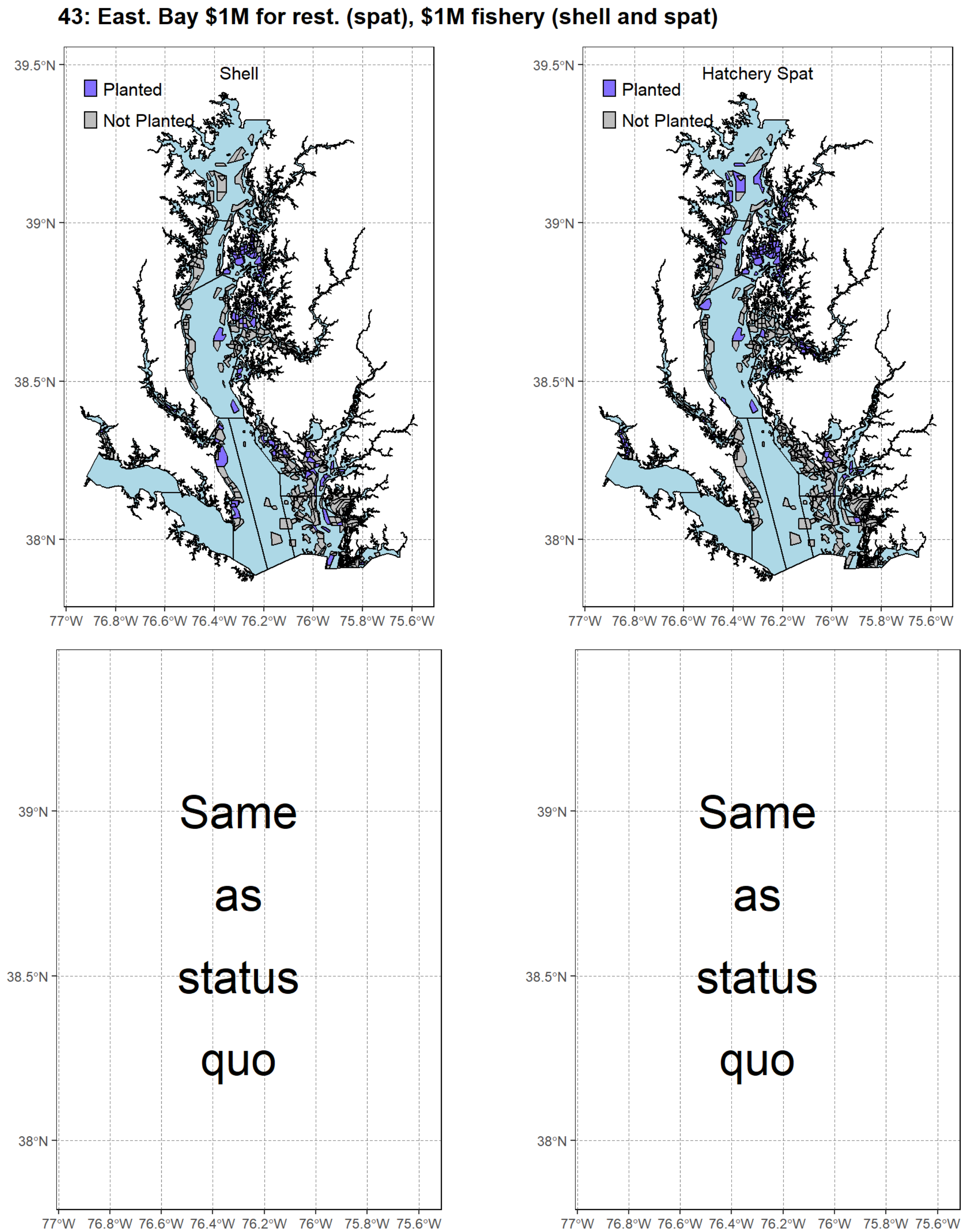

Fig. A85. Locations of shell, hatchery spat, alternate substrate, and wild seed plantings for option 43.

Fig. A86. Bars open to harvest, seed bars, bars open to rotational harvest, and shell dredging bars for option 43.

44: Combo 19 + 3

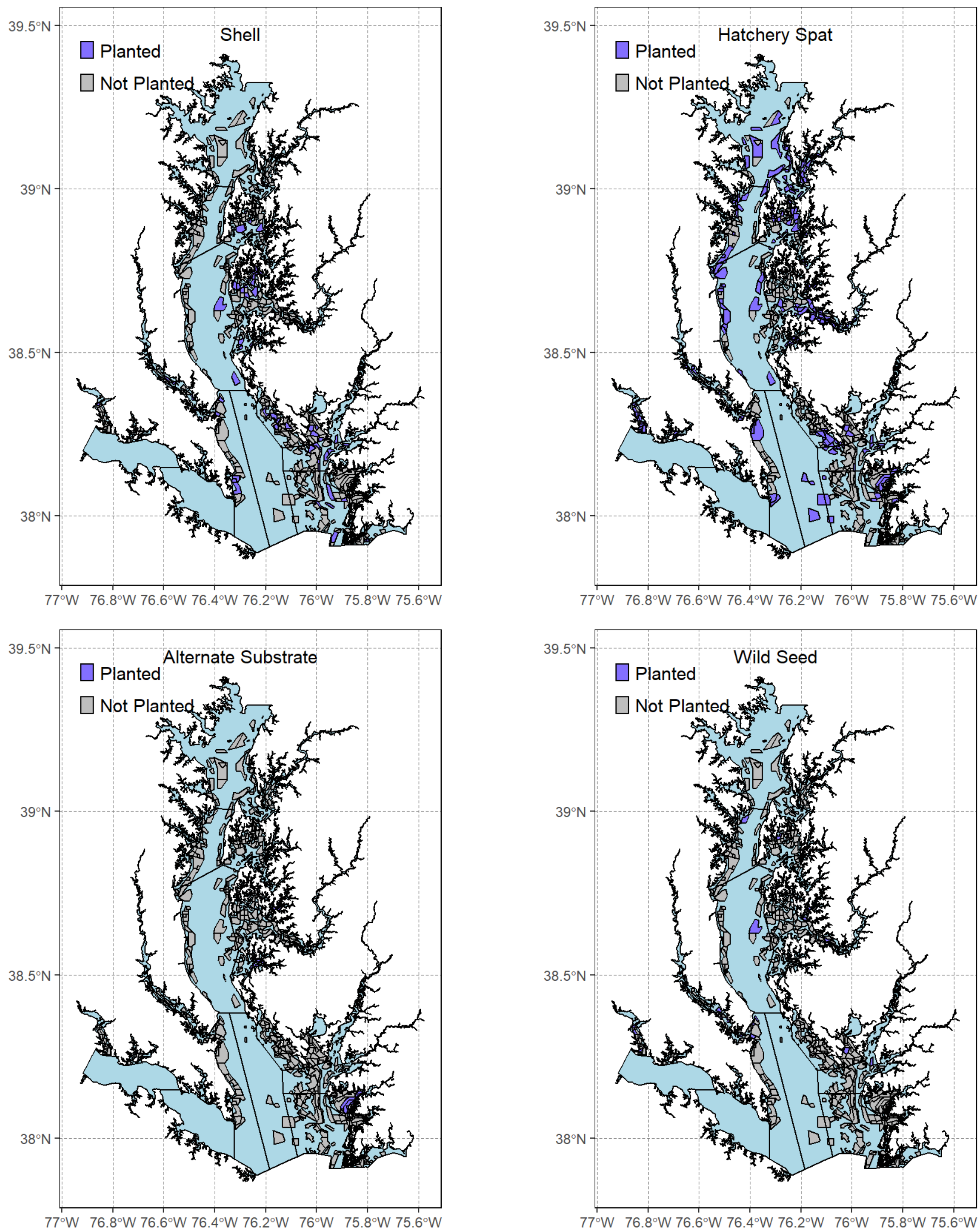

Fig. A87. Locations of shell, hatchery spat, alternate substrate, and wild seed plantings for option 44.

44: Combo 19 + 3

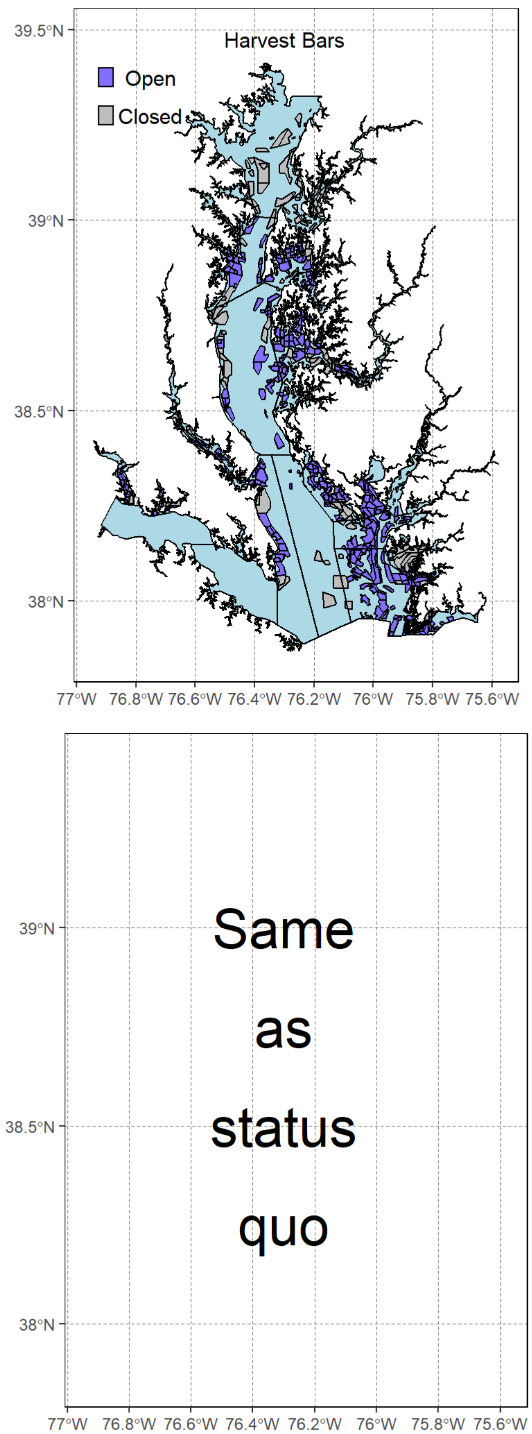

Fig. A88. Bars open to harvest, seed bars, bars open to rotational harvest, and shell dredging bars for option 44.

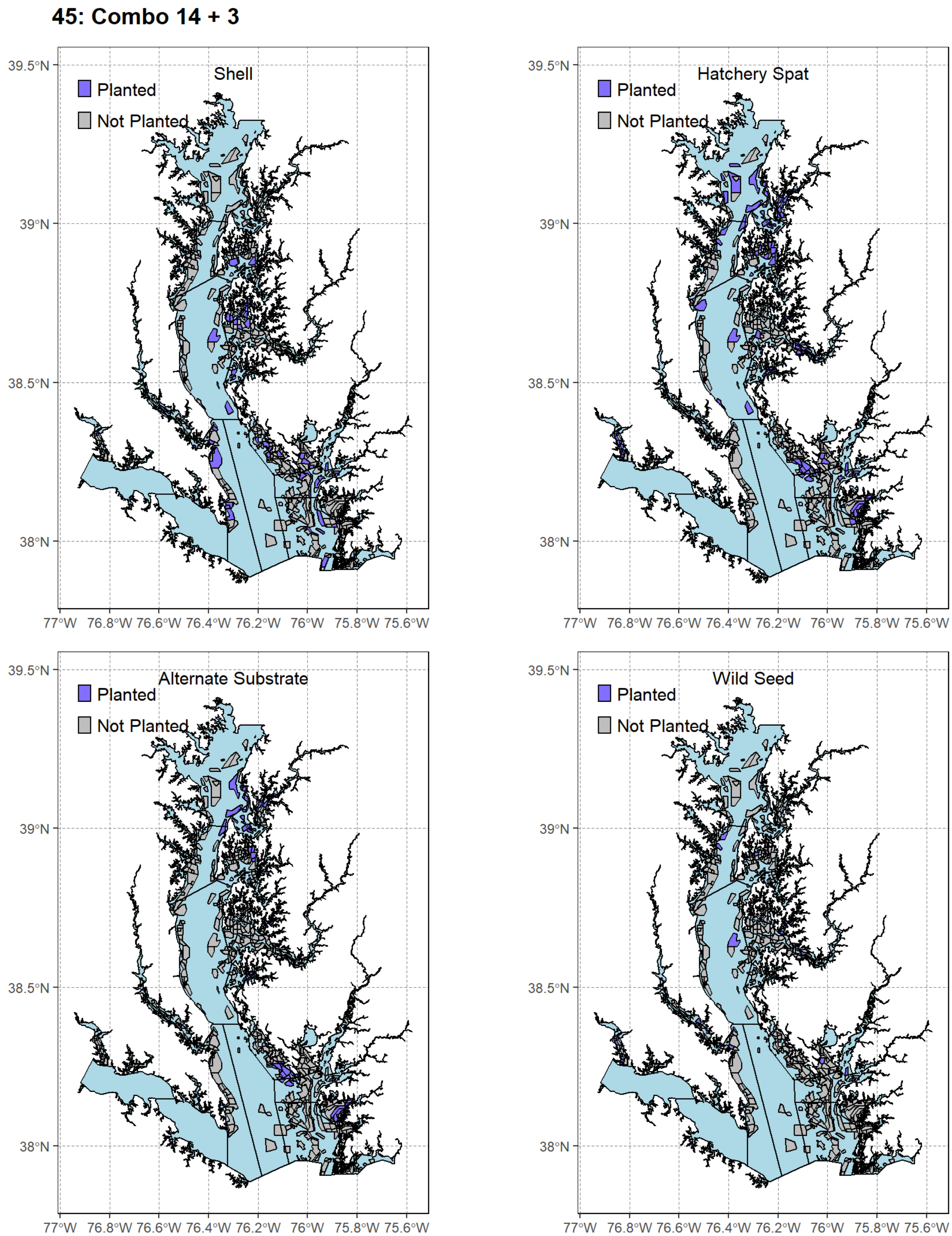

Fig. A89. Locations of shell, hatchery spat, alternate substrate, and wild seed plantings for option 45.

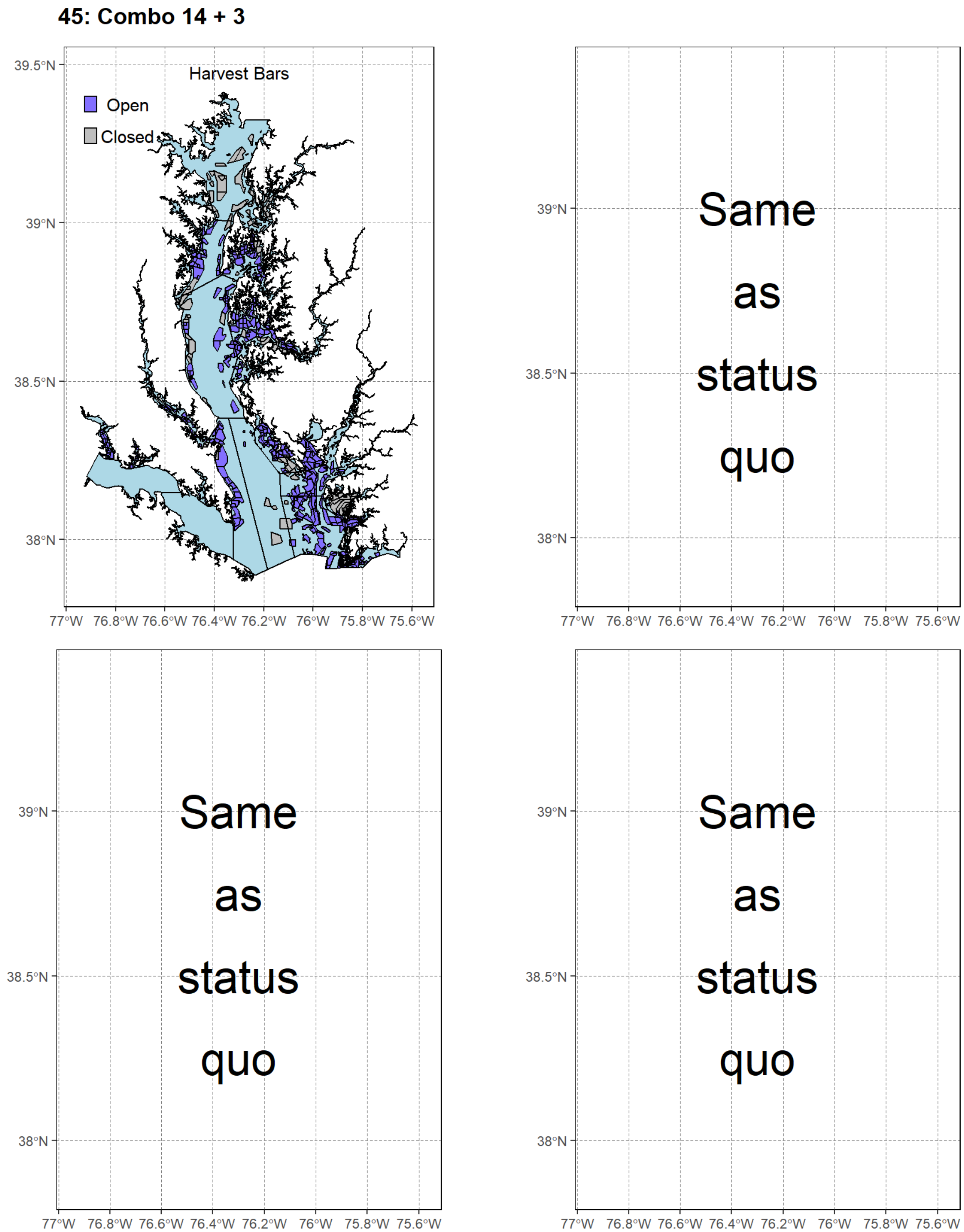

Fig. A90. Bars open to harvest, seed bars, bars open to rotational harvest, and shell dredging bars for option 45.

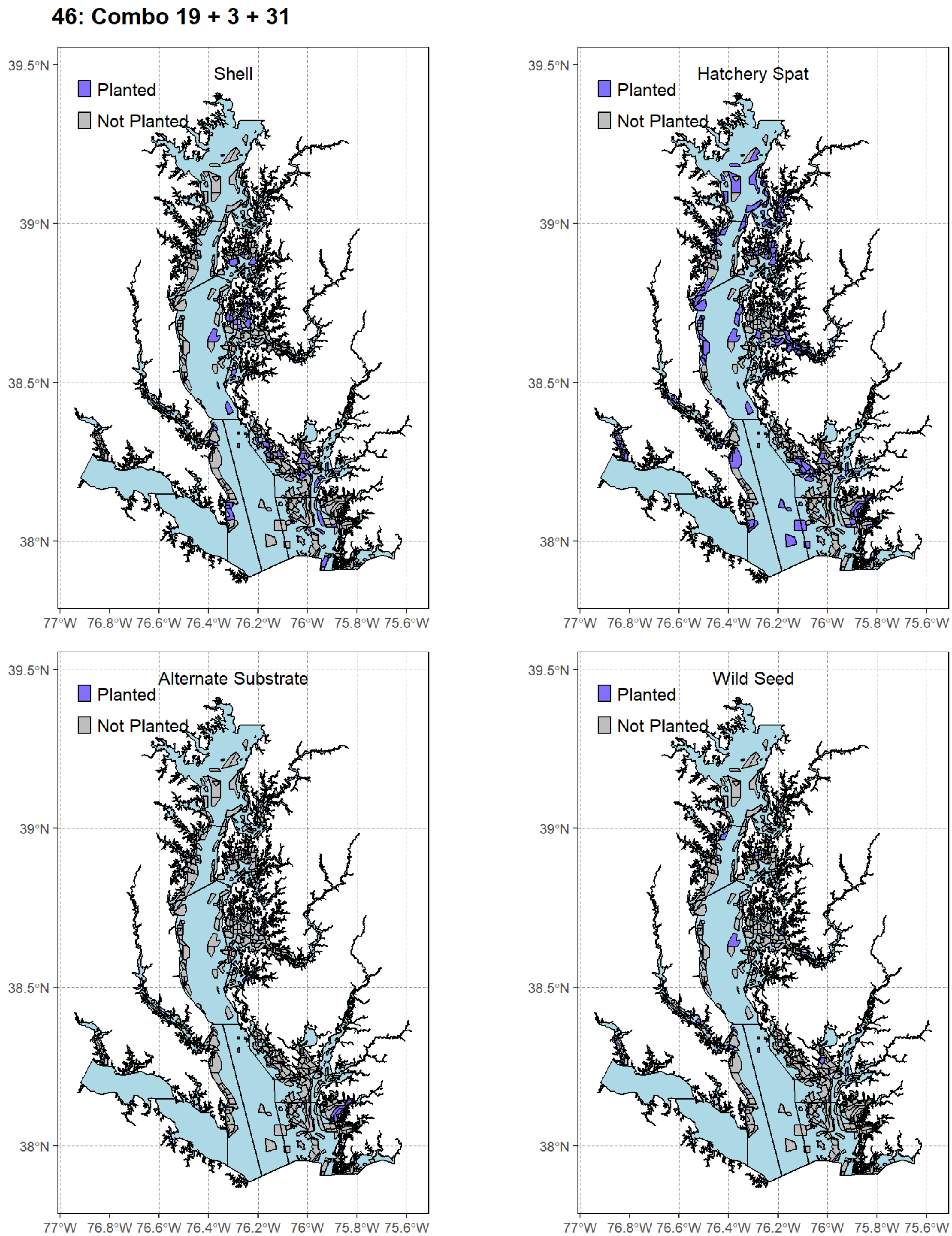

Fig. A91. Locations of shell, hatchery spat, alternate substrate, and wild seed plantings for option 46.

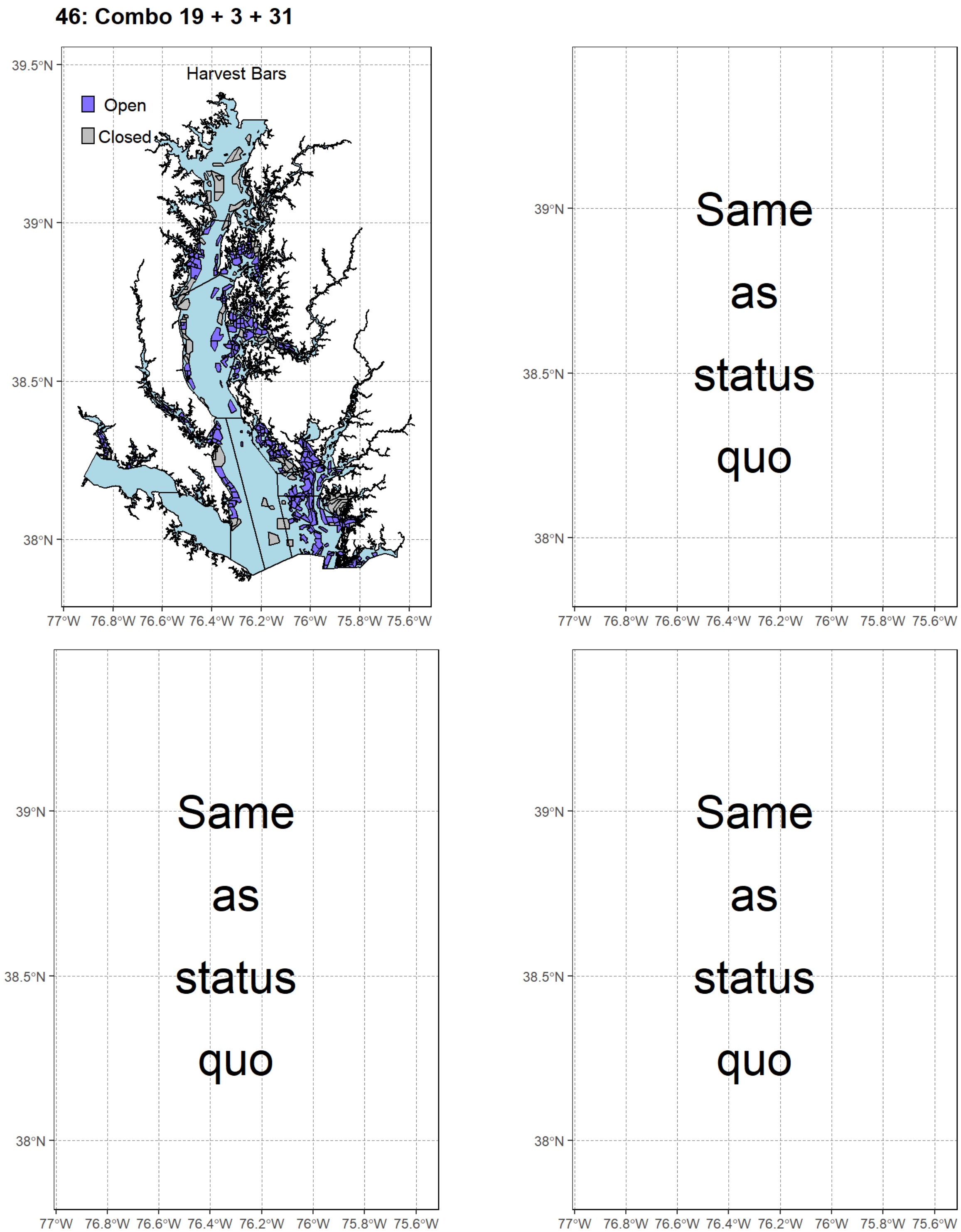

Fig. A92. Bars open to harvest, seed bars, bars open to rotational harvest, and shell dredging bars for option 46.

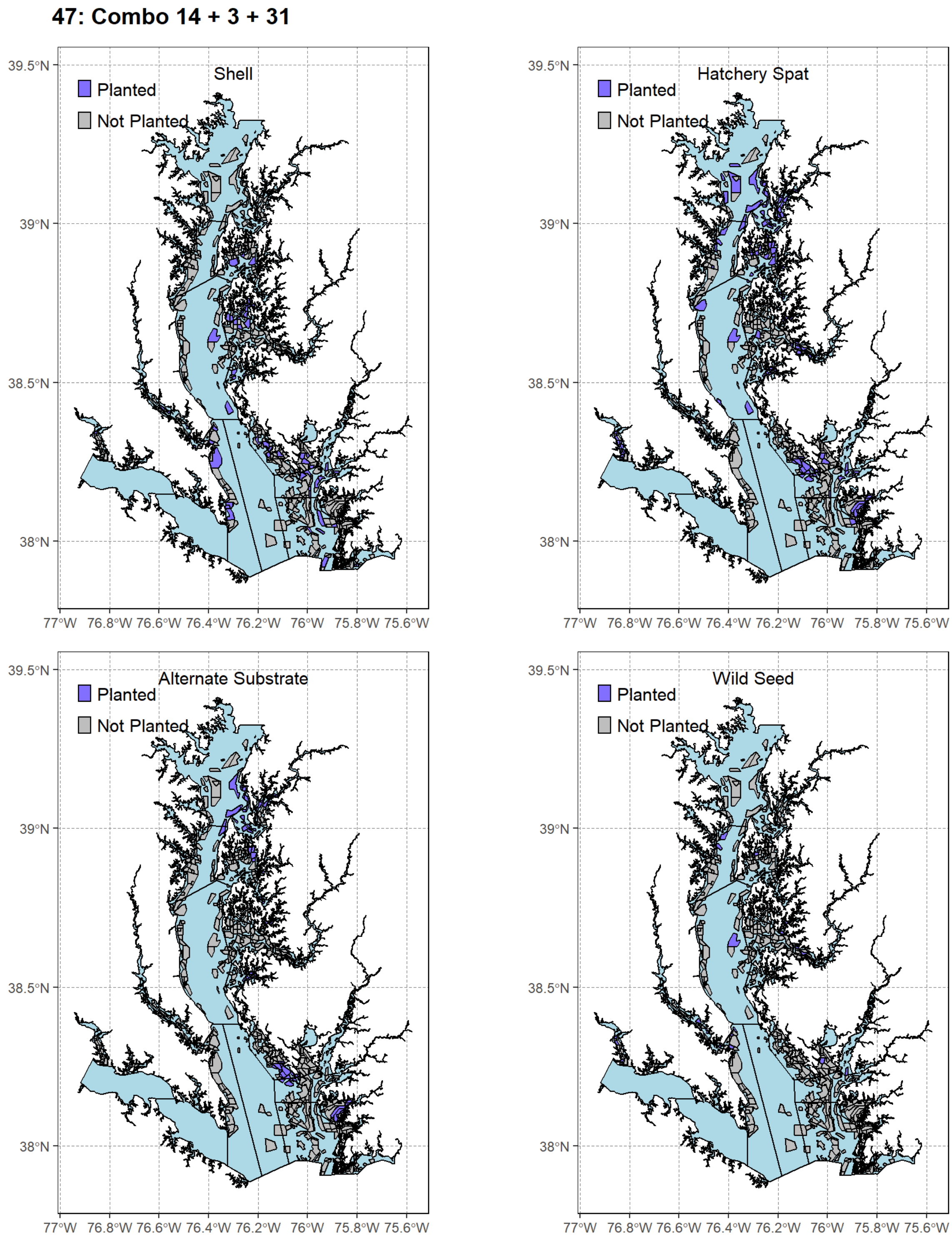

Fig. A93. Locations of shell, hatchery spat, alternate substrate, and wild seed plantings for option 47.

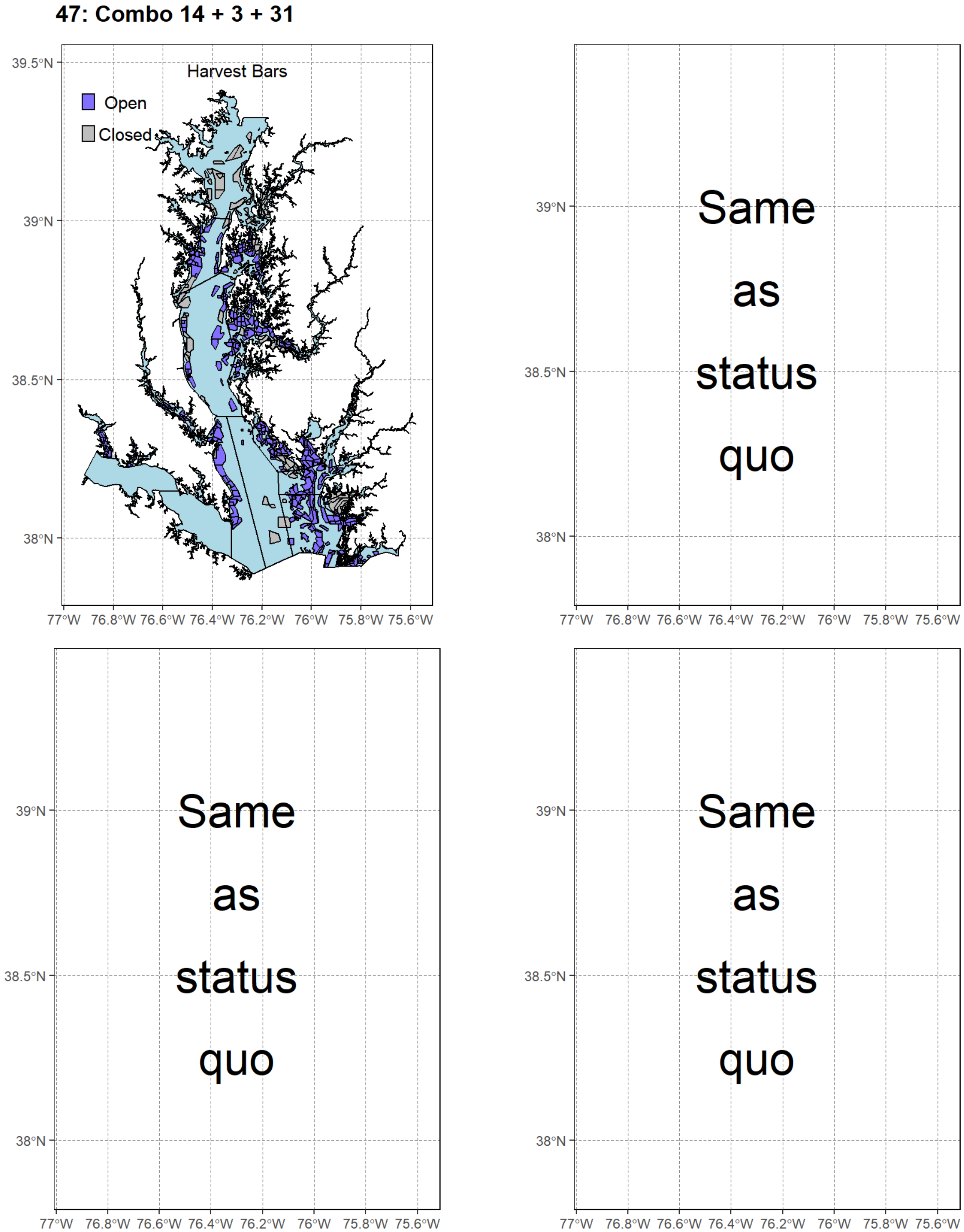

Fig. A94. Bars open to harvest, seed bars, bars open to rotational harvest, and shell dredging bars for option 47.

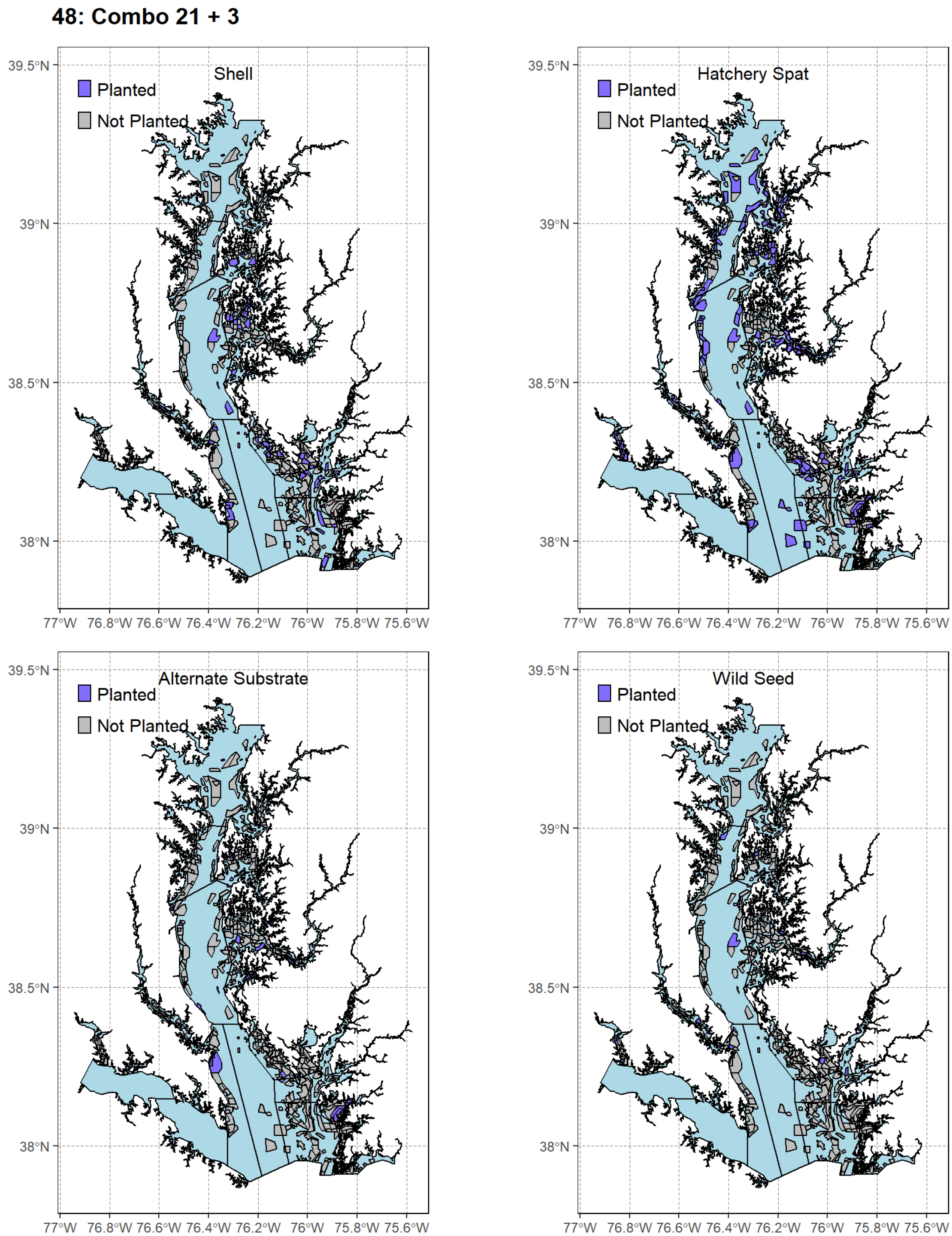

Fig. A95. Locations of shell, hatchery spat, alternate substrate, and wild seed plantings for option 48.

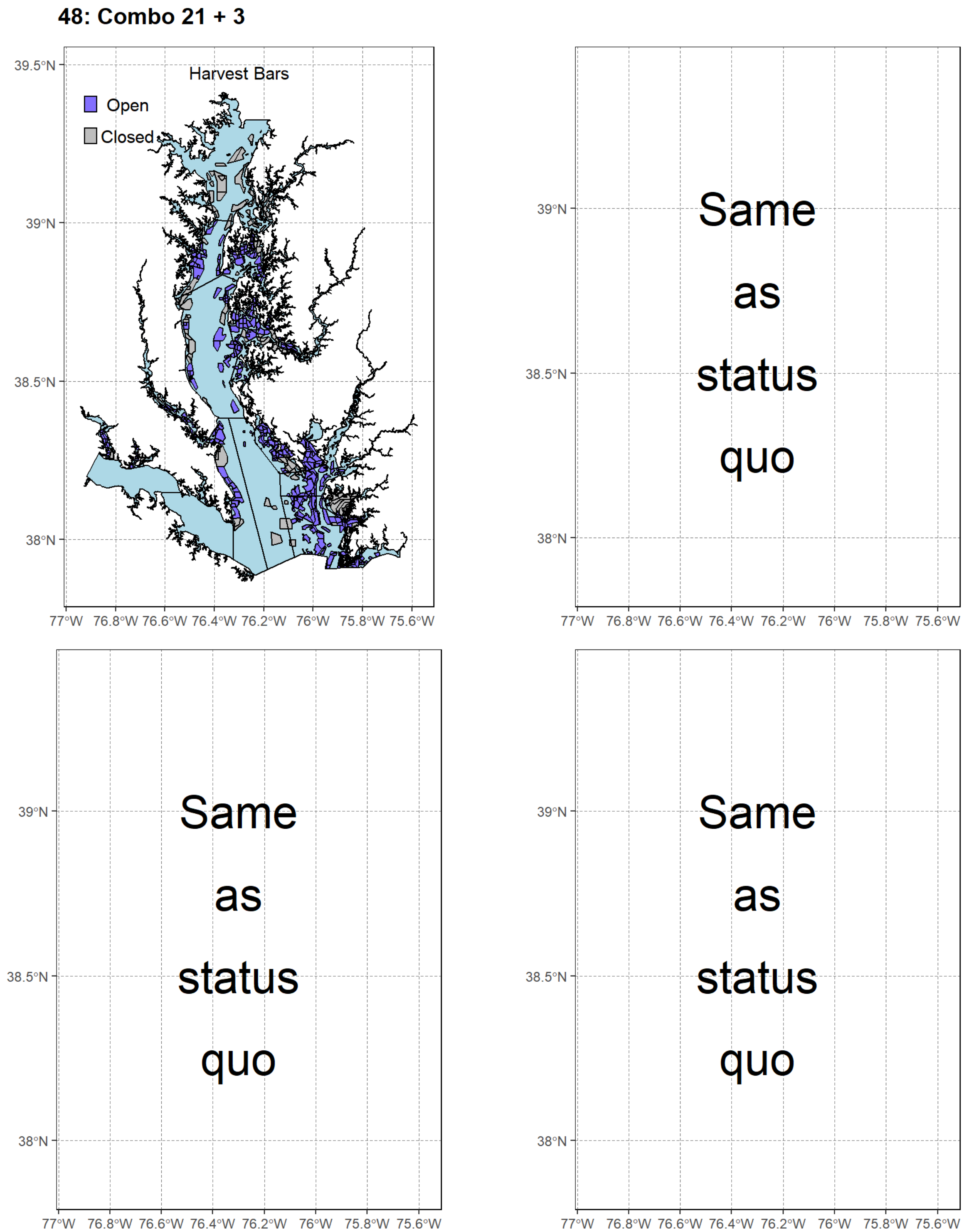

Fig. A96. Bars open to harvest, seed bars, bars open to rotational harvest, and shell dredging bars for option 48.

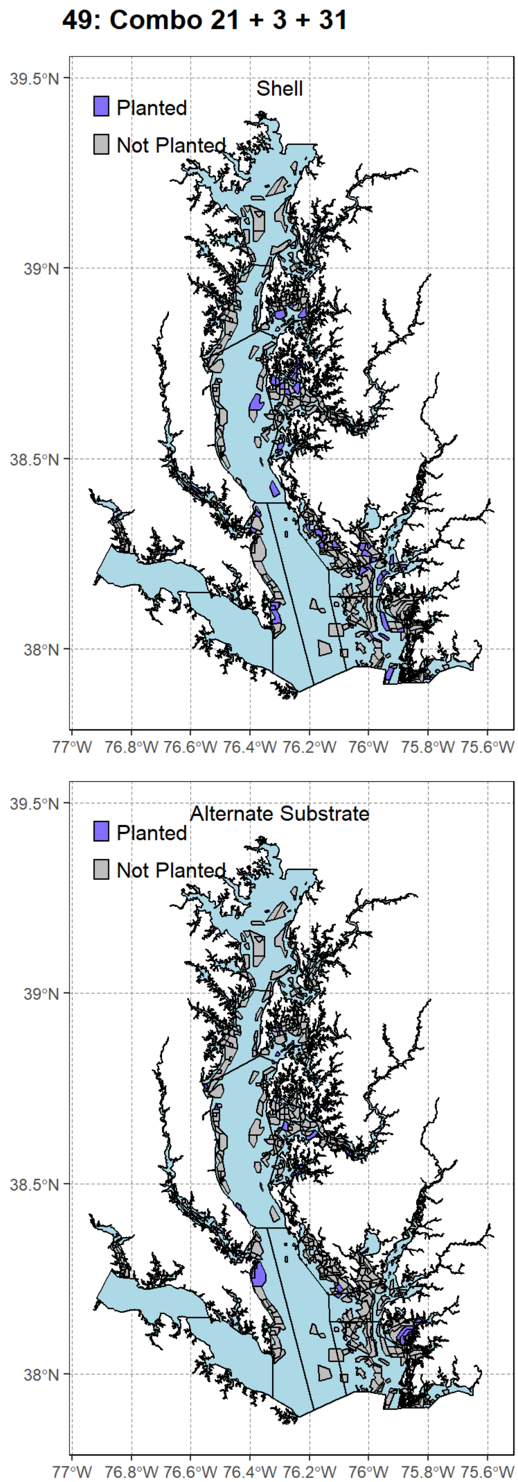

Fig. A97. Locations of shell, hatchery spat, alternate substrate, and wild seed plantings for option 49.

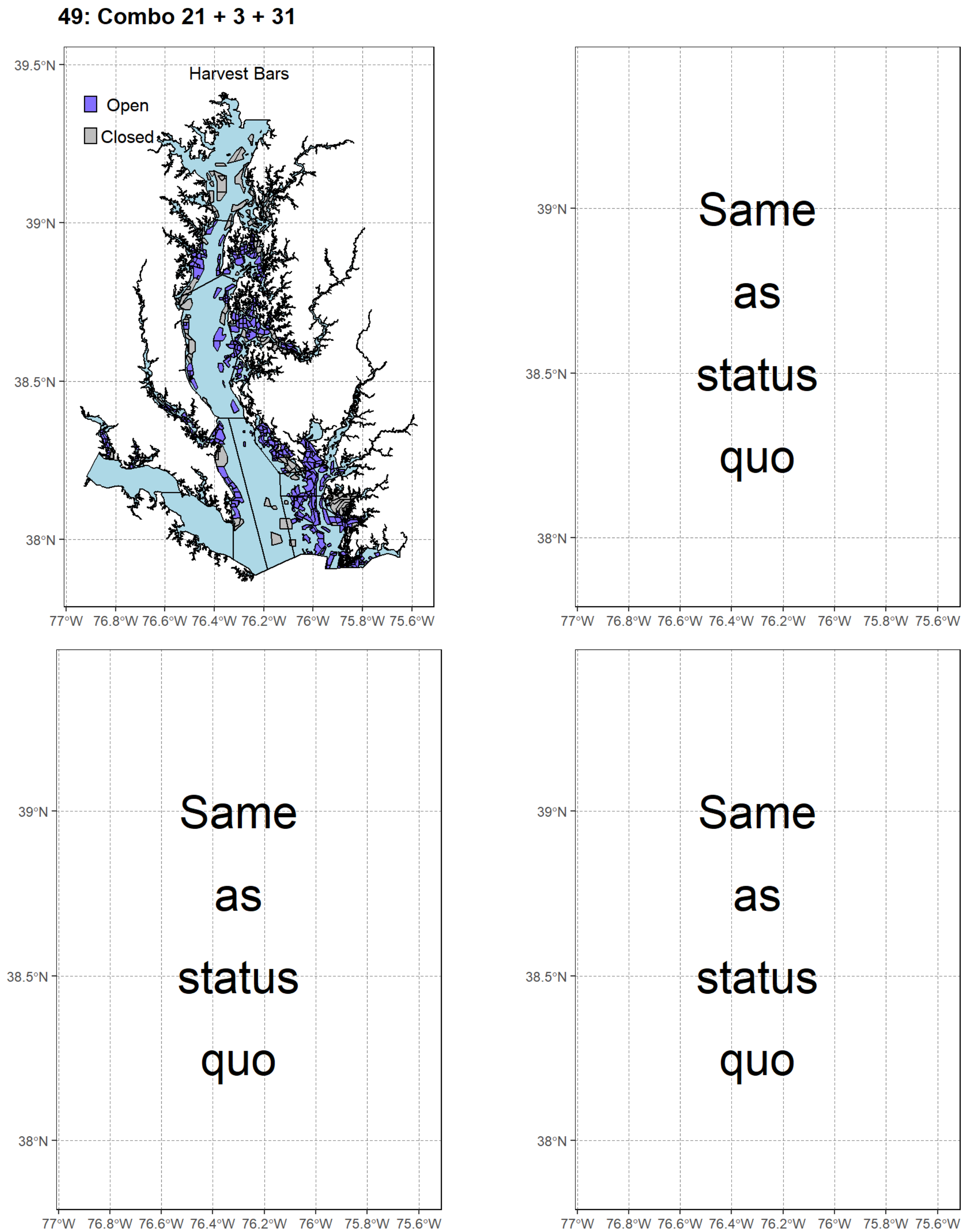

Fig. A98. Bars open to harvest, seed bars, bars open to rotational harvest, and shell dredging bars for option 49.

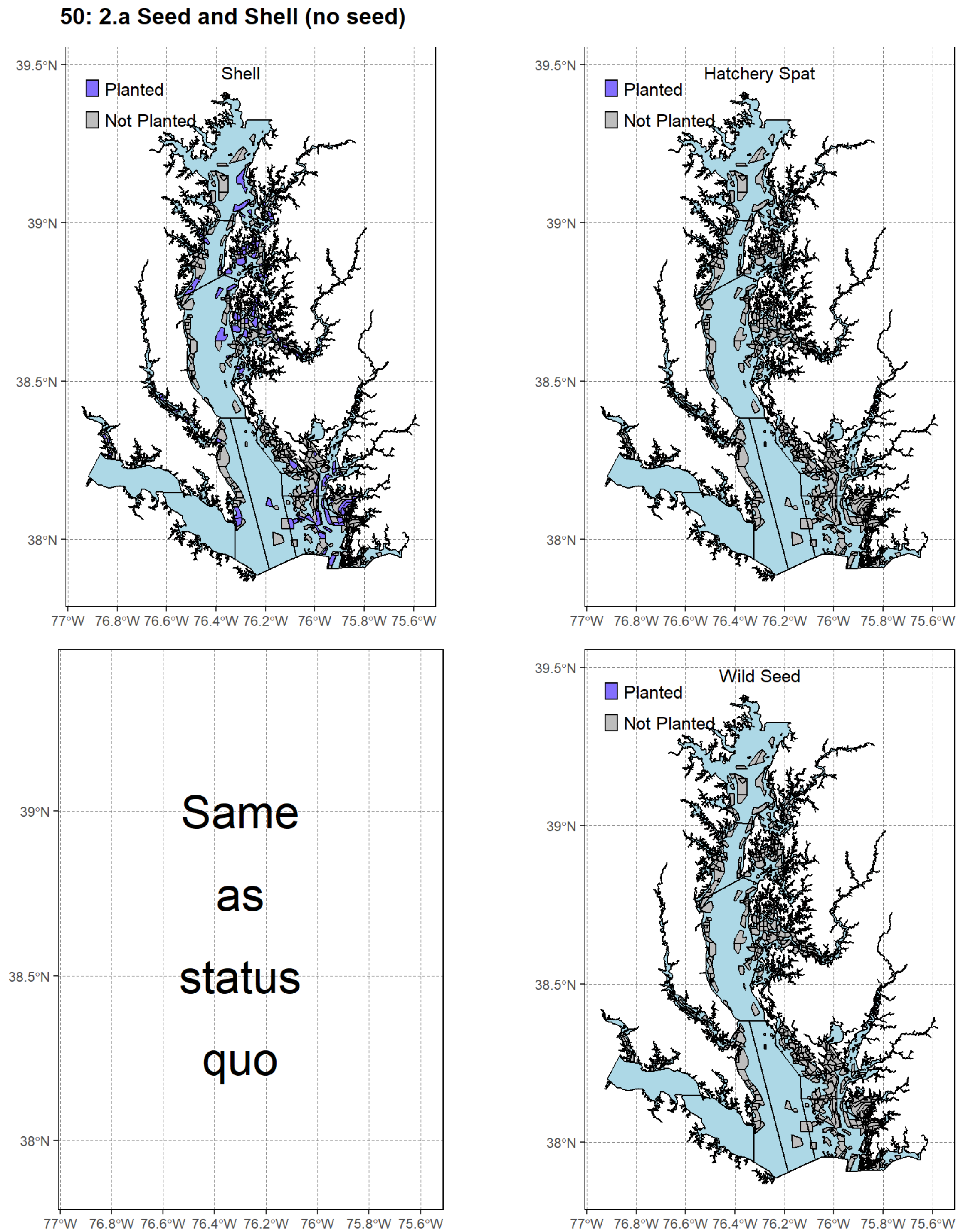

Fig. A99. Locations of shell, hatchery spat, alternate substrate, and wild seed plantings for option 50.

50: 2.a Seed and Shell (no seed)

Fig. A100. Bars open to harvest, seed bars, bars open to rotational harvest, and shell dredging bars for option 50.

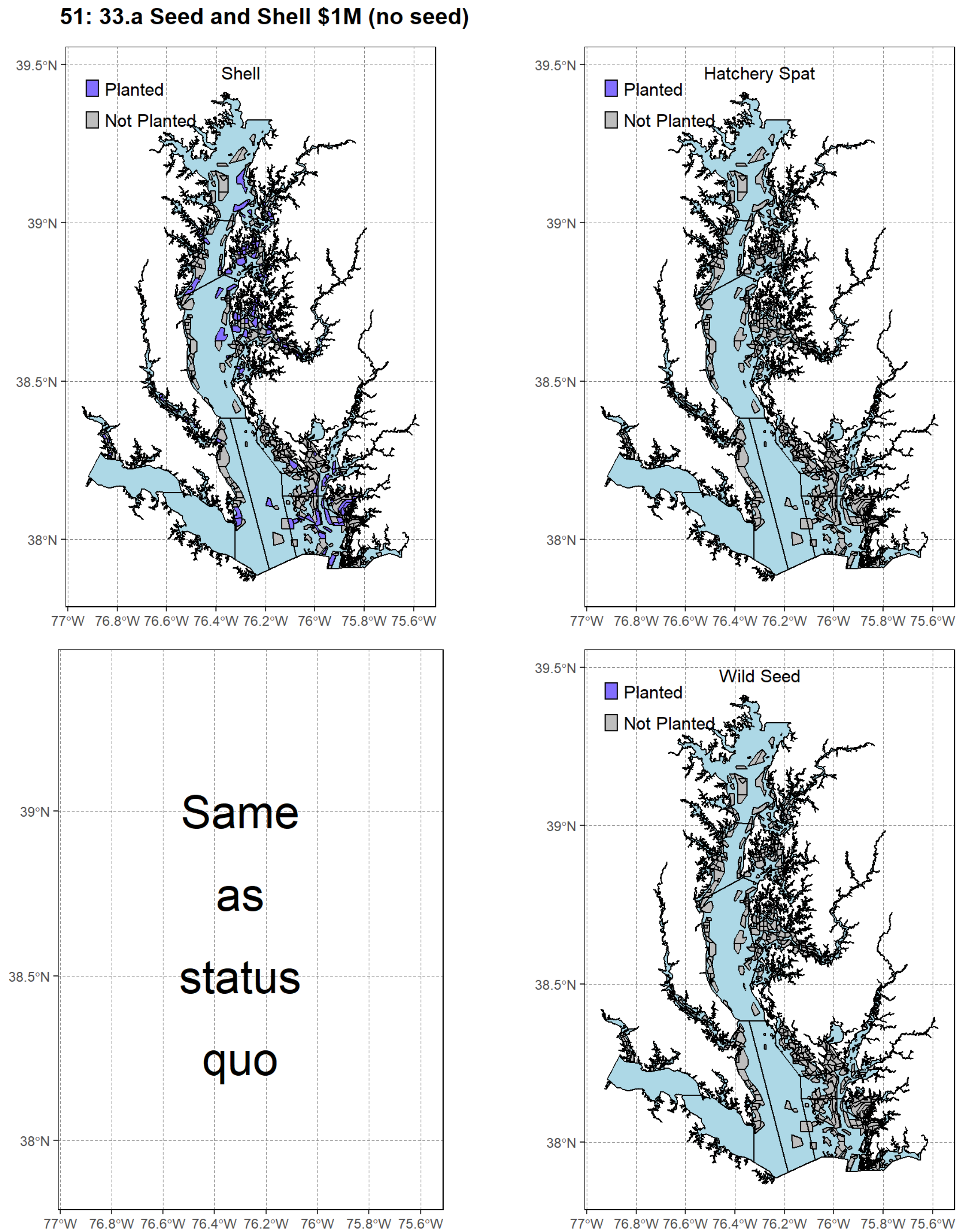

Fig. A101. Locations of shell, hatchery spat, alternate substrate, and wild seed plantings for option 51.

Fig. A102. Bars open to harvest, seed bars, bars open to rotational harvest, and shell dredging bars for option 51.

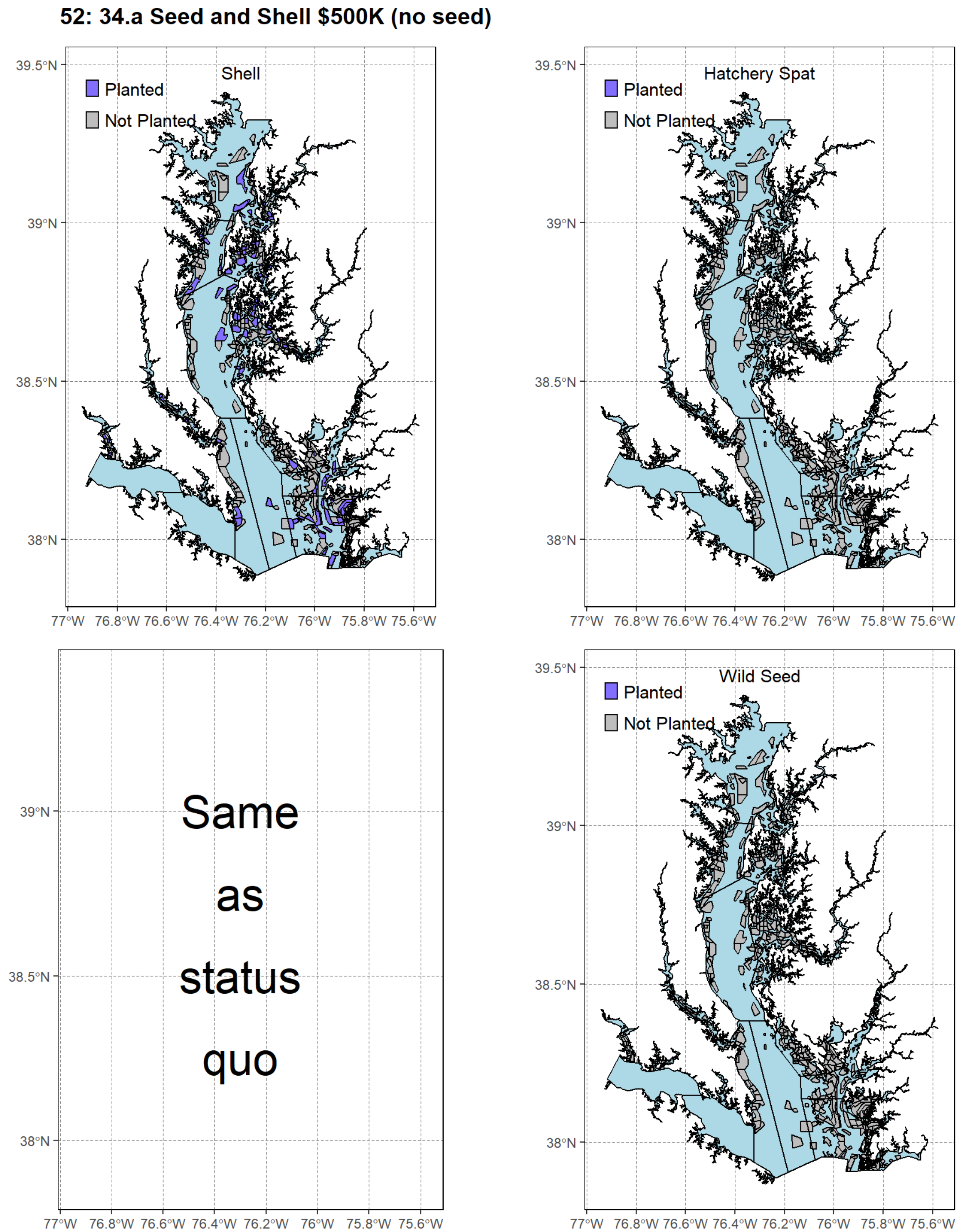

Fig. A103. Locations of shell, hatchery spat, alternate substrate, and wild seed plantings for option 52.

Fig. A104. Bars open to harvest, seed bars, bars open to rotational harvest, and shell dredging bars for option 52.

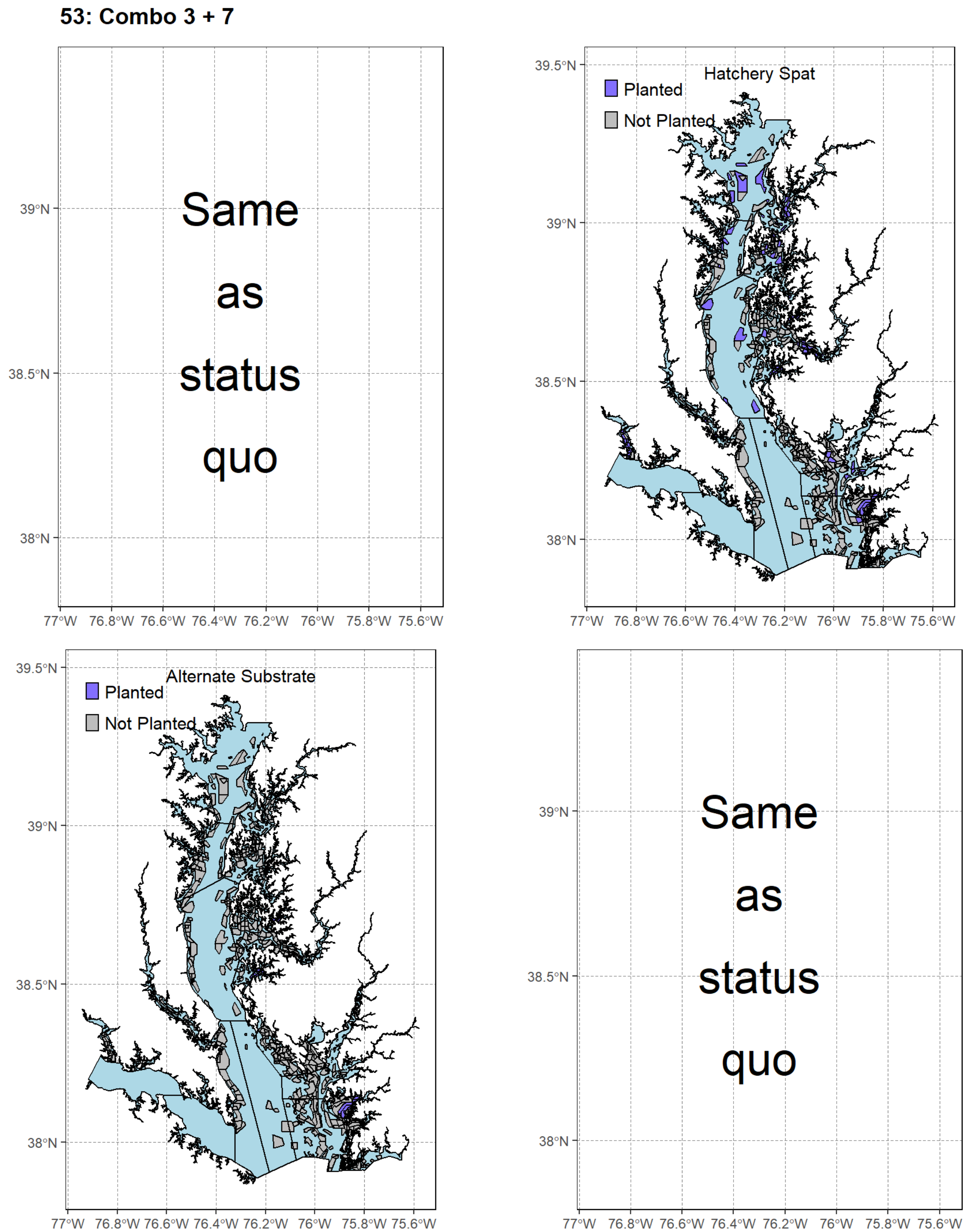

Fig. A105. Locations of shell, hatchery spat, alternate substrate, and wild seed plantings for option 53.

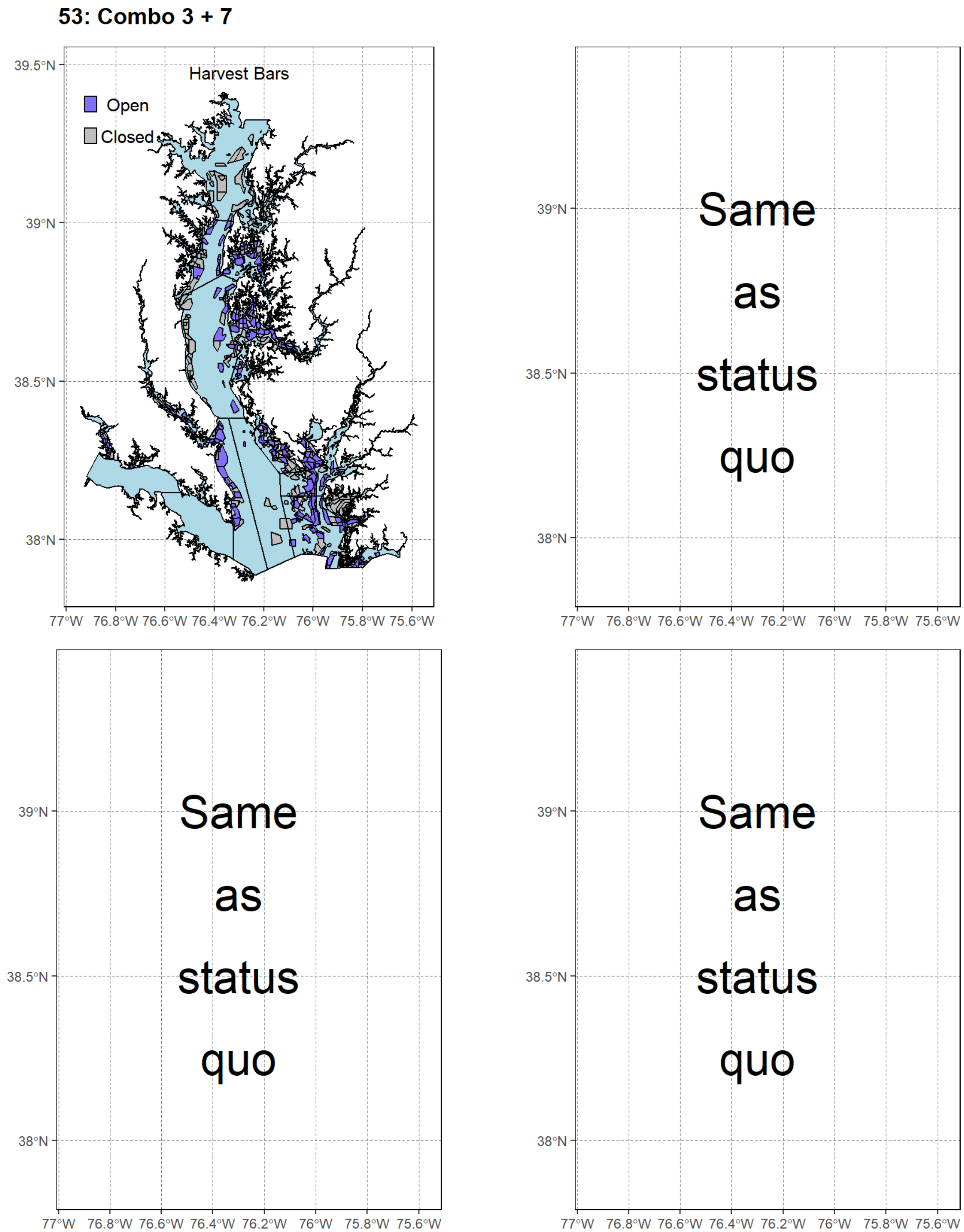

Fig. A106. Bars open to harvest, seed bars, bars open to rotational harvest, and shell dredging bars for option 53.

54: Rotational harvest Up. Bay sanc. (no planting)

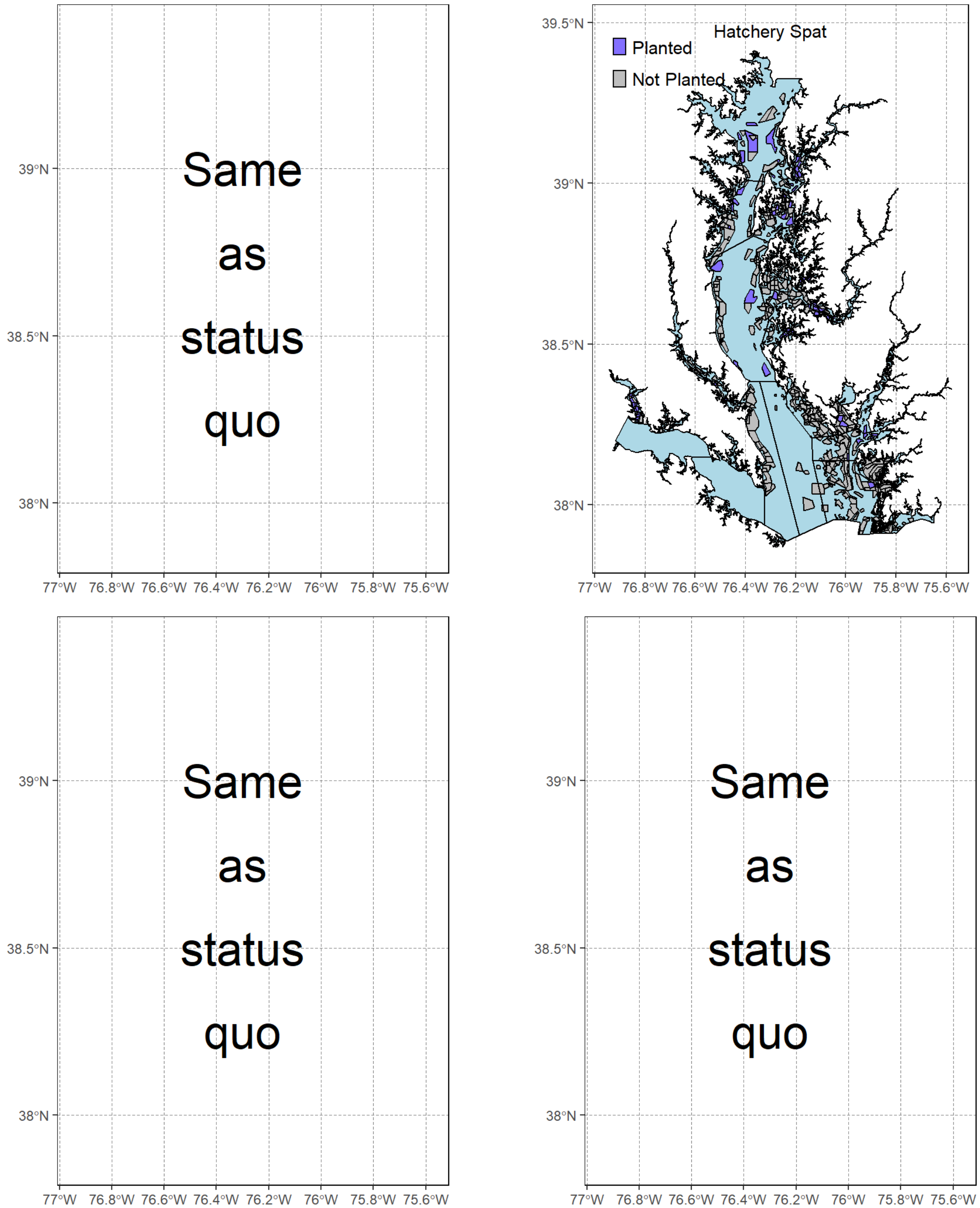

Fig. A107. Locations of shell, hatchery spat, alternate substrate, and wild seed plantings for option 54.

54: Rotational harvest Up. Bay sanc. (no planting)

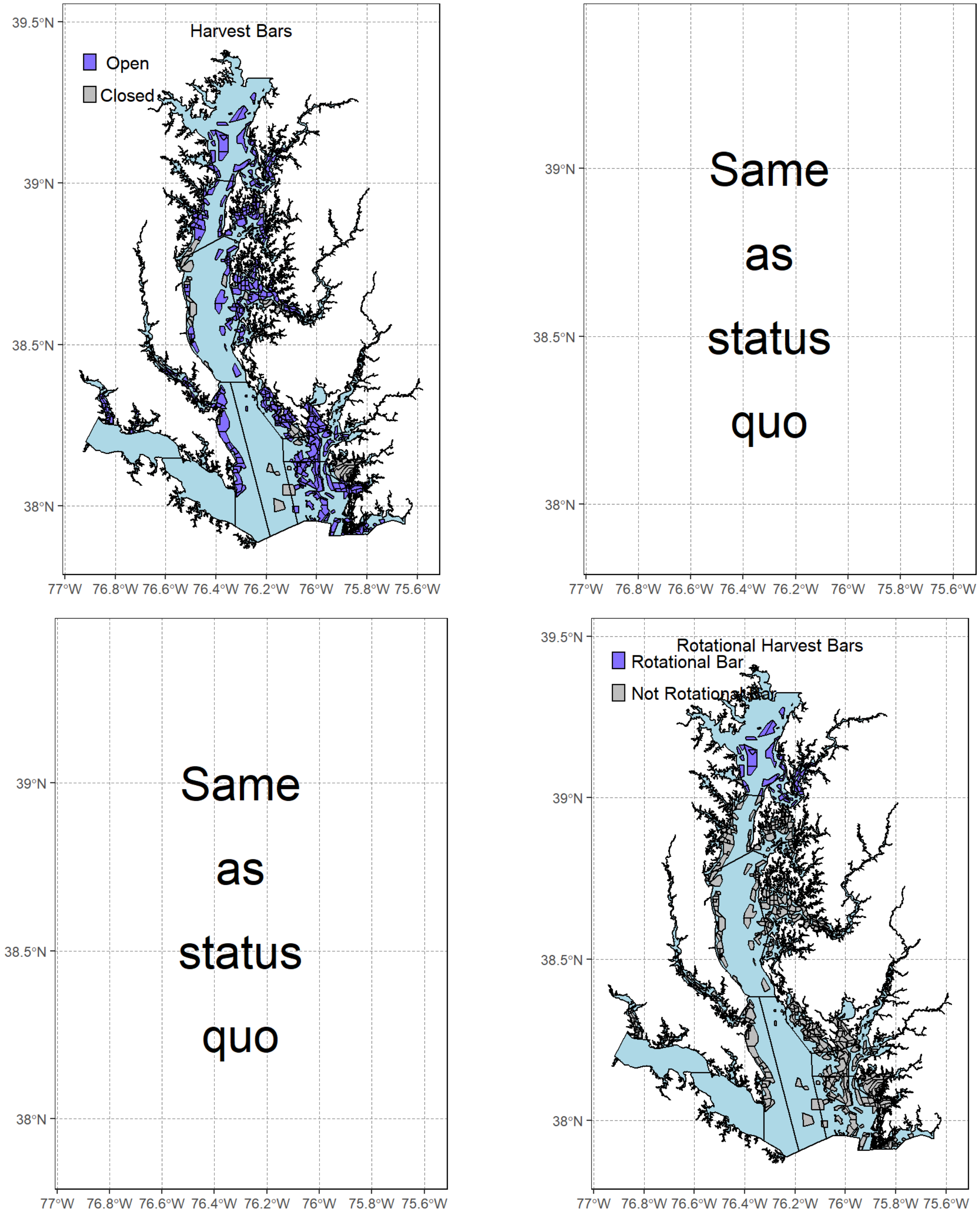

Fig. A108. Bars open to harvest, seed bars, bars open to rotational harvest, and shell dredging bars for option 54.

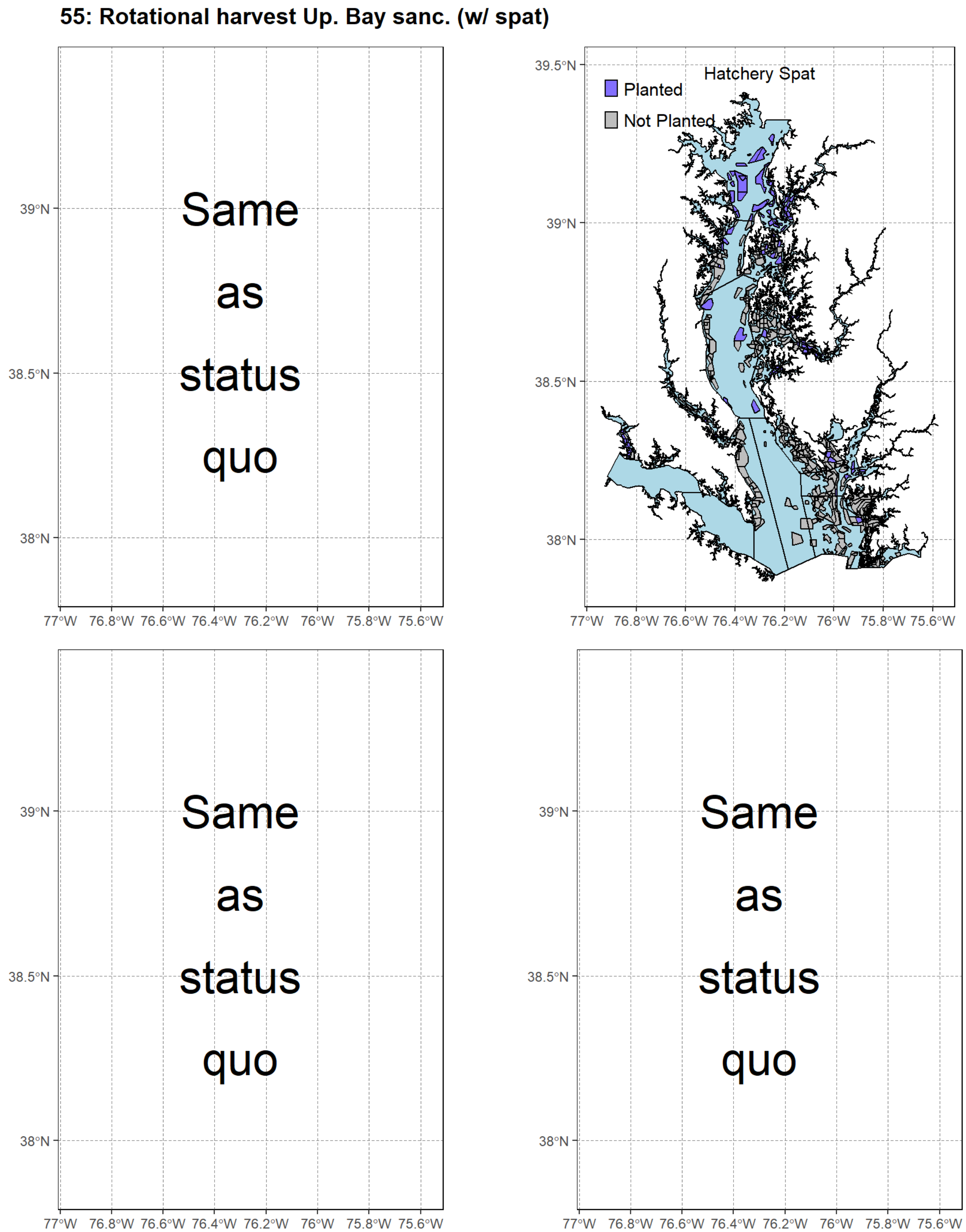

Fig. A109. Locations of shell, hatchery spat, alternate substrate, and wild seed plantings for option 55.

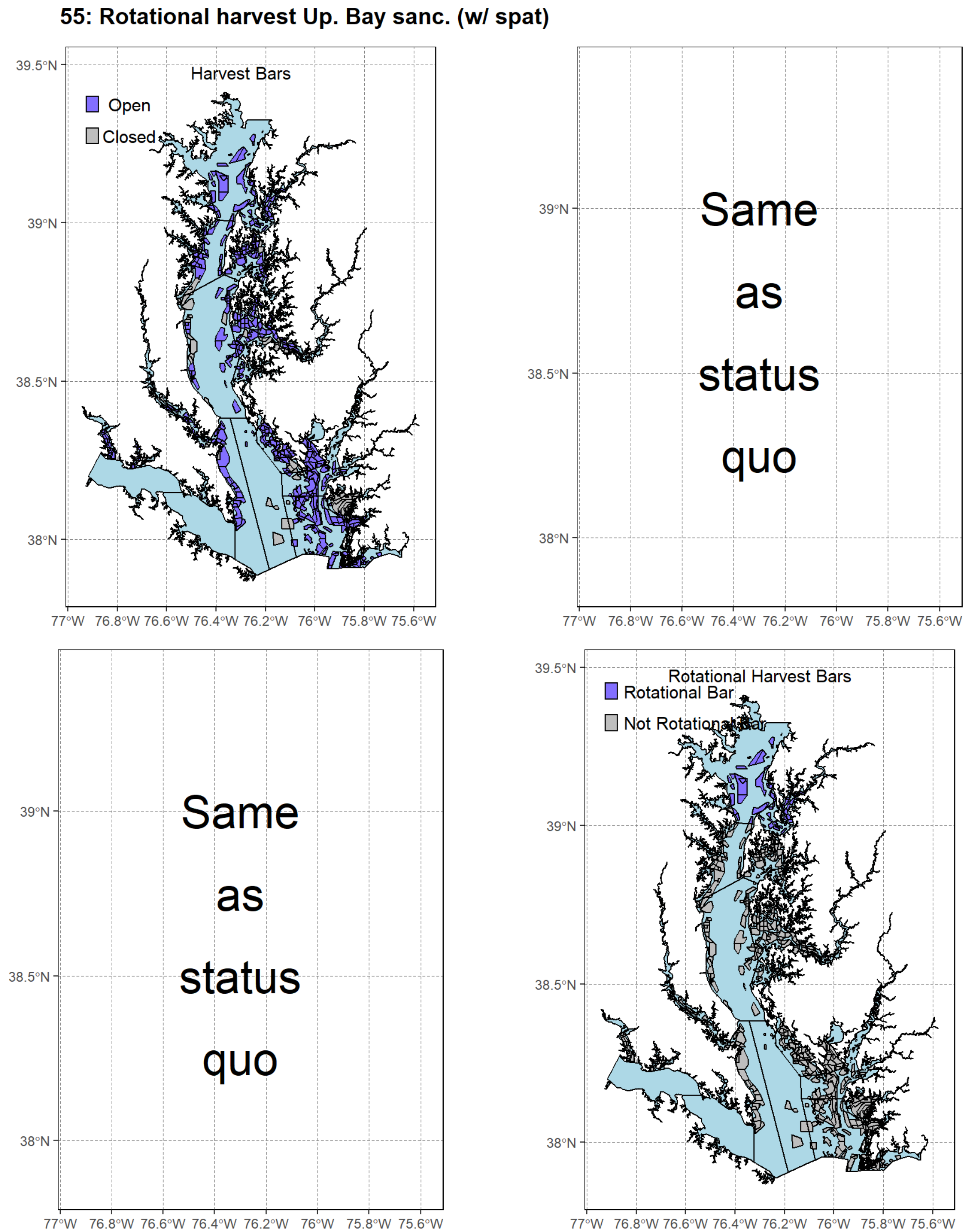

Fig. A110. Bars open to harvest, seed bars, bars open to rotational harvest, and shell dredging bars for option 55.

56: Remove low productivity sanctuaries (cat. C&D)

Fig. A111. Locations of shell, hatchery spat, alternate substrate, and wild seed plantings for option 56.

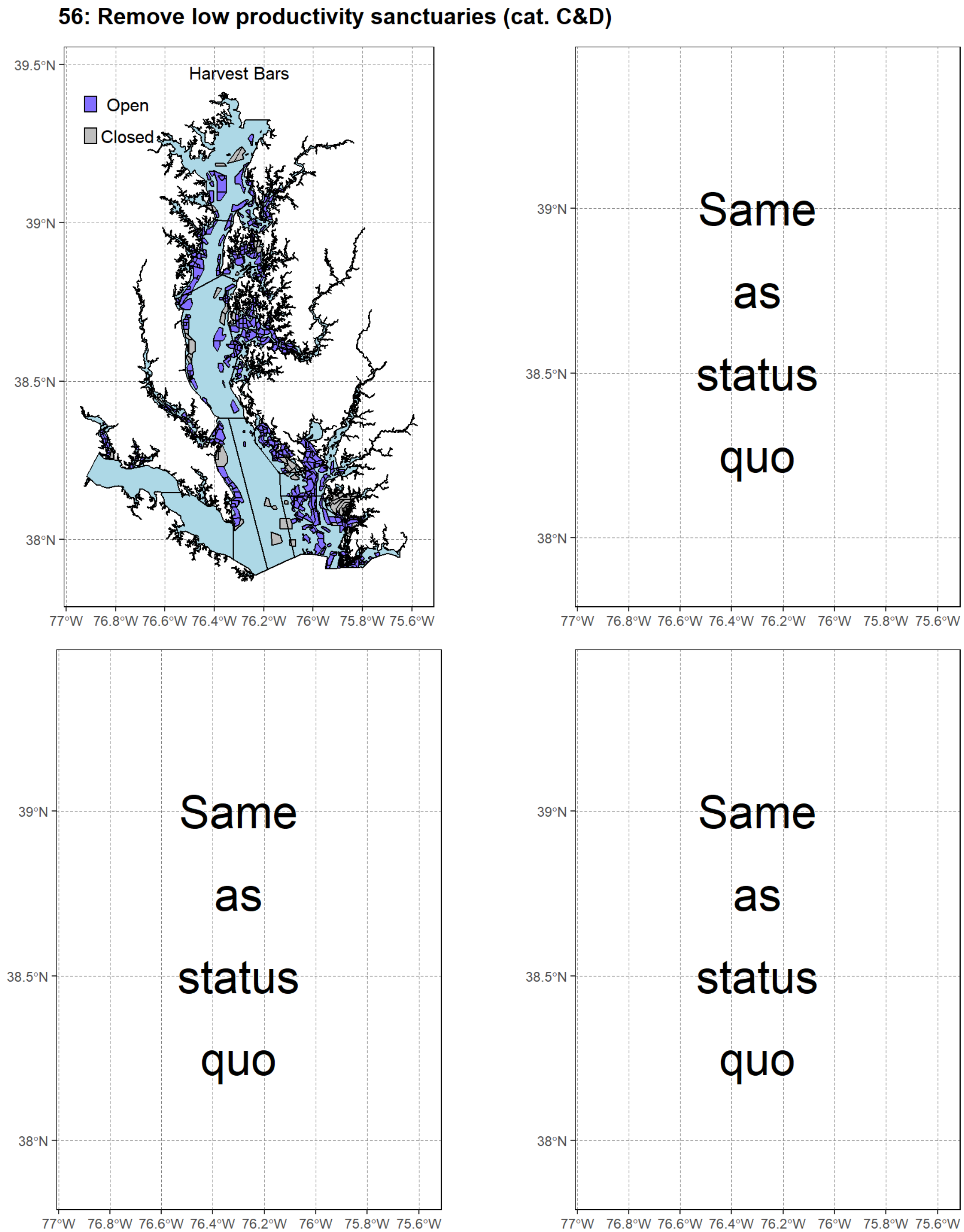

Fig. A112. Bars open to harvest, seed bars, bars open to rotational harvest, and shell dredging bars for option 56.

Fig. A113. Locations of shell, hatchery spat, alternate substrate, and wild seed plantings for option 57.

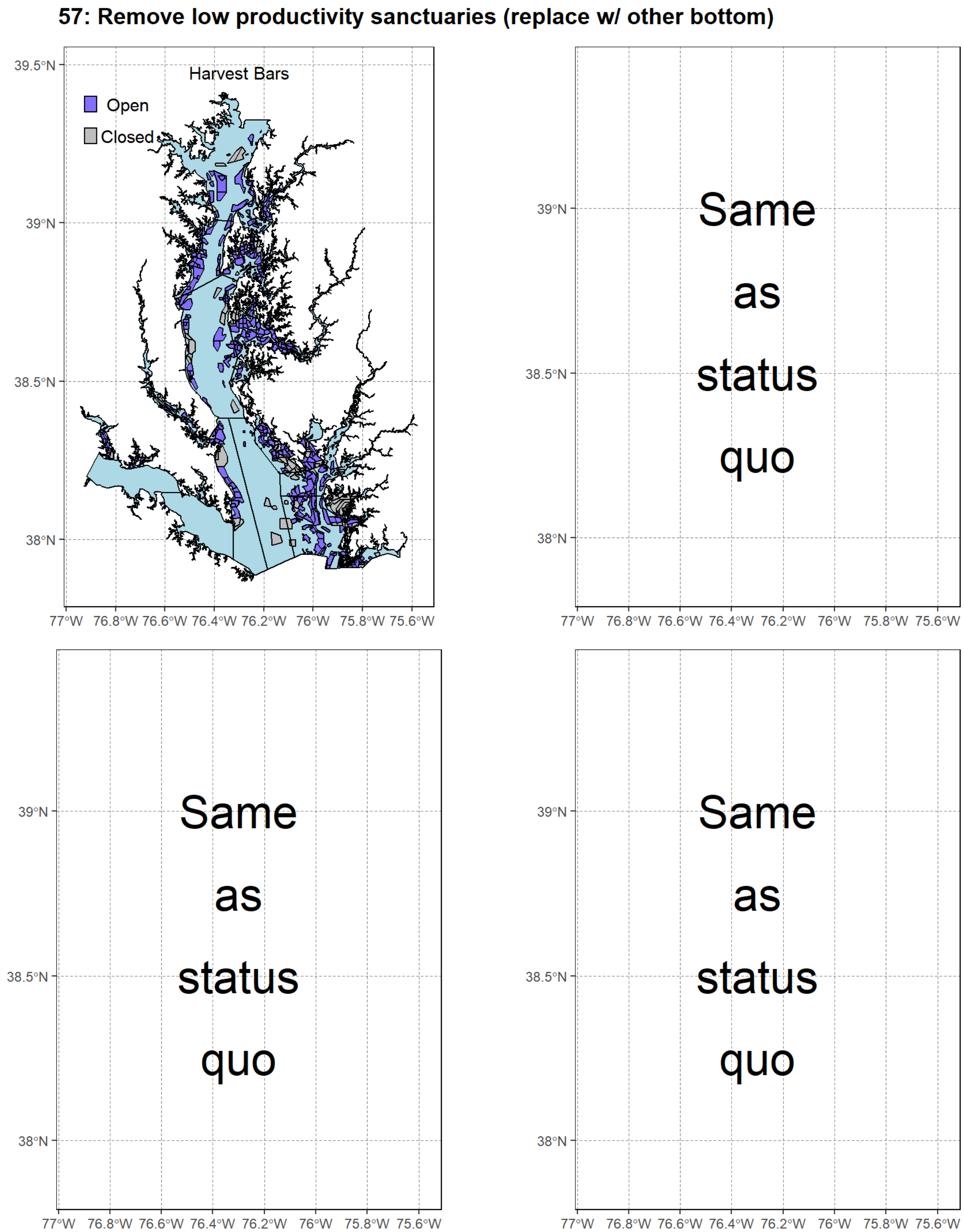

Fig. A114. Bars open to harvest, seed bars, bars open to rotational harvest, and shell dredging bars for option 57.

Fig. A115. Locations of shell, hatchery spat, alternate substrate, and wild seed plantings for option 58.

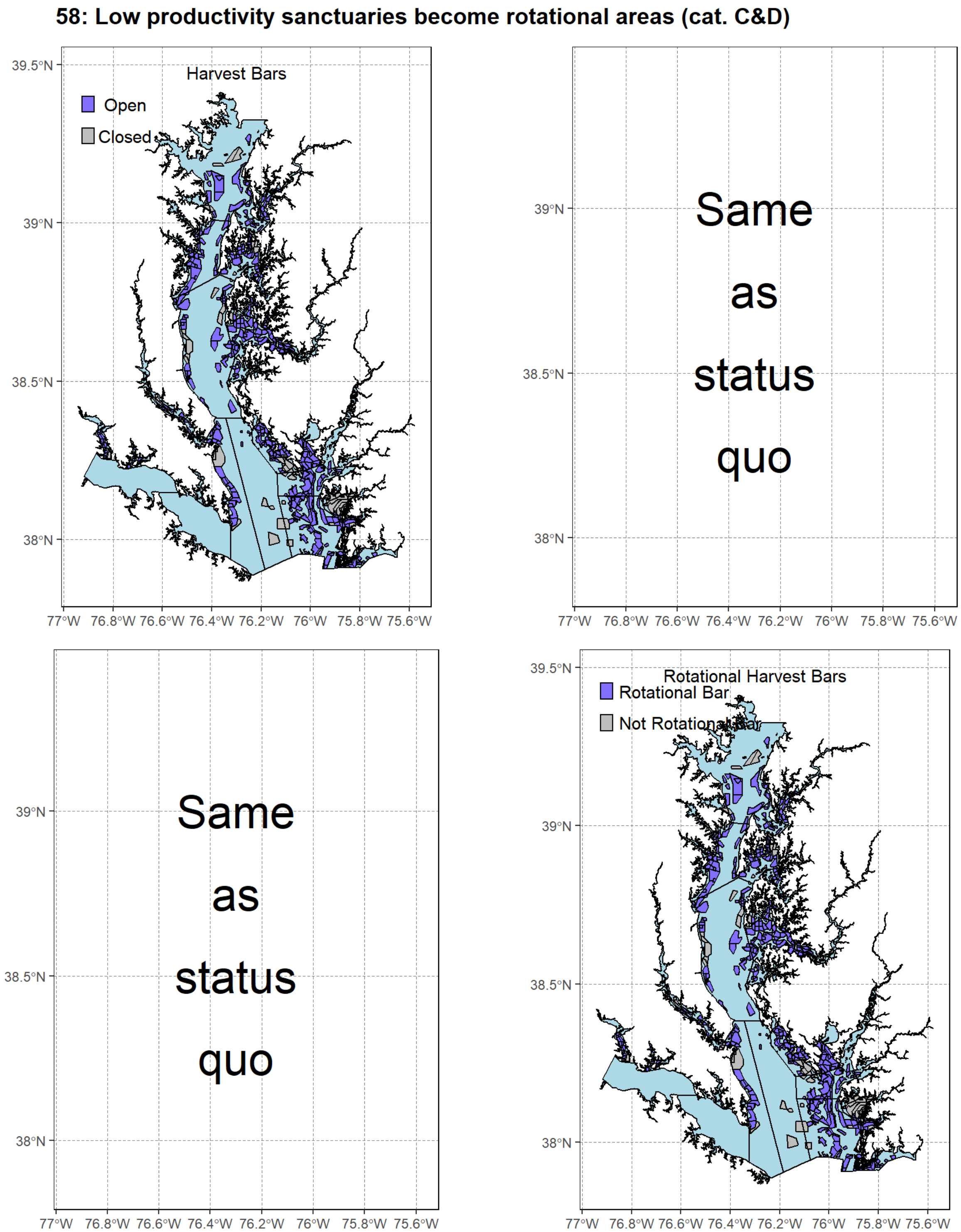

Fig. A116. Bars open to harvest, seed bars, bars open to rotational harvest, and shell dredging bars for option 58.

Fig. A117. Locations of shell, hatchery spat, alternate substrate, and wild seed plantings for option 59.

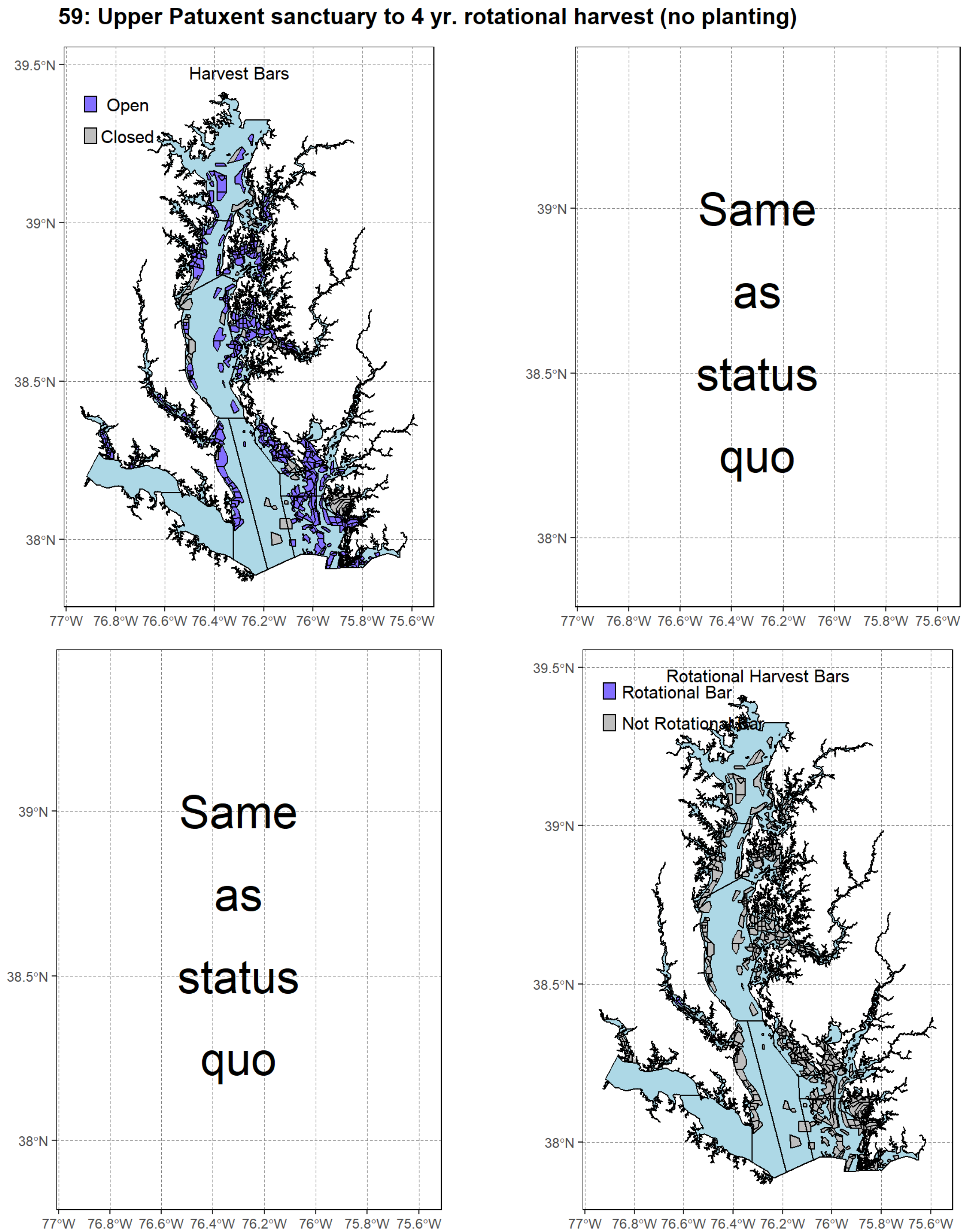

Fig. A118. Bars open to harvest, seed bars, bars open to rotational harvest, and shell dredging bars for option 59.

60: Upper Patuxent sanctuary to 4 yr. rotational harvest (spat)

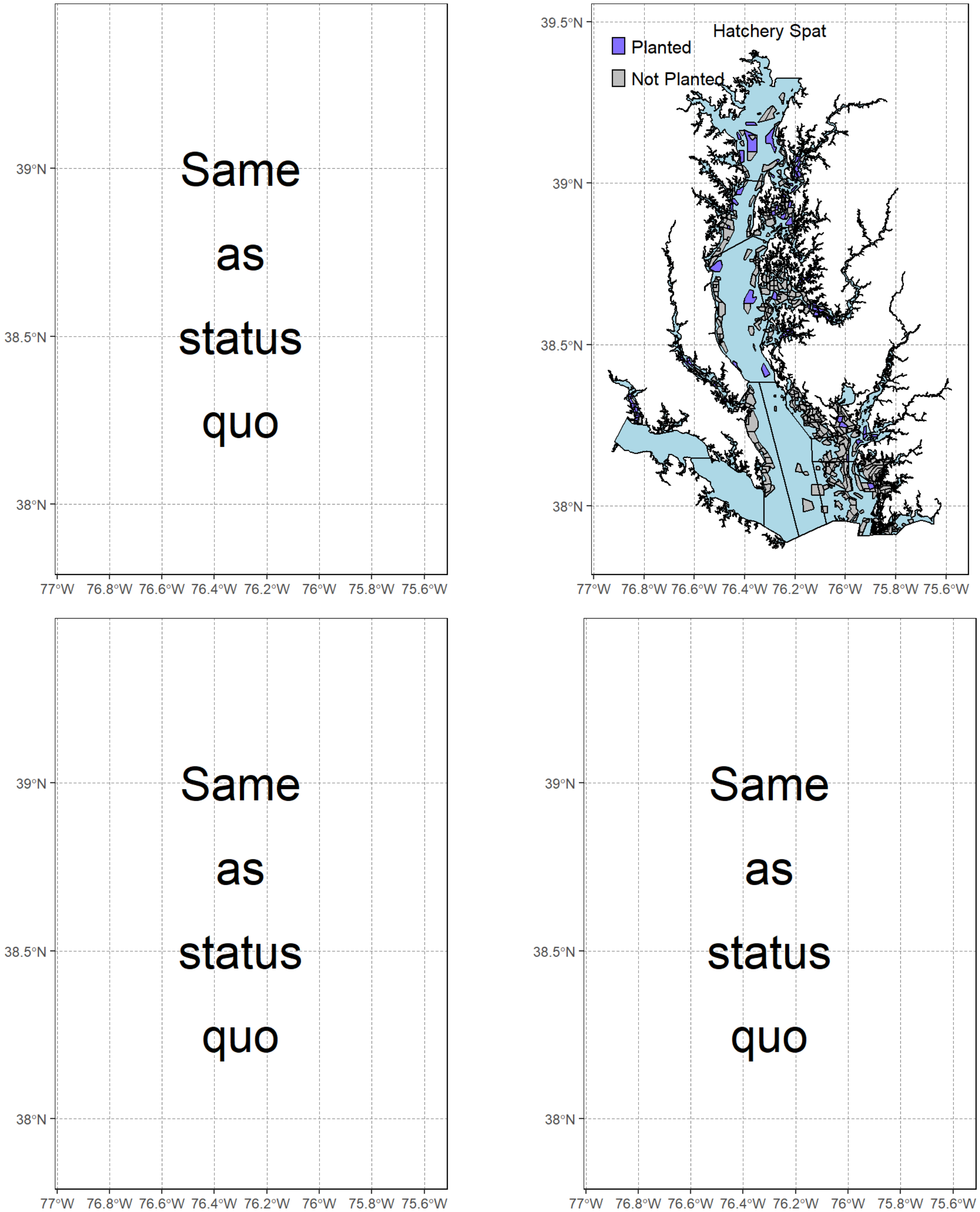

Fig. A119. Locations of shell, hatchery spat, alternate substrate, and wild seed plantings for option 60.

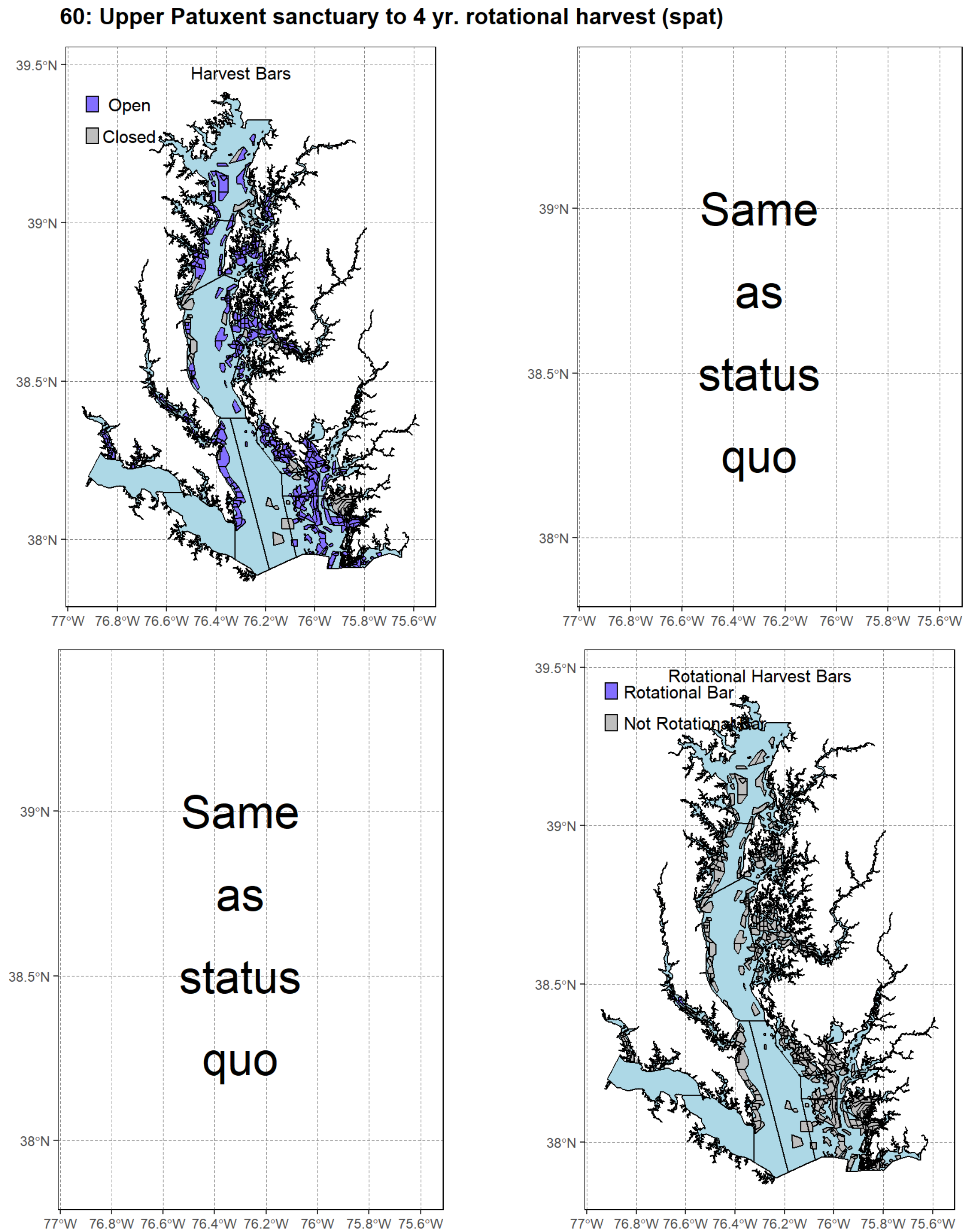

Fig. A120. Bars open to harvest, seed bars, bars open to rotational harvest, and shell dredging bars for option 60.

61: All 51 sanctuaries open to public fishery

Fig. A121. Locations of shell, hatchery spat, alternate substrate, and wild seed plantings for option 61.

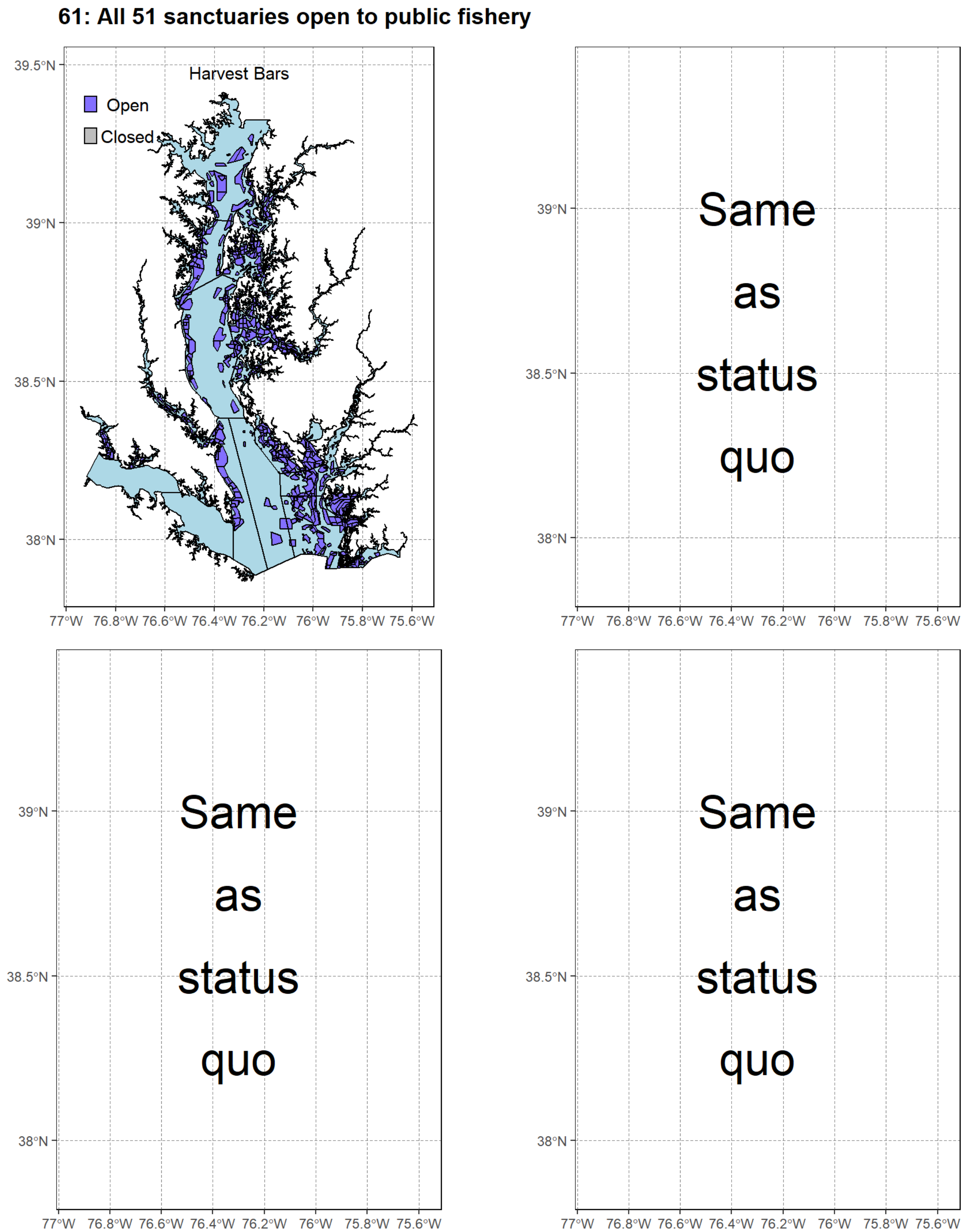

Fig. A122. Bars open to harvest, seed bars, bars open to rotational harvest, and shell dredging bars for option 61.

62: All 51 sanctuaries open to public fishery as rotational areas

Fig. A123. Locations of shell, hatchery spat, alternate substrate, and wild seed plantings for option 62.

62: All 51 sanctuaries open to public fishery as rotational areas

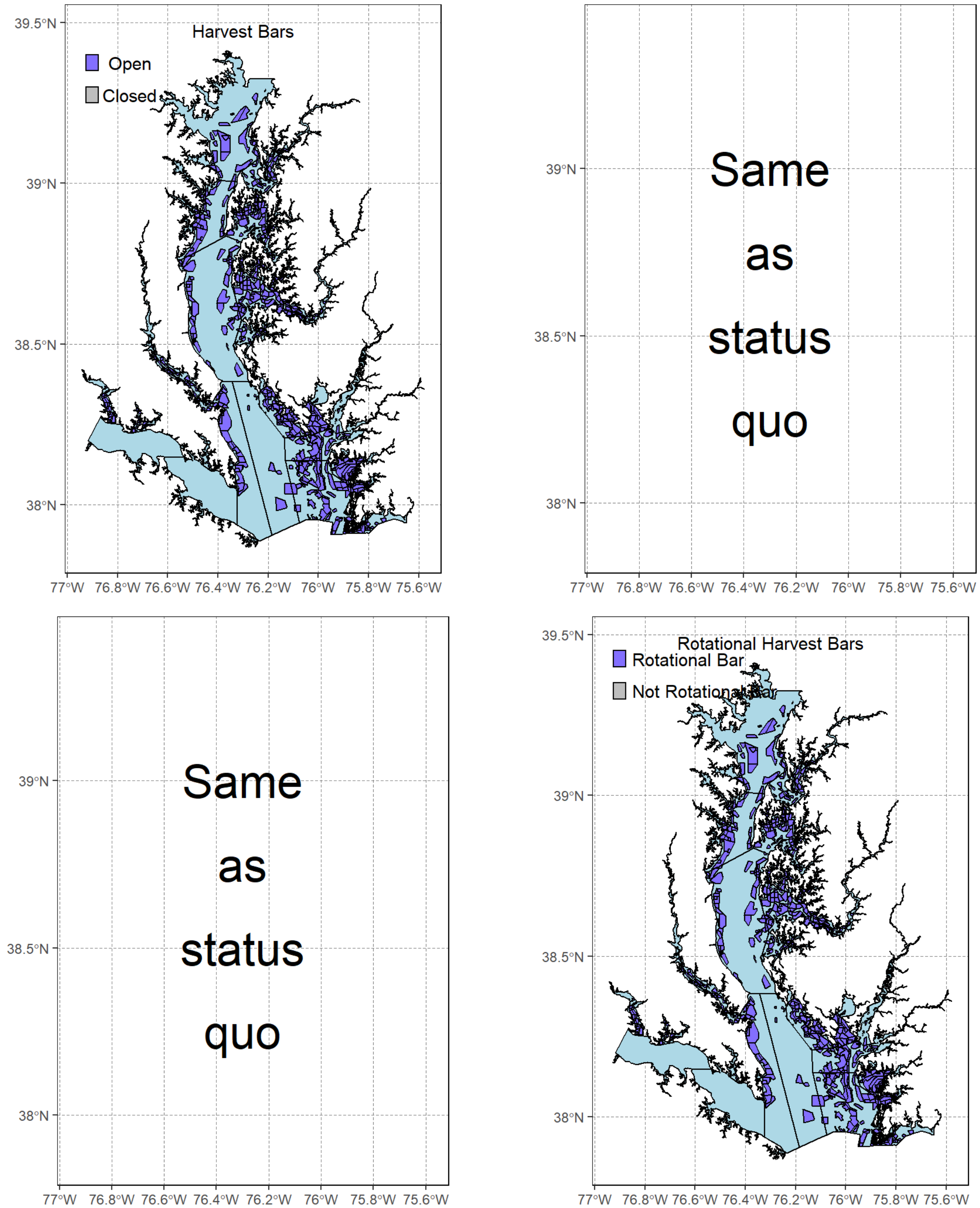

Fig. A124. Bars open to harvest, seed bars, bars open to rotational harvest, and shell dredging bars for option 62.

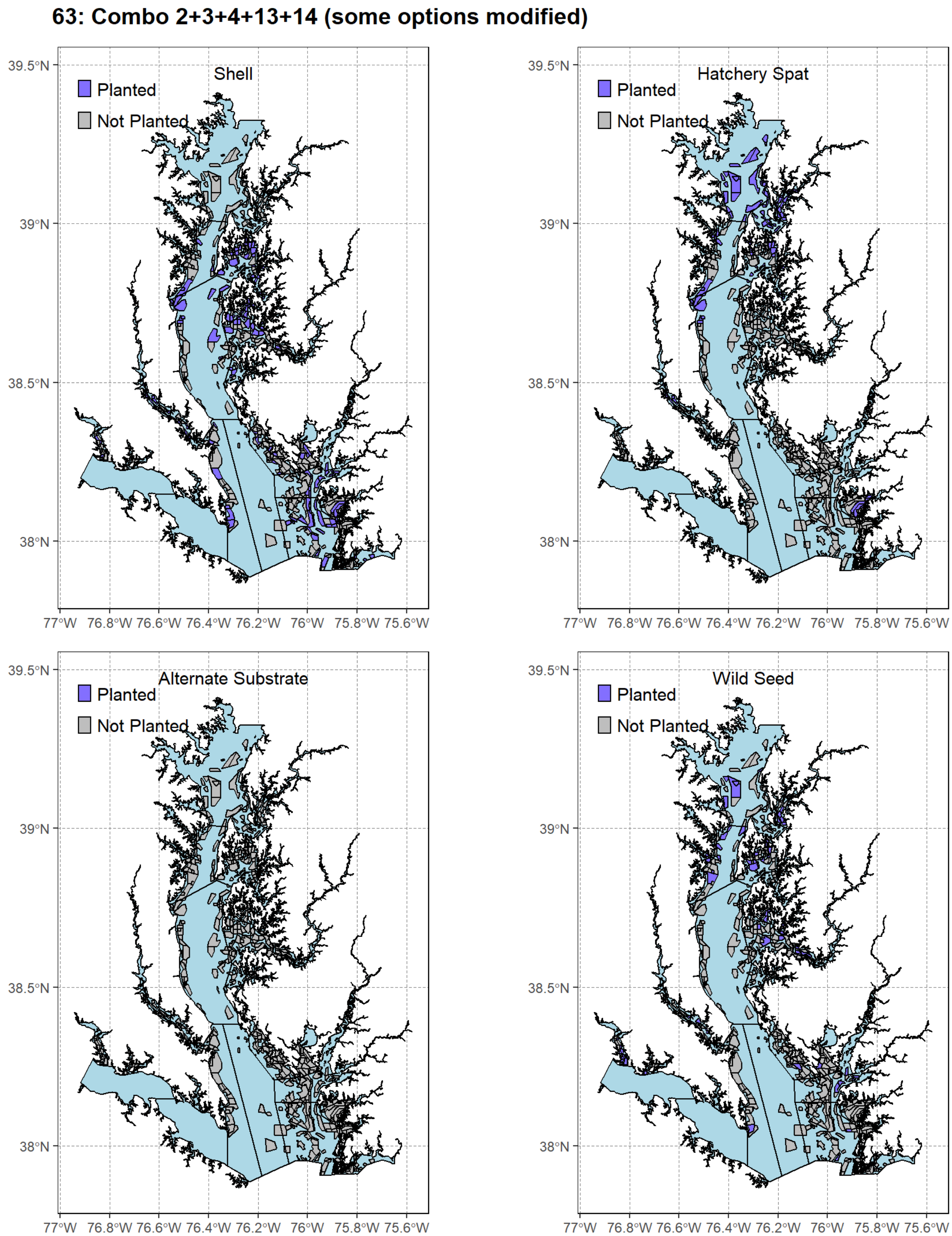

Fig. A125. Locations of shell, hatchery spat, alternate substrate, and wild seed plantings for option 63.

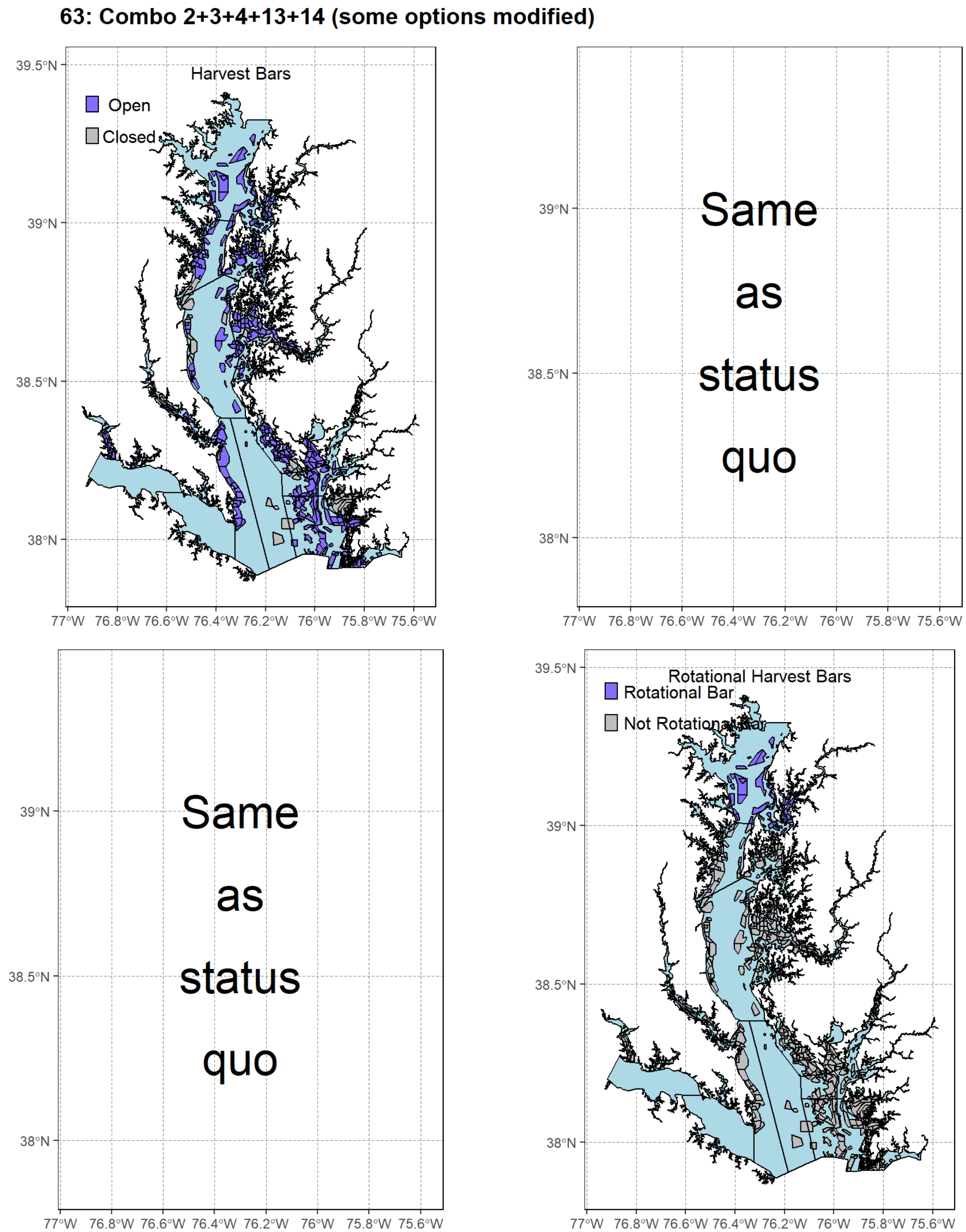

Fig. A126. Bars open to harvest, seed bars, bars open to rotational harvest, and shell dredging bars for option 63.

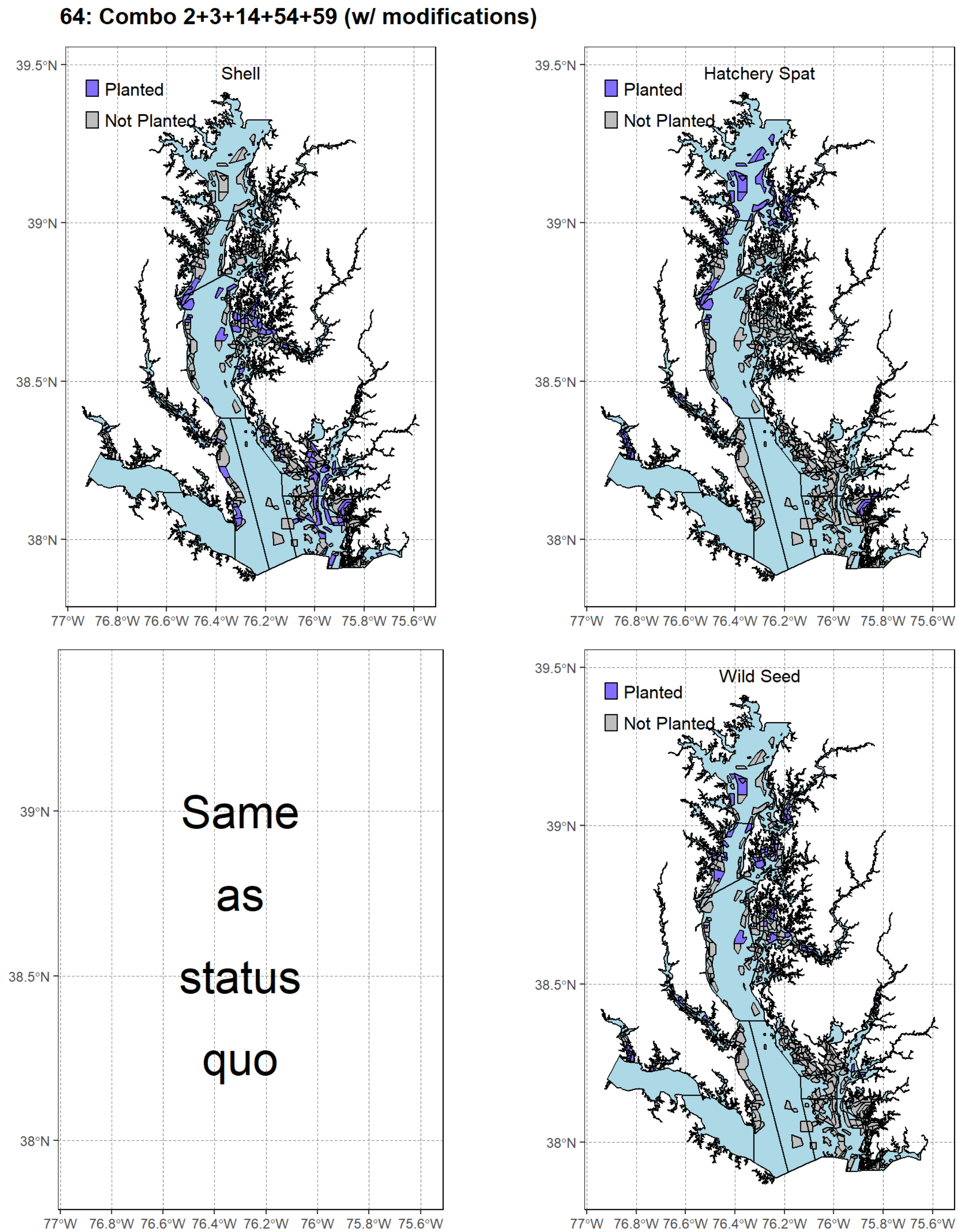

Fig. A127. Locations of shell, hatchery spat, alternate substrate, and wild seed plantings for option 64.

64: Combo 2+3+14+54+59 (w/ modifications)

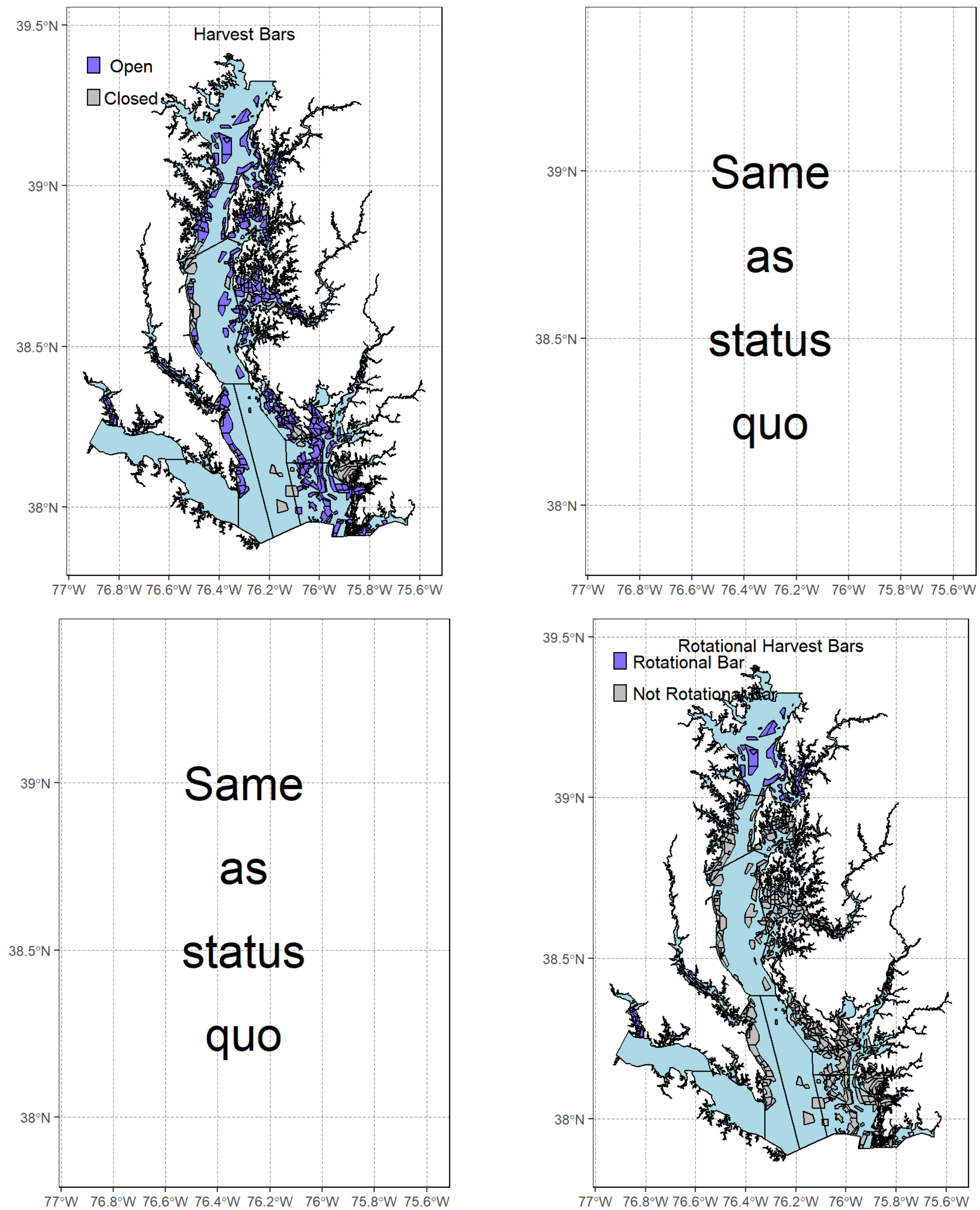

Fig. A128. Bars open to harvest, seed bars, bars open to rotational harvest, and shell dredging bars for option 64.

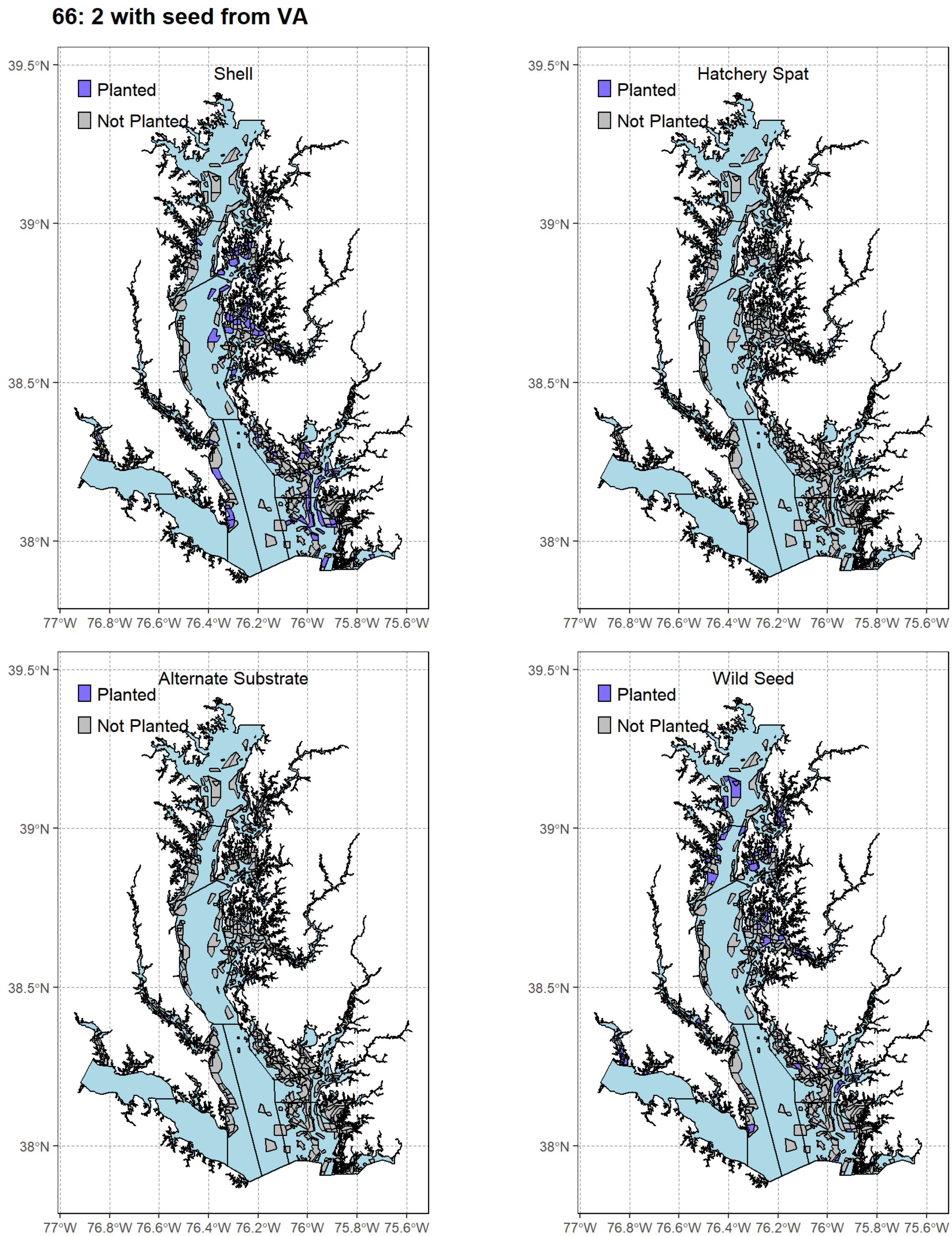

Fig. A129. Locations of shell, hatchery spat, alternate substrate, and wild seed plantings for option 66.

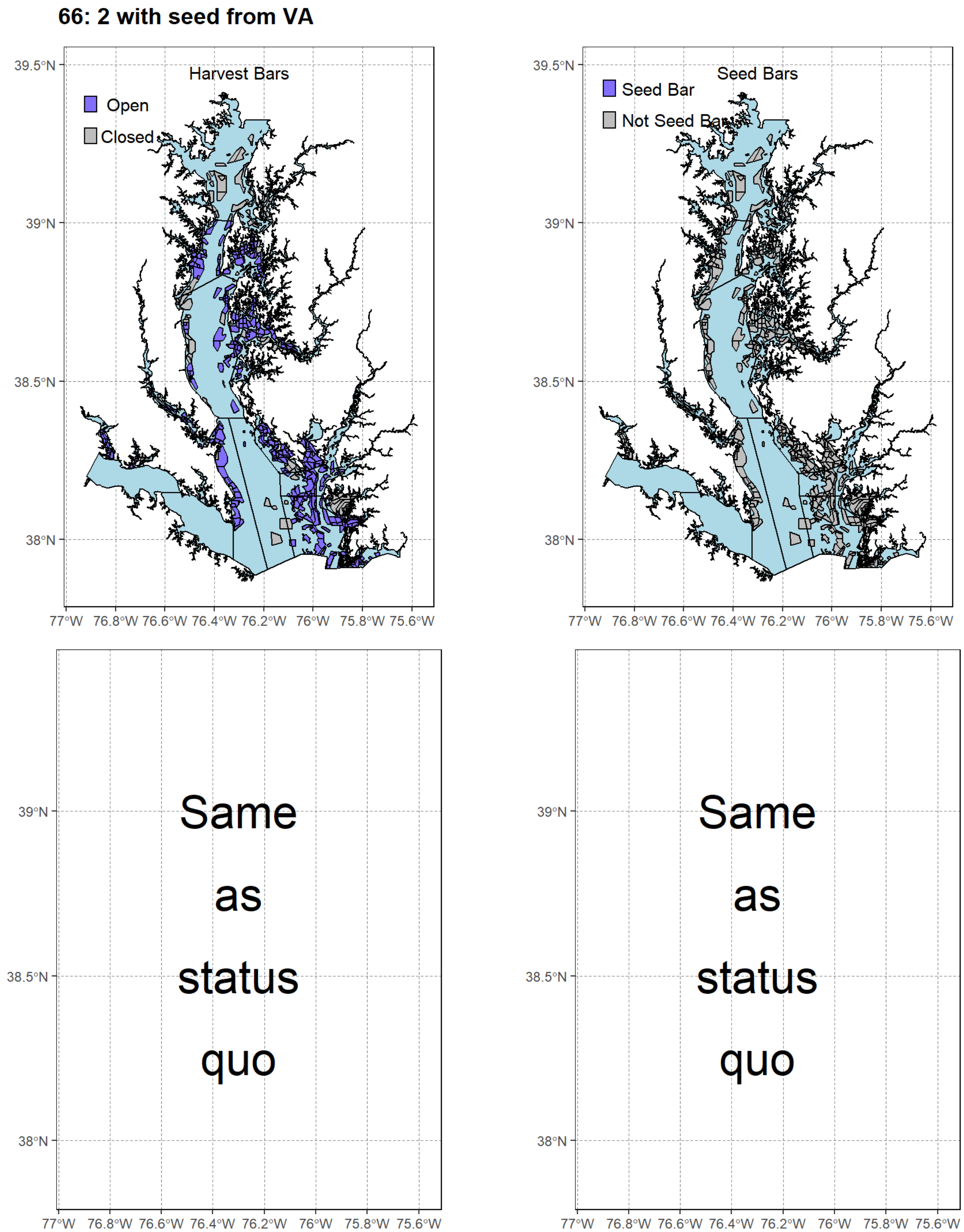

Fig. A130. Bars open to harvest, seed bars, bars open to rotational harvest, and shell dredging bars for option 66.

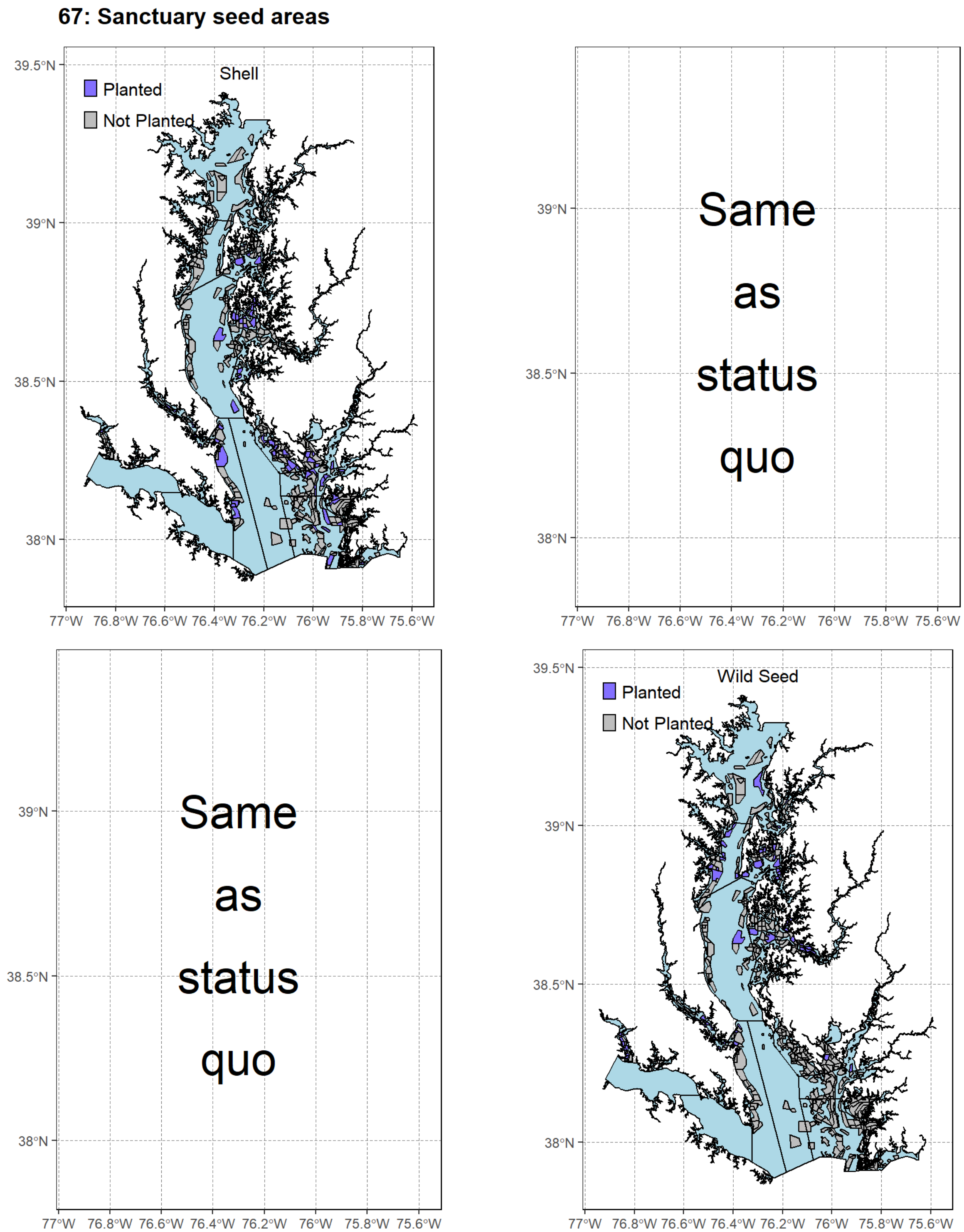

Fig. A131. Locations of shell, hatchery spat, alternate substrate, and wild seed plantings for option 67.

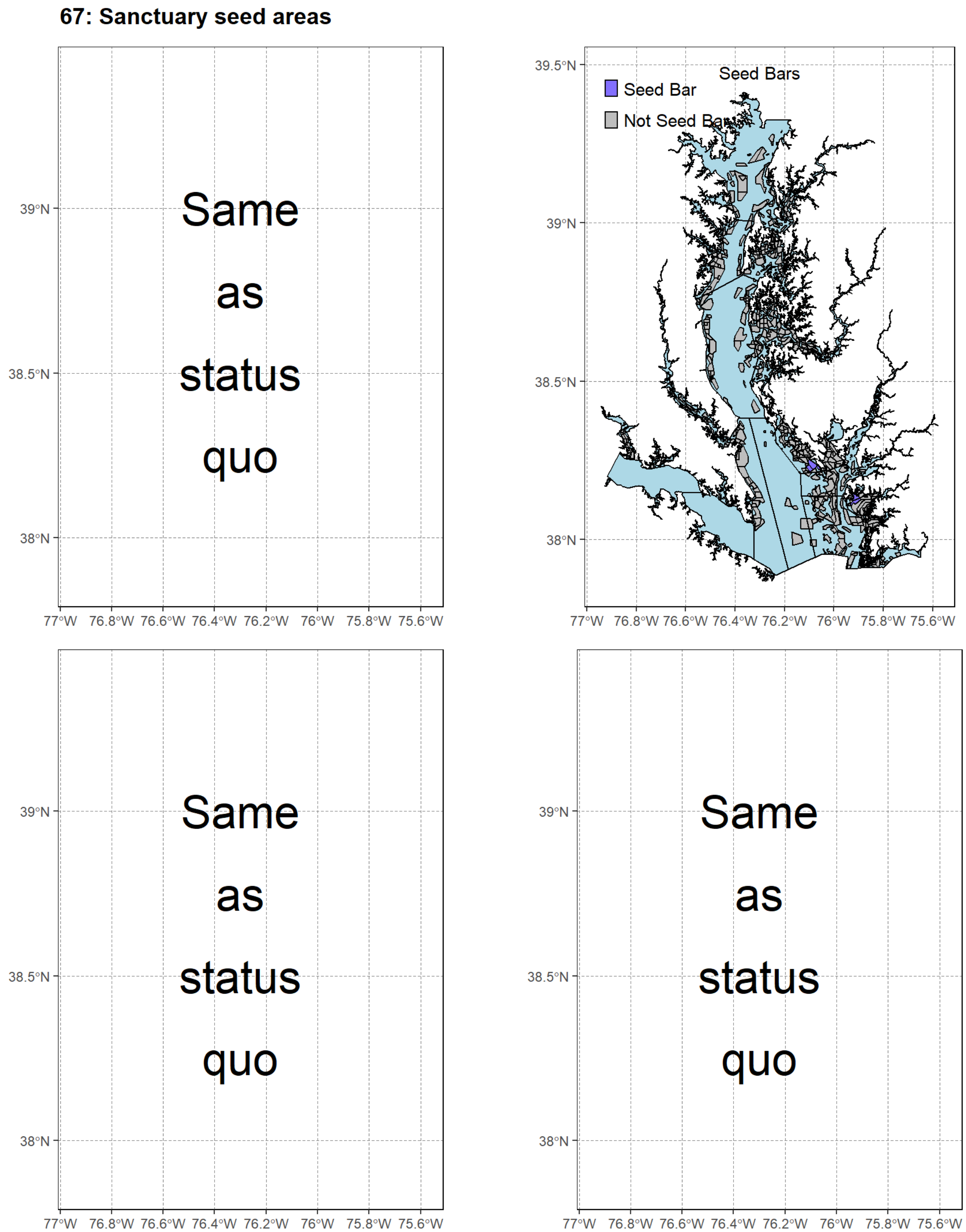

Fig. A132. Bars open to harvest, seed bars, bars open to rotational harvest, and shell dredging bars for option 67.

68: SOAR plant aquaculture adults in sanctuaries

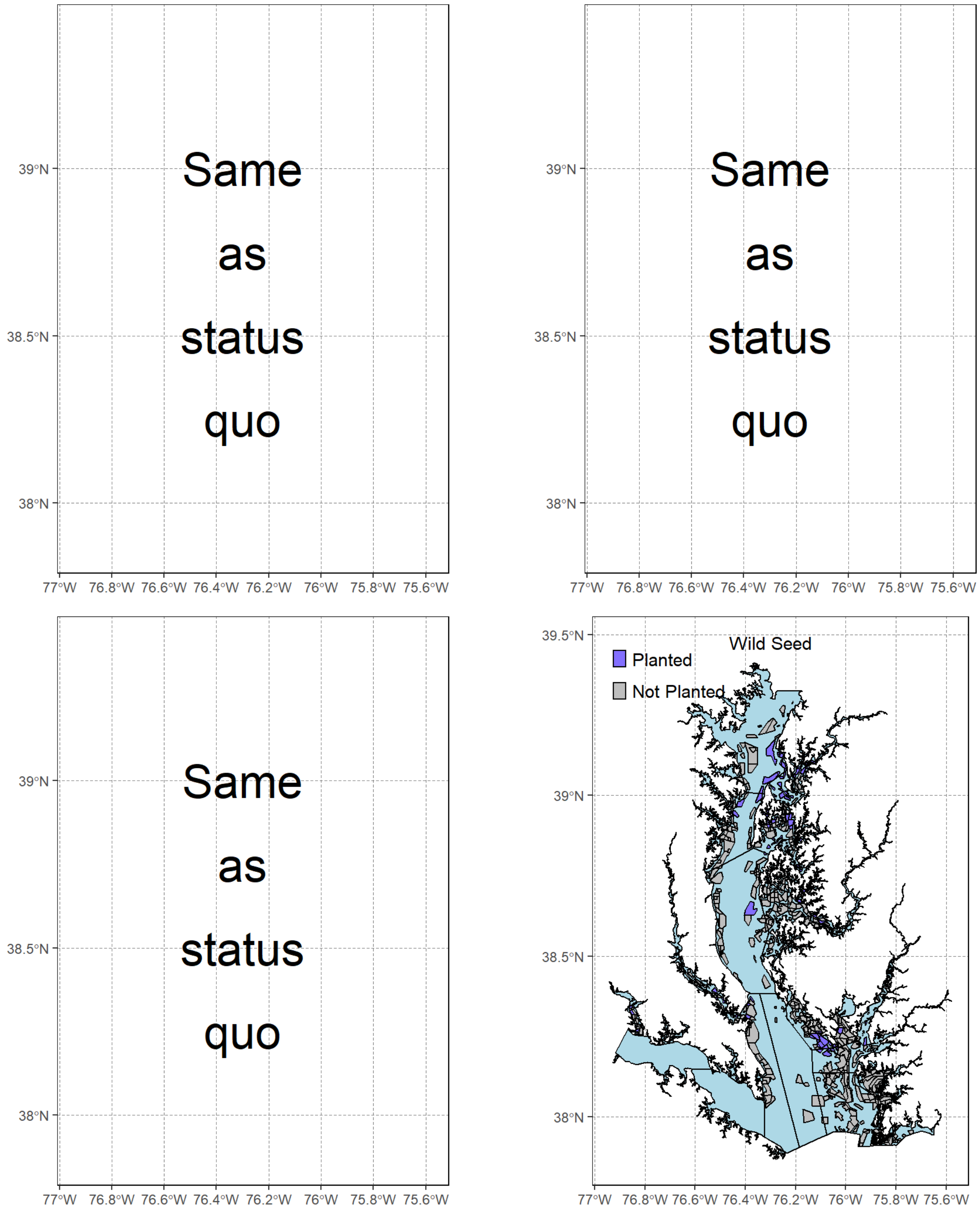

Fig. A133. Locations of shell, hatchery spat, alternate substrate, and wild seed plantings for option 68.

68: SOAR plant aquaculture adults in sanctuaries

Fig. A134. Bars open to harvest, seed bars, bars open to rotational harvest, and shell dredging bars for option 68.

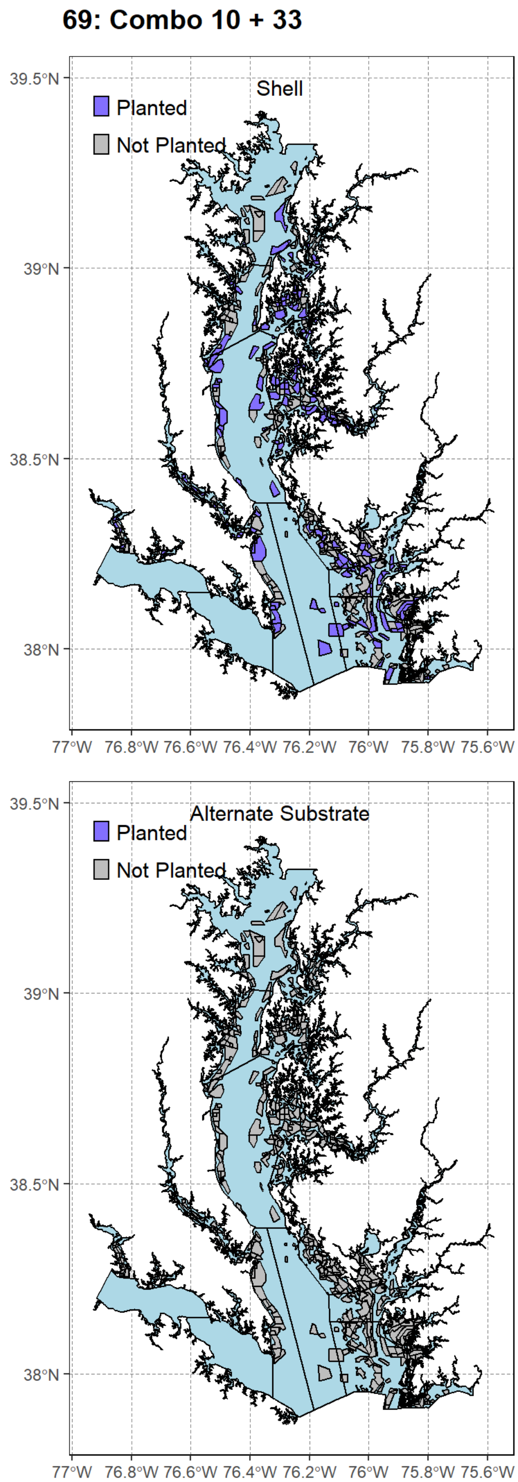

Fig. A135. Locations of shell, hatchery spat, alternate substrate, and wild seed plantings for option 69.

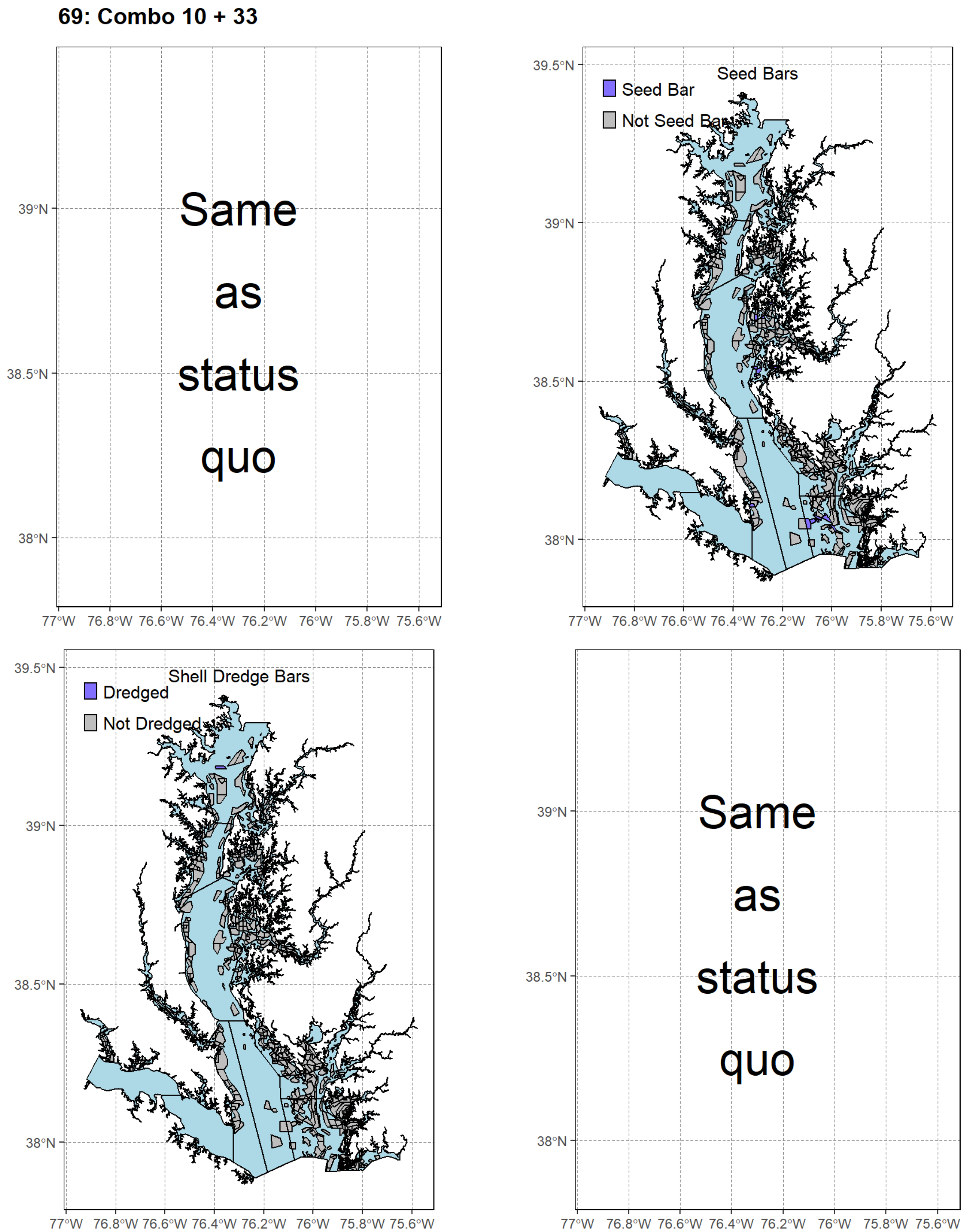

Fig. A136. Bars open to harvest, seed bars, bars open to rotational harvest, and shell dredging bars for option 69.

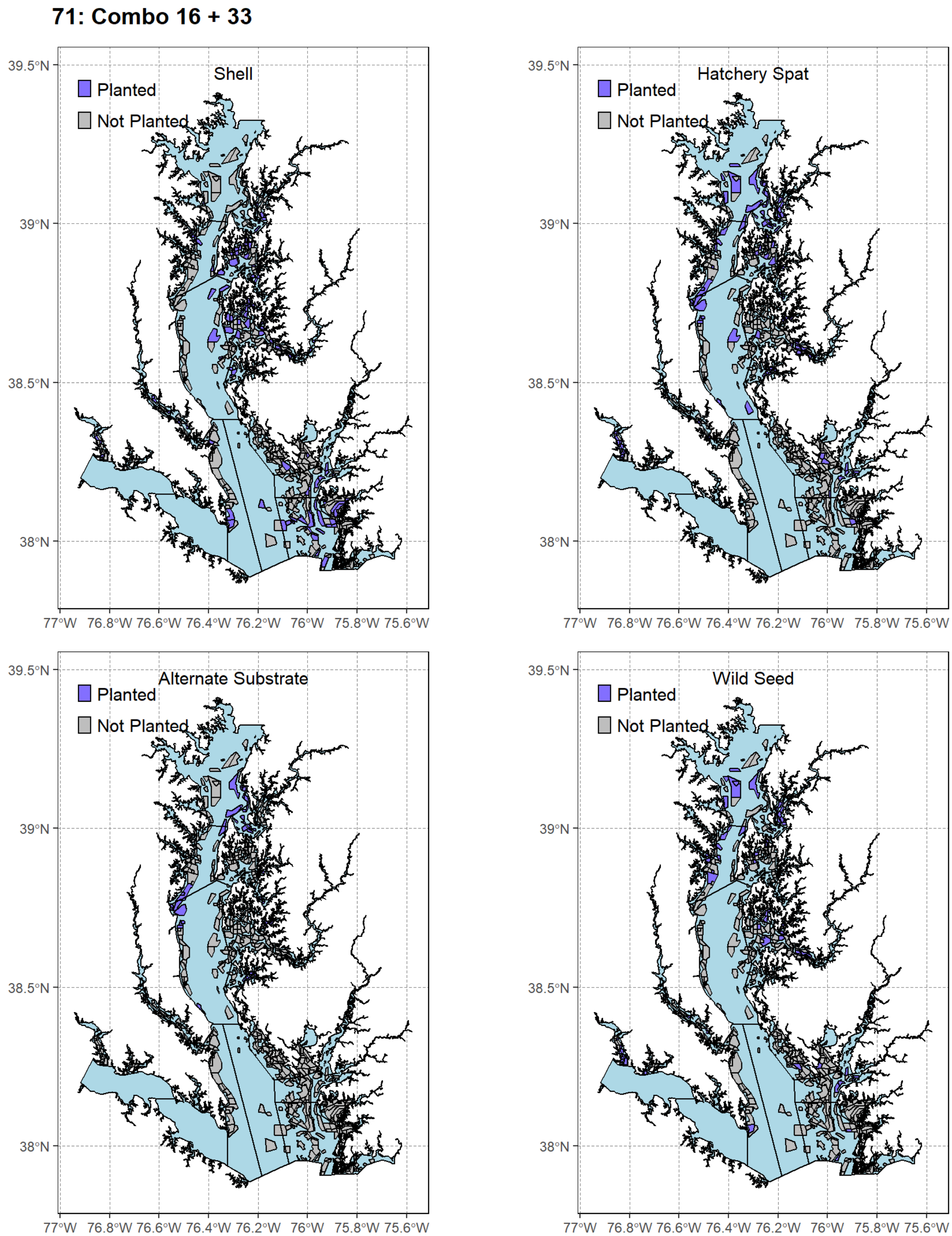

Fig. A137. Locations of shell, hatchery spat, alternate substrate, and wild seed plantings for option 71.

71: Combo 16 + 33

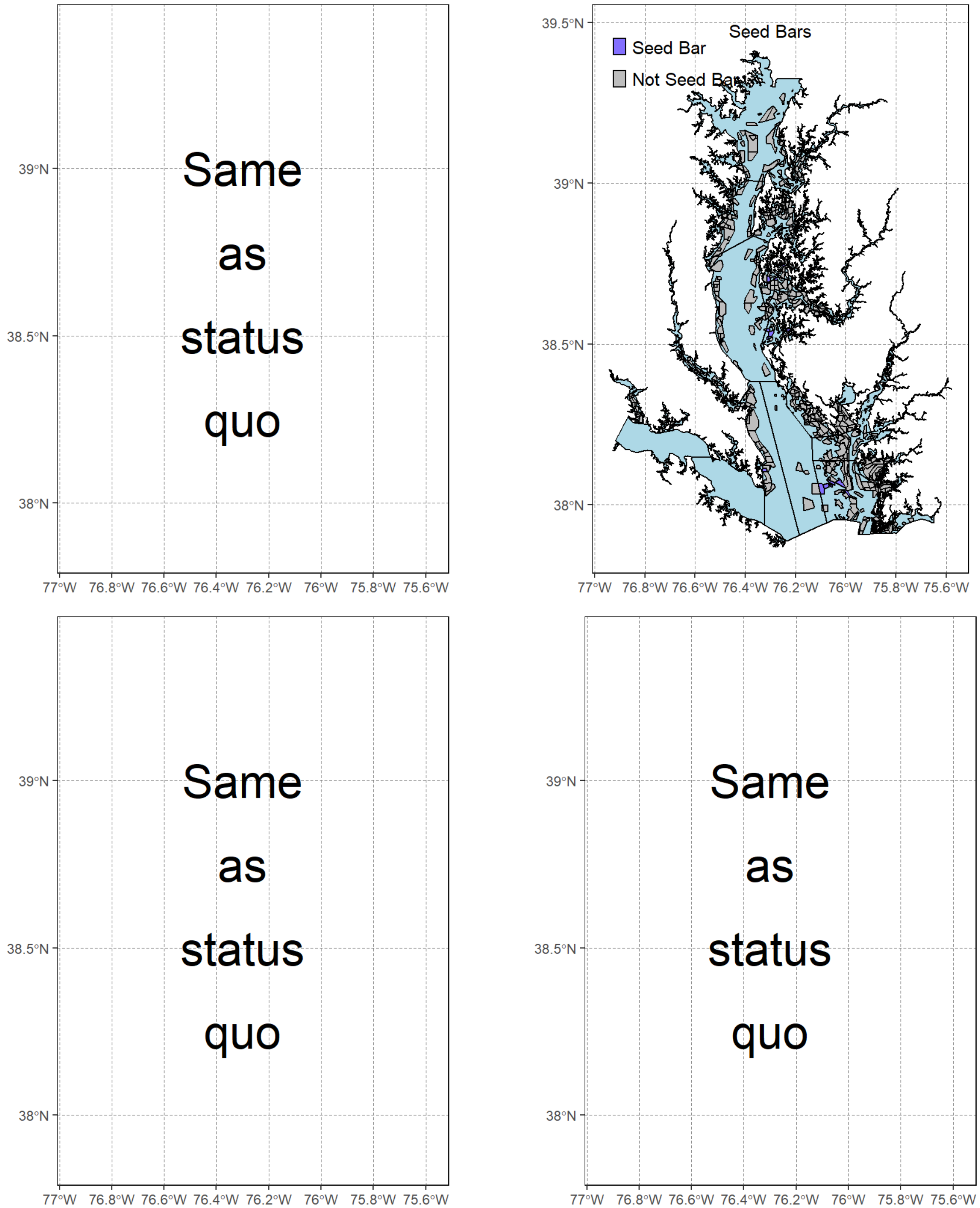

Fig. A138. Bars open to harvest, seed bars, bars open to rotational harvest, and shell dredging bars for option 71.

72: Combo 31 + 33

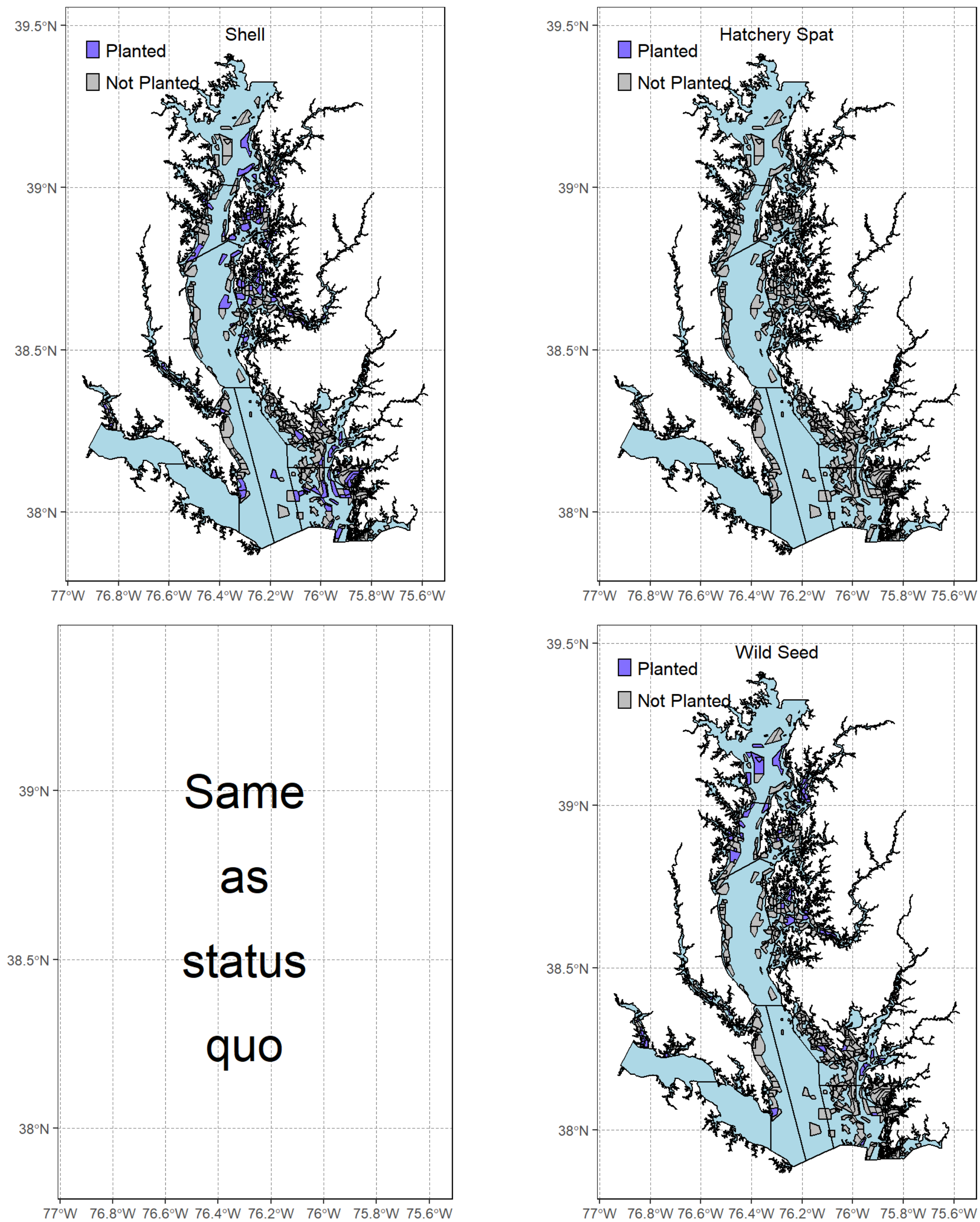

Fig. A139. Locations of shell, hatchery spat, alternate substrate, and wild seed plantings for option 72.

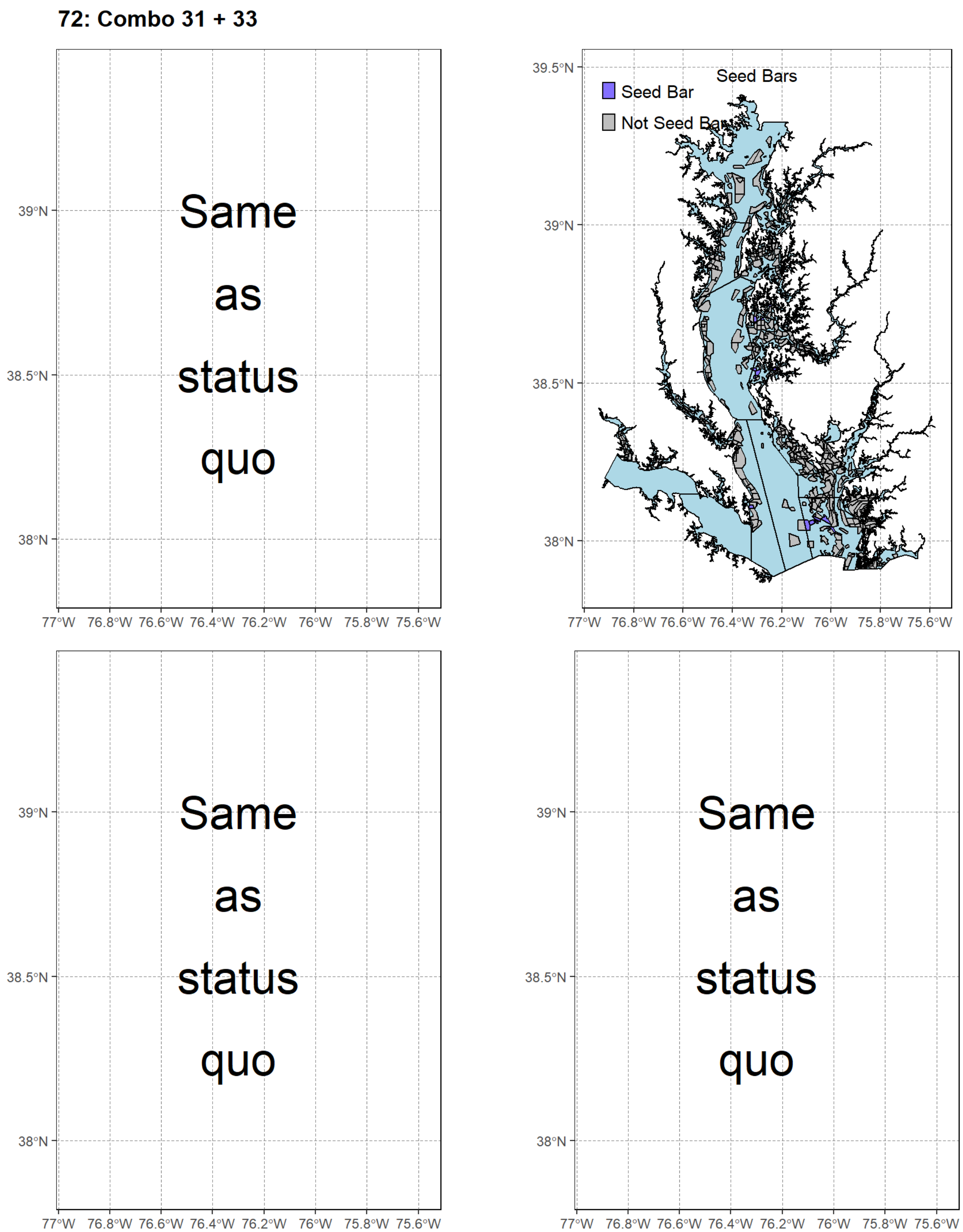

Fig. A140. Bars open to harvest, seed bars, bars open to rotational harvest, and shell dredging bars for option 72.

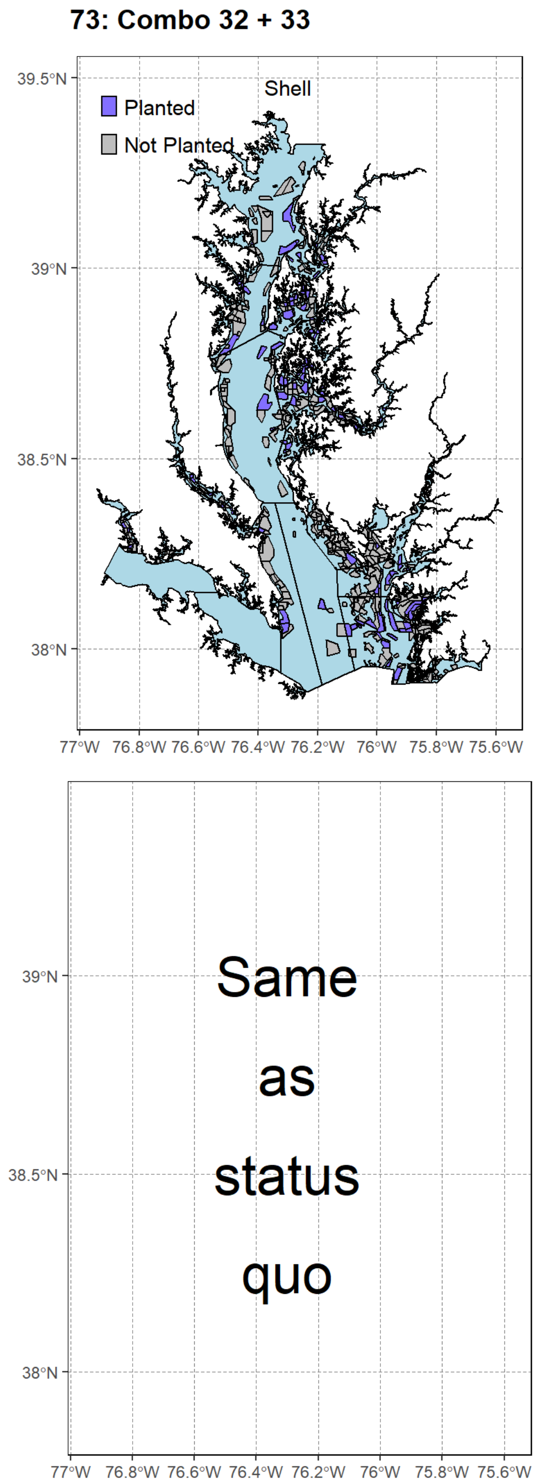

Fig. A141. Locations of shell, hatchery spat, alternate substrate, and wild seed plantings for option 73.

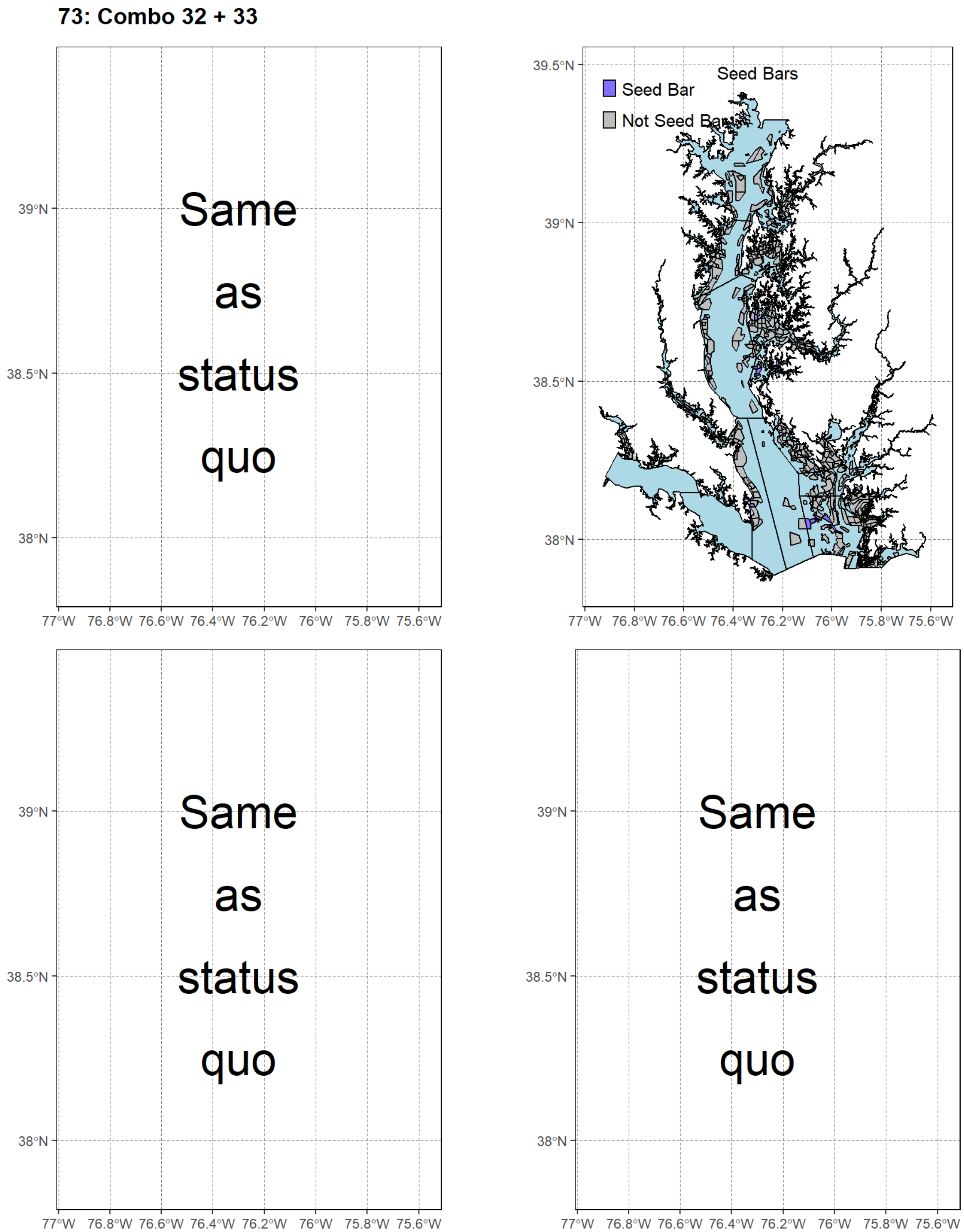

Fig. A142. Bars open to harvest, seed bars, bars open to rotational harvest, and shell dredging bars for option 73.

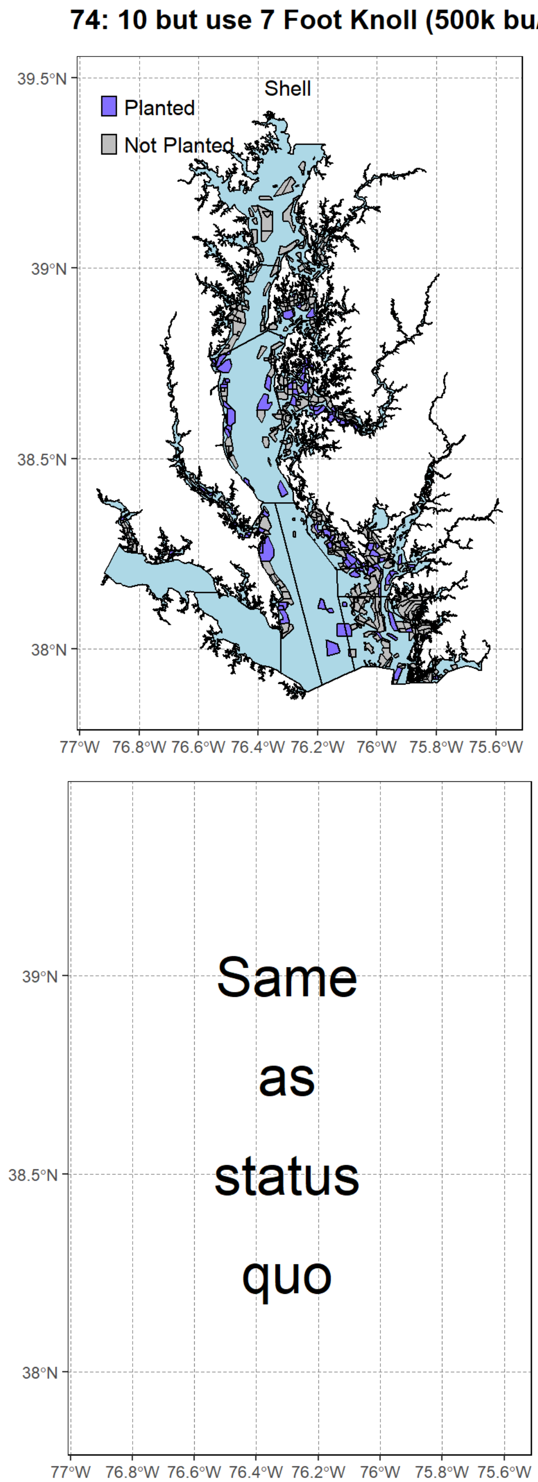

Fig. A143. Locations of shell, hatchery spat, alternate substrate, and wild seed plantings for option 74.

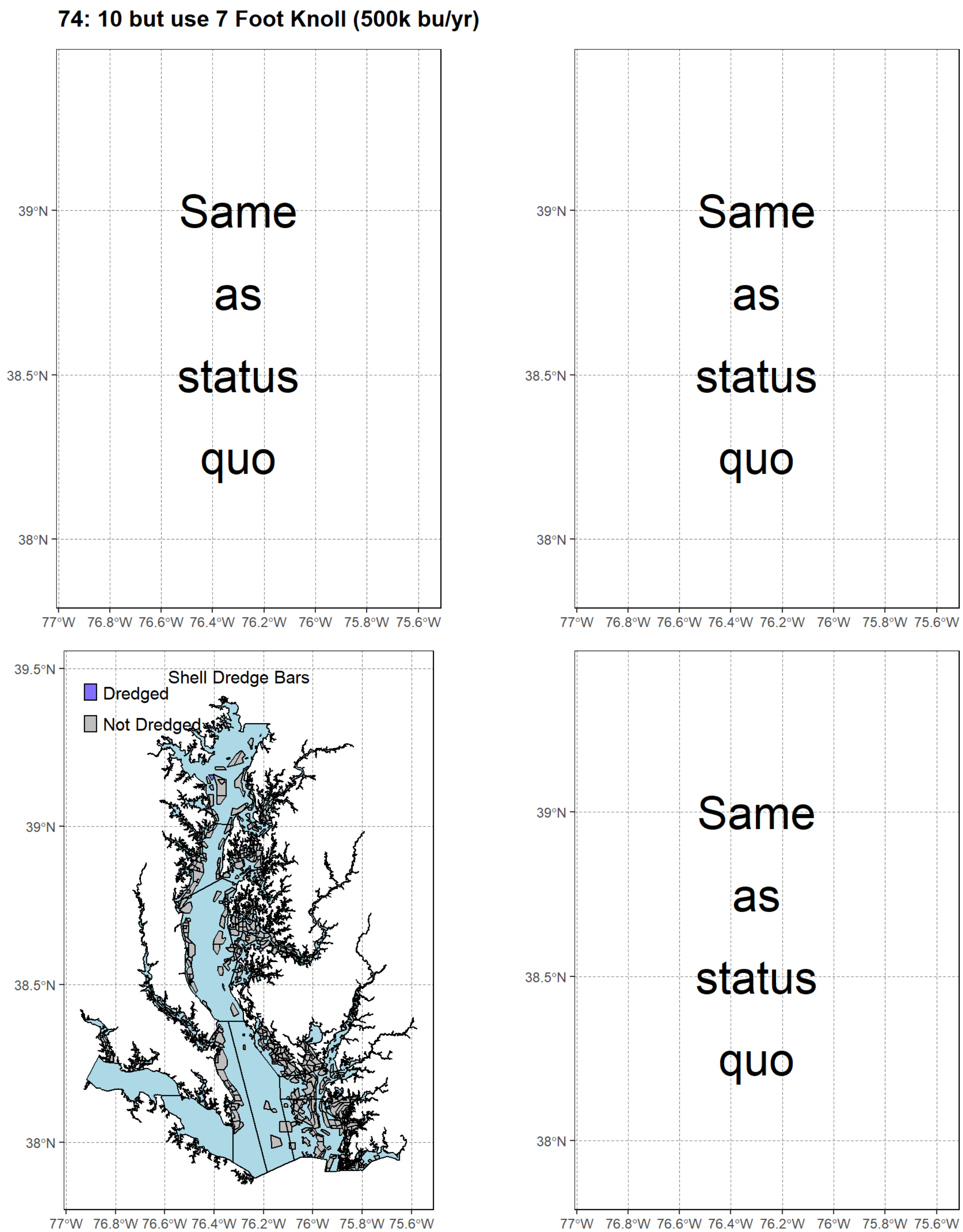

Fig. A144. Bars open to harvest, seed bars, bars open to rotational harvest, and shell dredging bars for option 74.

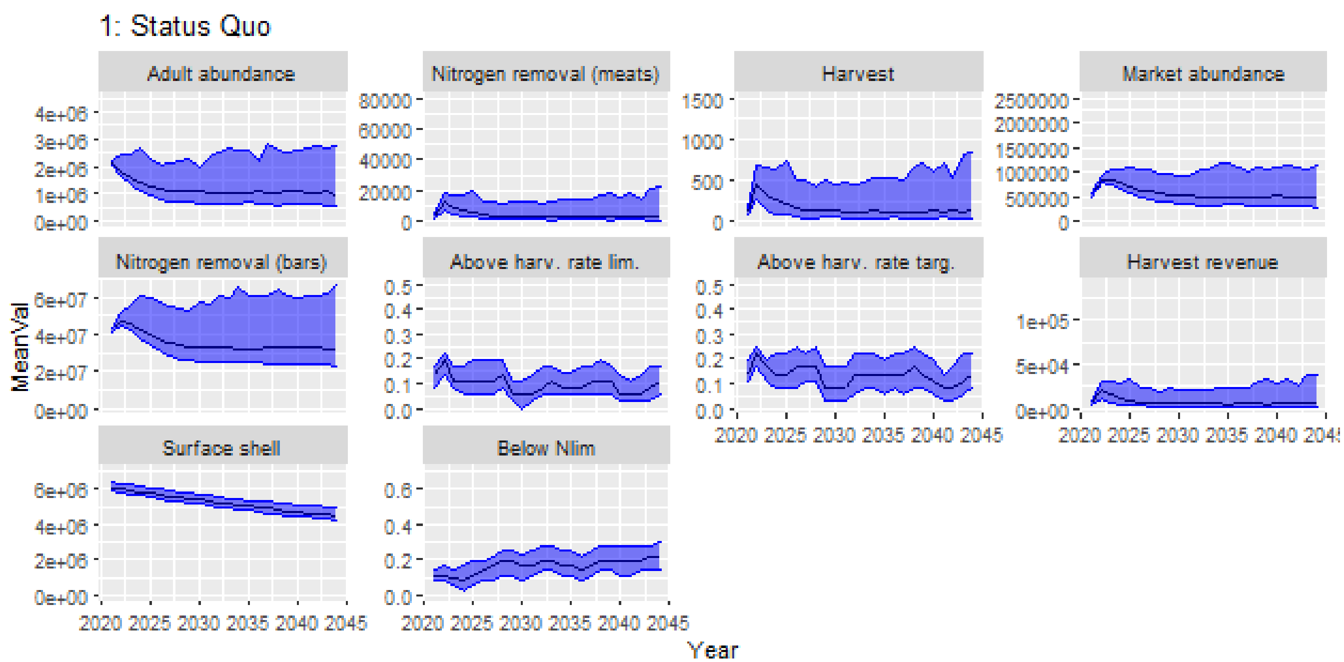

Fig. A145. Forecasted performance of Option 1 during 2022-2044. The solid lines indicate the medians and the shaded areas indicate the area between the upper 90th percentile and the lower 10th percentile.

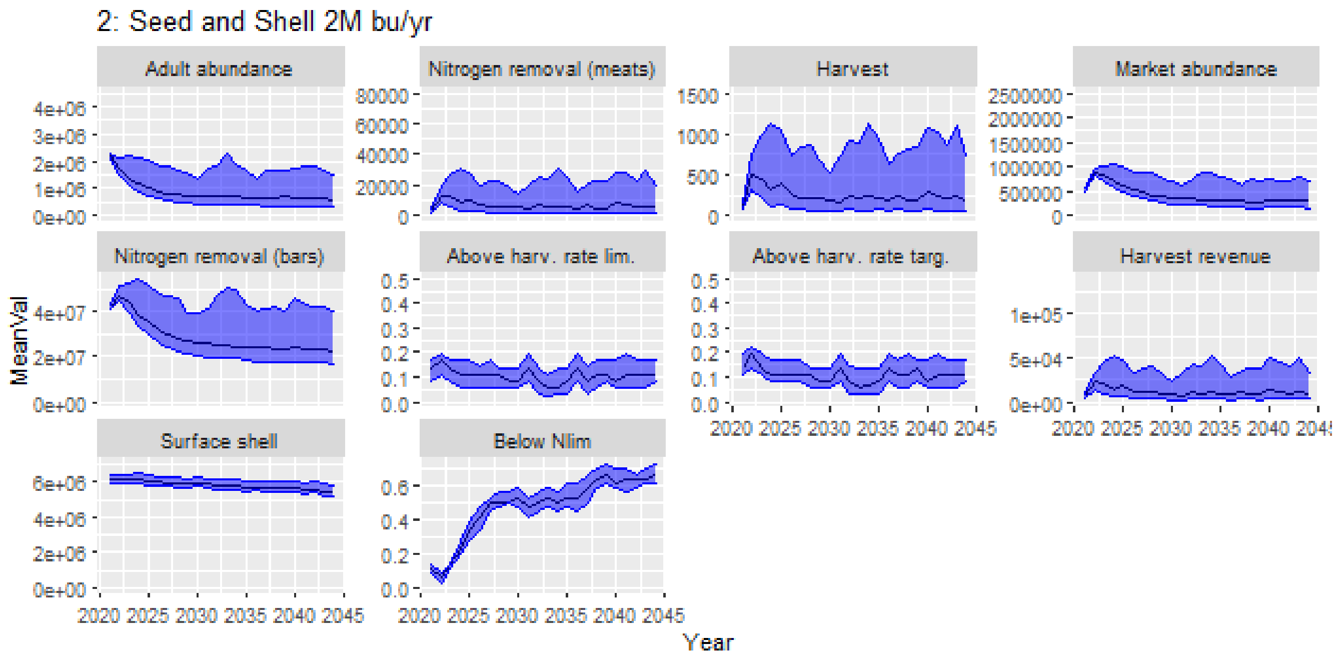

Fig. A146. Forecasted performance of Option 2 during 2022-2044. The solid lines indicate the medians and the shaded areas indicate the area between the upper 90th percentile and the lower 10th percentile.

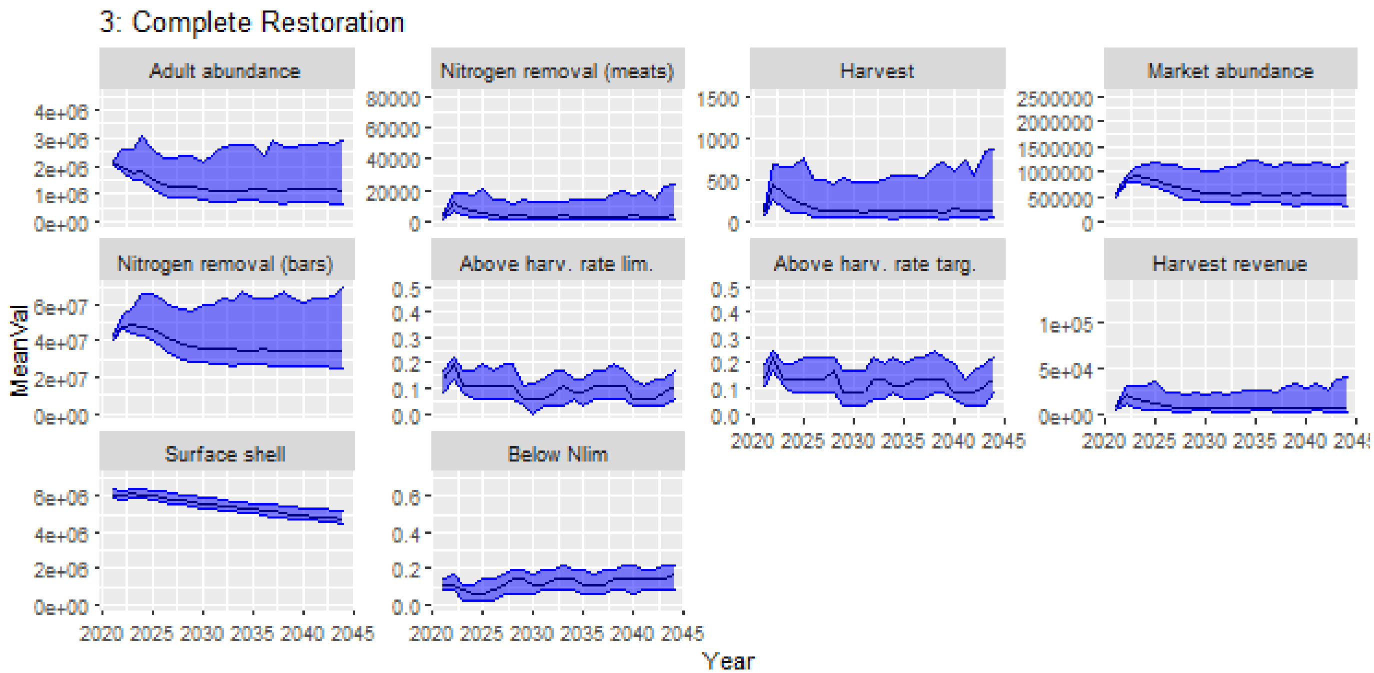

Fig. A147. Forecasted performance of Option 3 during 2022-2044. The solid lines indicate the medians and the shaded areas indicate the area between the upper 90th percentile and the lower 10th percentile.

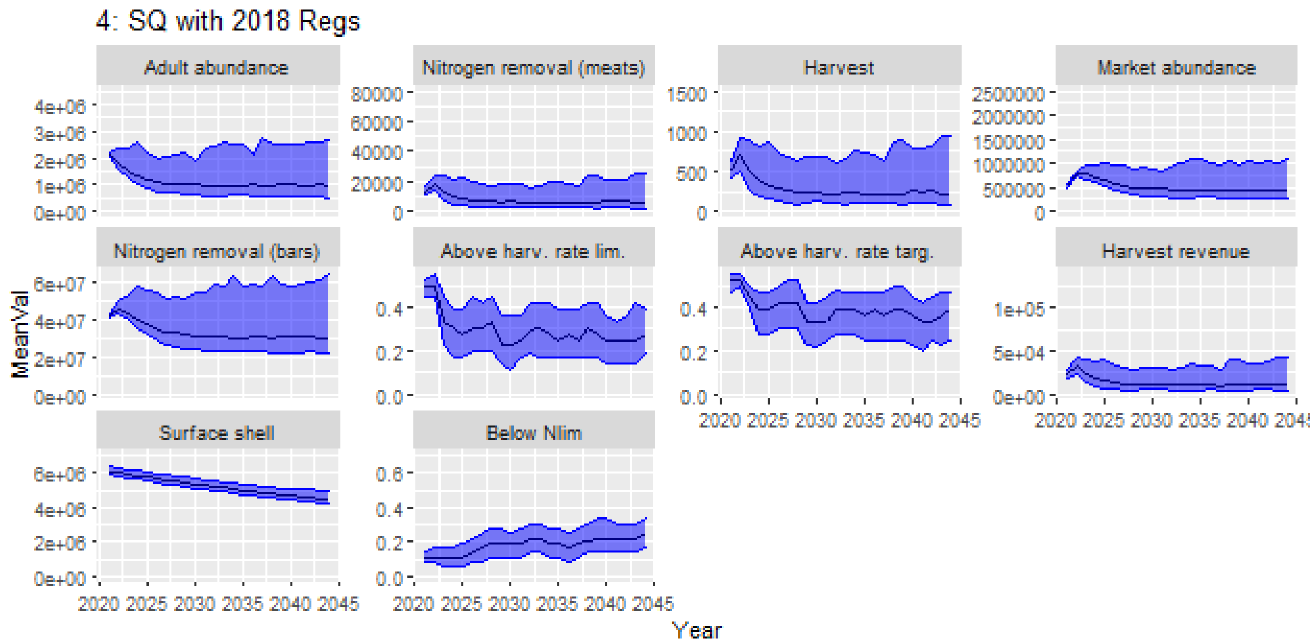

Fig. A148. Forecasted performance of Option 4 during 2022-2044. The solid lines indicate the medians and the shaded areas indicate the area between the upper 90th percentile and the lower 10th percentile.

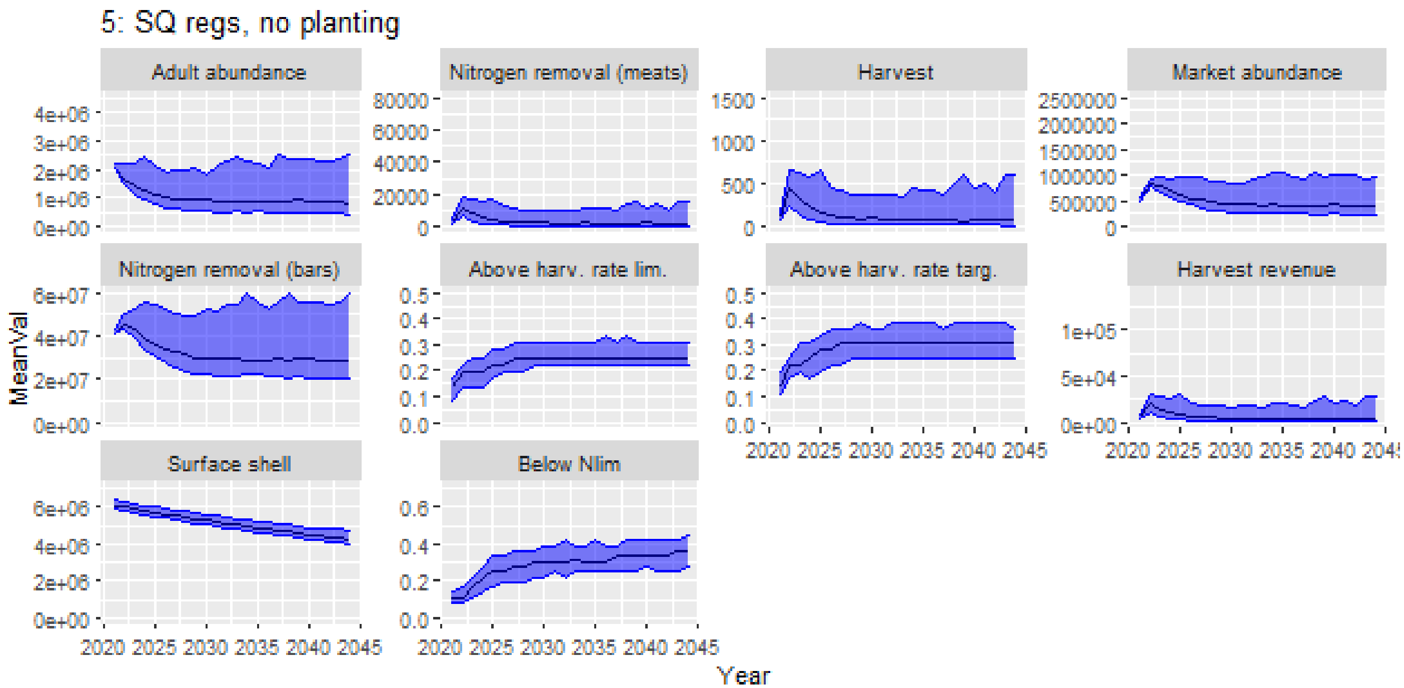

Fig. A149. Forecasted performance of Option 5 during 2022-2044. The solid lines indicate the medians and the shaded areas indicate the area between the upper 90th percentile and the lower 10th percentile.

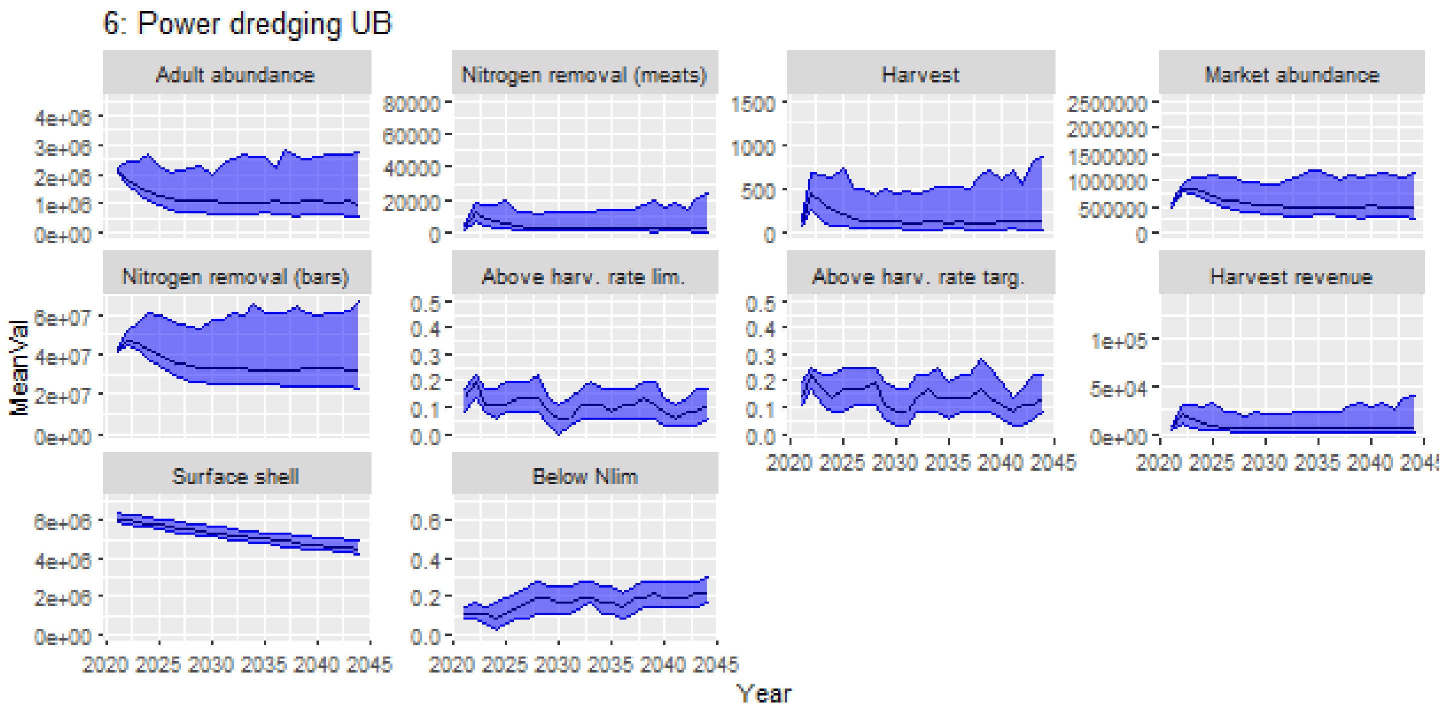

Fig. A150. Forecasted performance of Option 6 during 2022-2044. The solid lines indicate the medians and the shaded areas indicate the area between the upper 90th percentile and the lower 10th percentile.

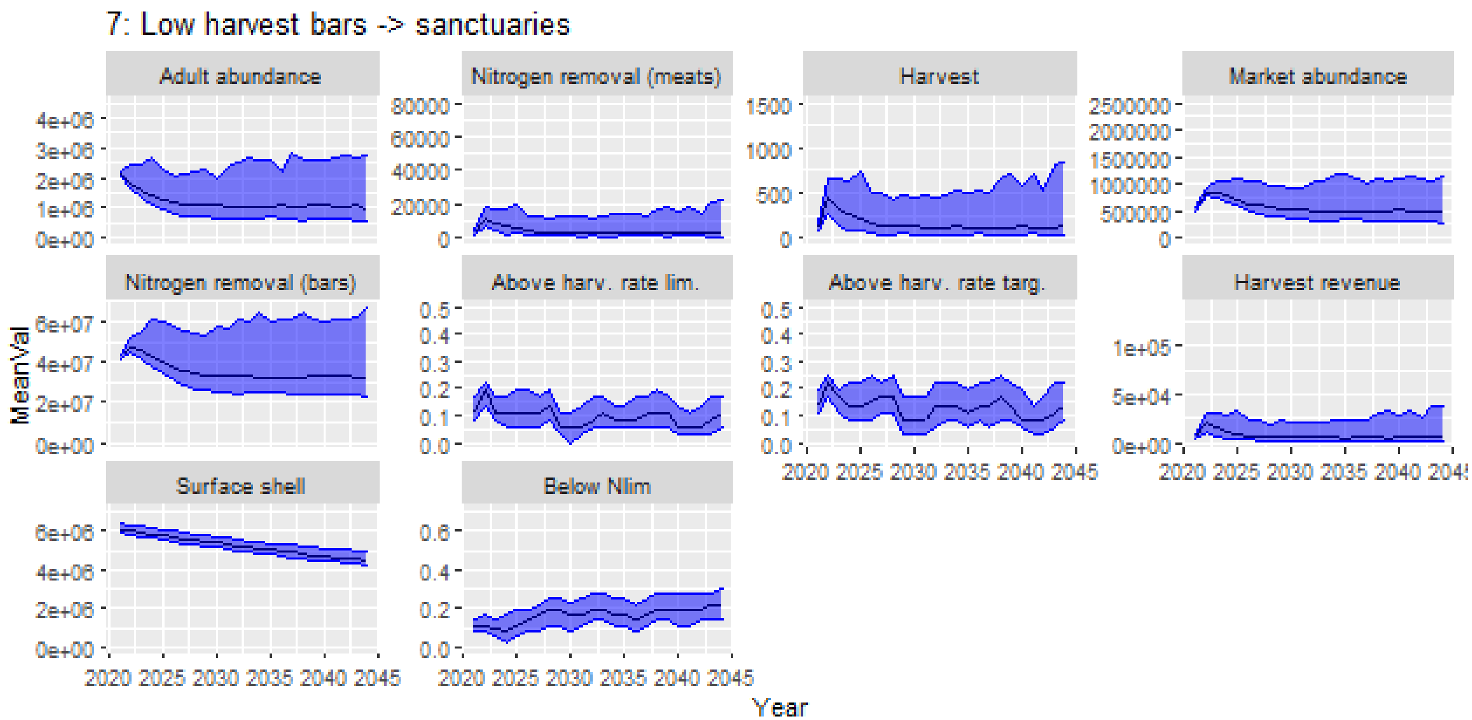

Fig. A151. Forecasted performance of Option 7 during 2022-2044. The solid lines indicate the medians and the shaded areas indicate the area between the upper 90th percentile and the lower 10th percentile.

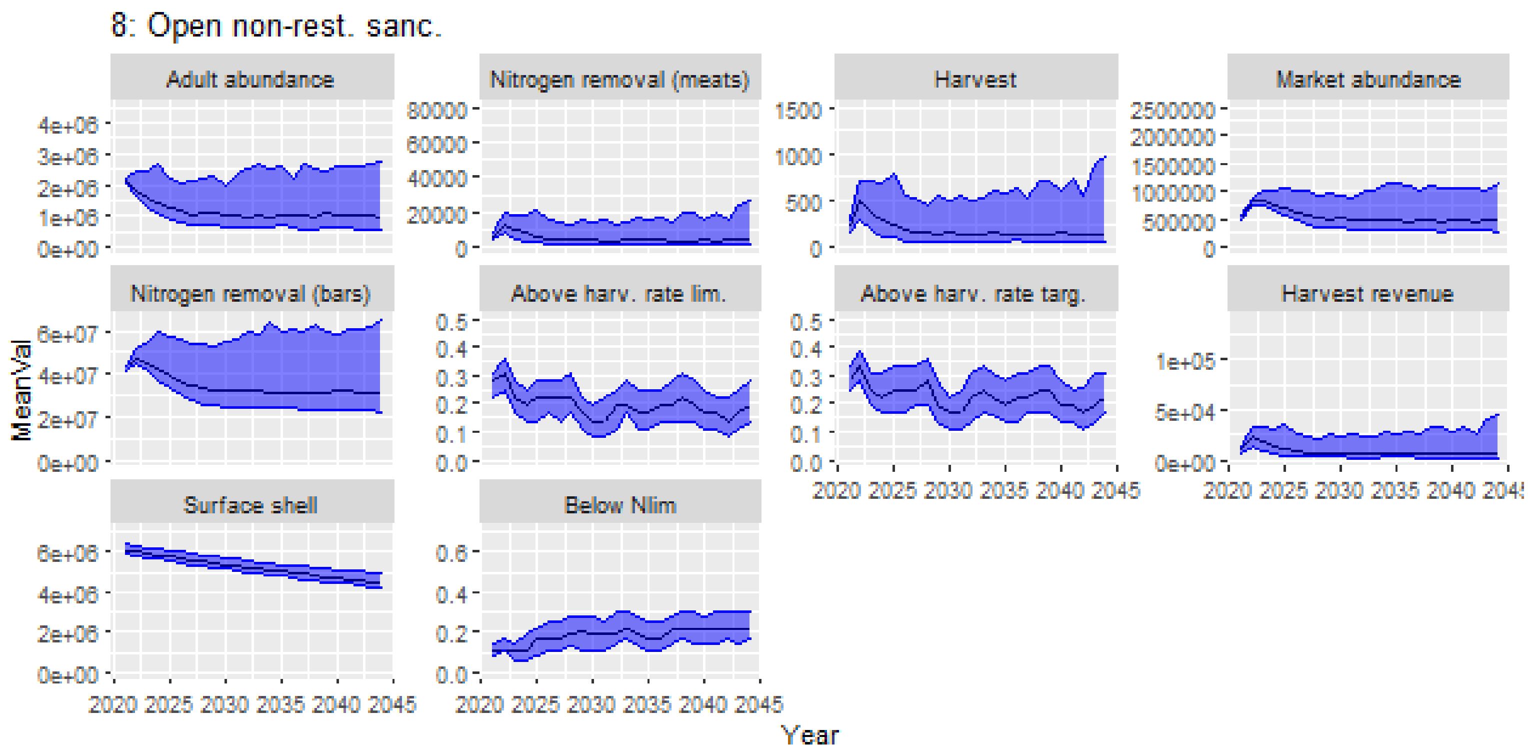

Fig. A152. Forecasted performance of Option 8 during 2022-2044. The solid lines indicate the medians and the shaded areas indicate the area between the upper 90th percentile and the lower 10th percentile.

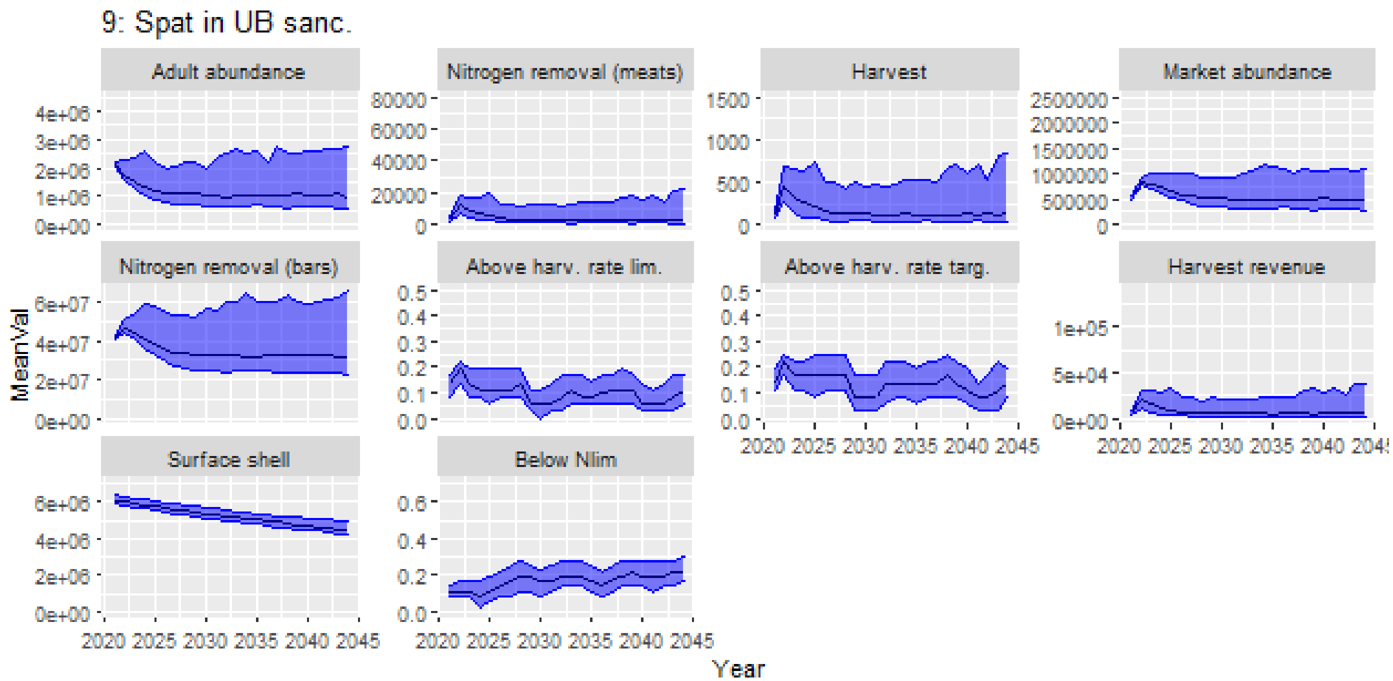

Fig. A153. Forecasted performance of Option 9 during 2022-2044. The solid lines indicate the medians and the shaded areas indicate the area between the upper 90th percentile and the lower 10th percentile.

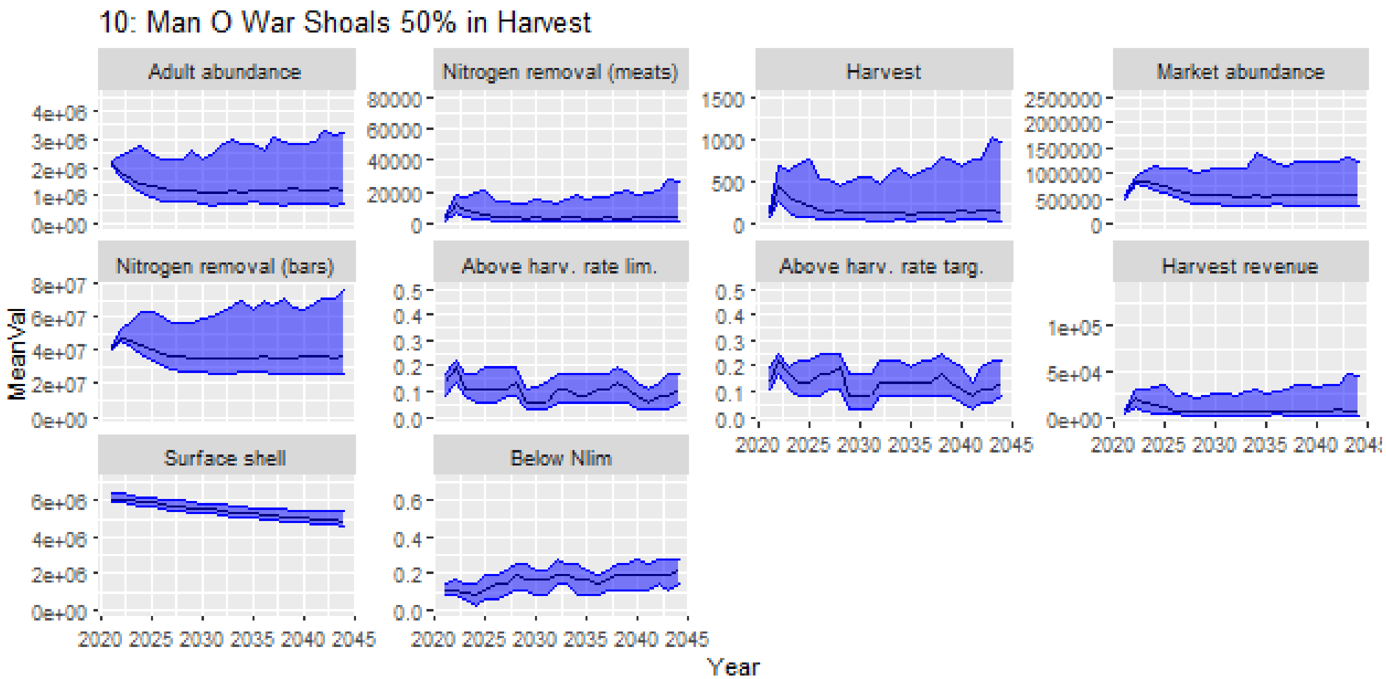

Fig. A154. Forecasted performance of Option 10 during 2022-2044. The solid lines indicate the medians and the shaded areas indicate the area between the upper 90th percentile and the lower 10th percentile.

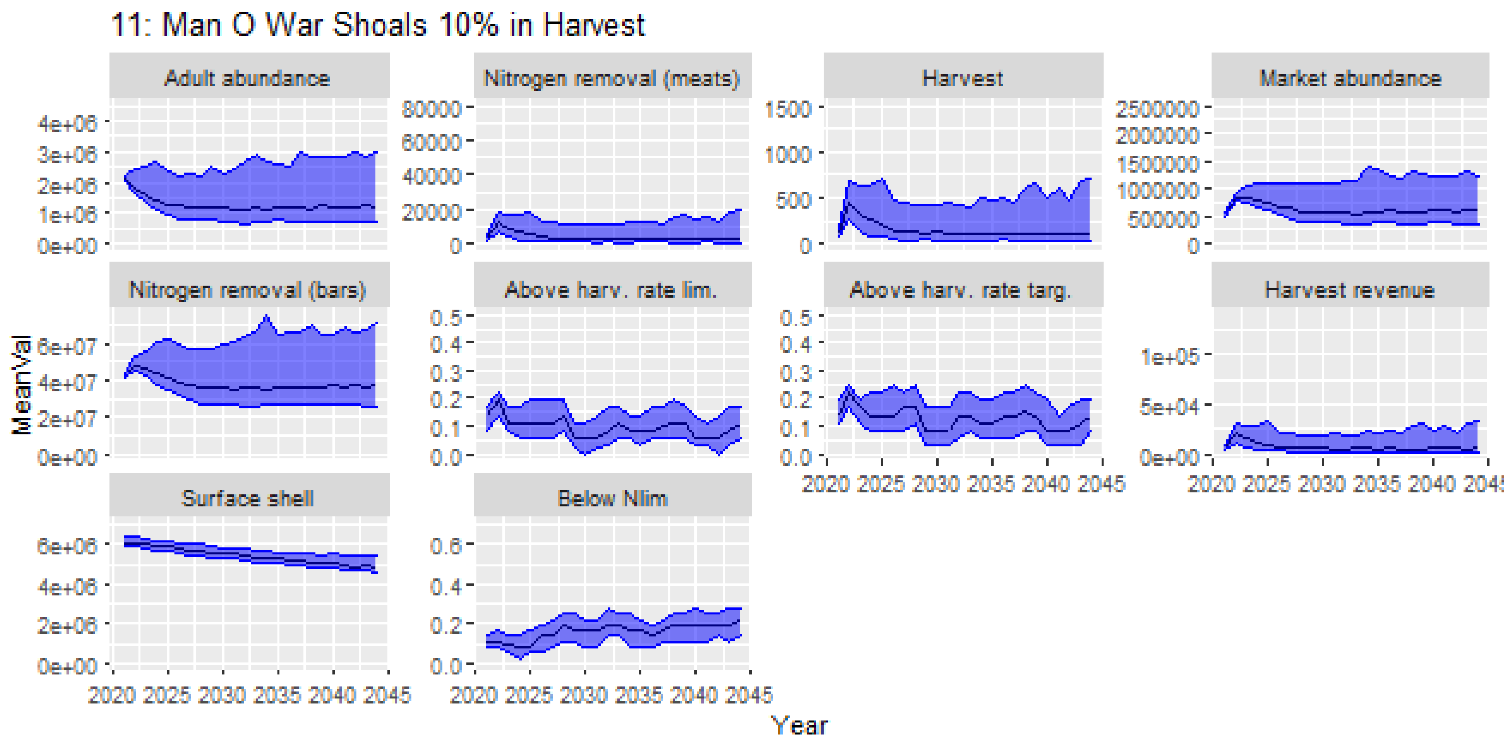

Fig. A155. Forecasted performance of Option 11 during 2022-2044. The solid lines indicate the medians and the shaded areas indicate the area between the upper 90th percentile and the lower 10th percentile.

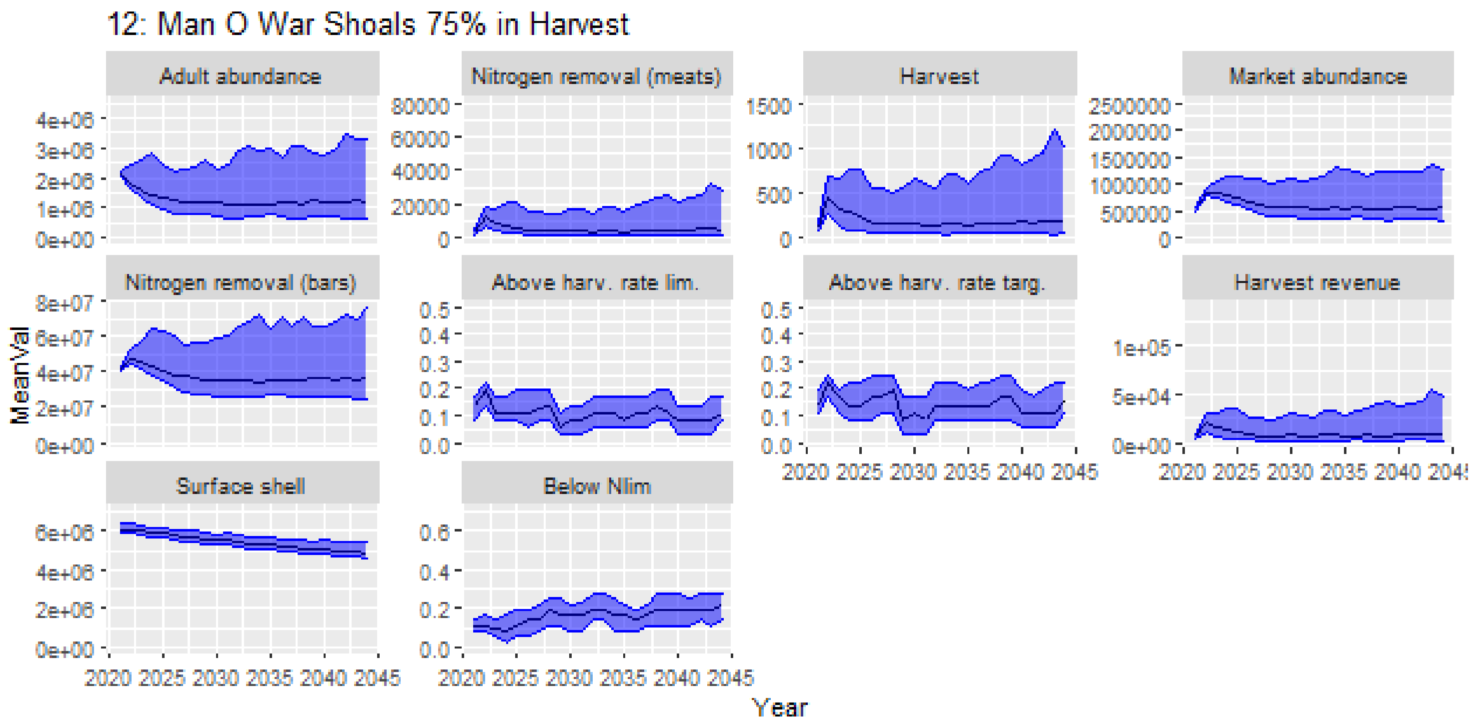

Fig. A156. Forecasted performance of Option 12 during 2022-2044. The solid lines indicate the medians and the shaded areas indicate the area between the upper 90th percentile and the lower 10th percentile.

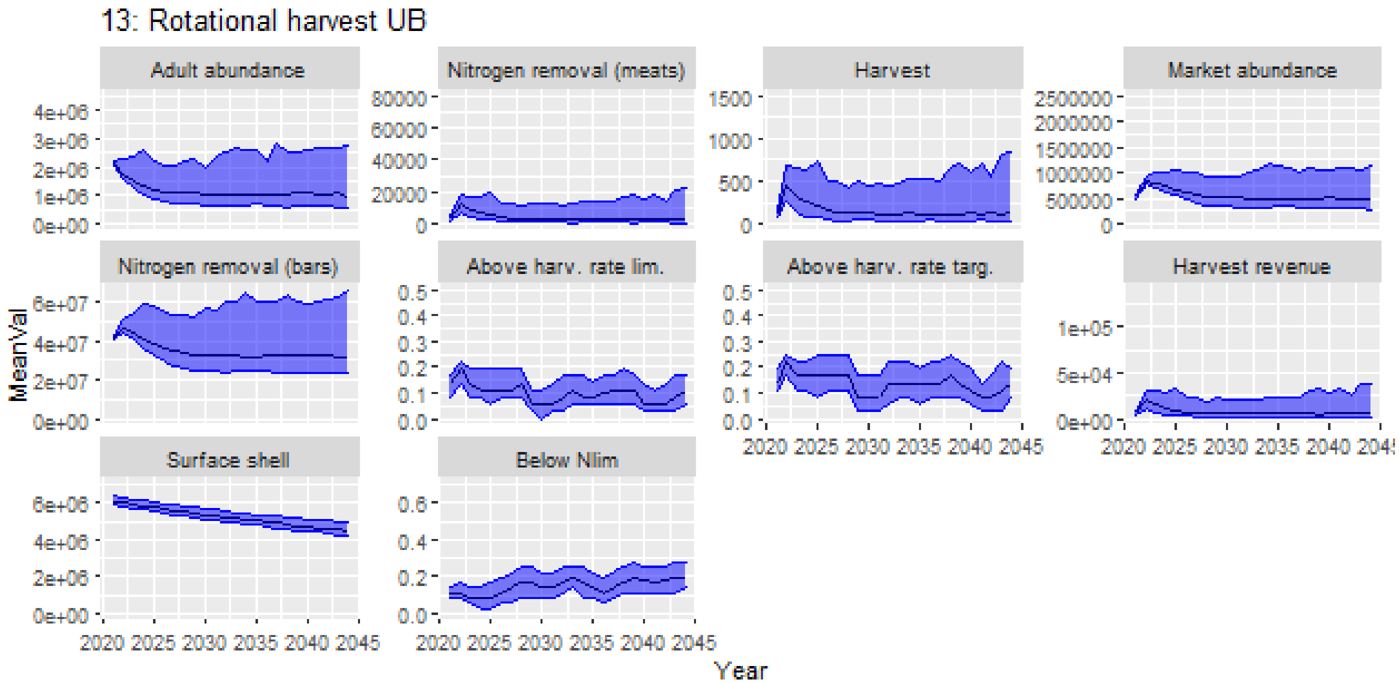

Fig. A157. Forecasted performance of Option 13 during 2022-2044. The solid lines indicate the medians and the shaded areas indicate the area between the upper 90th percentile and the lower 10th percentile.

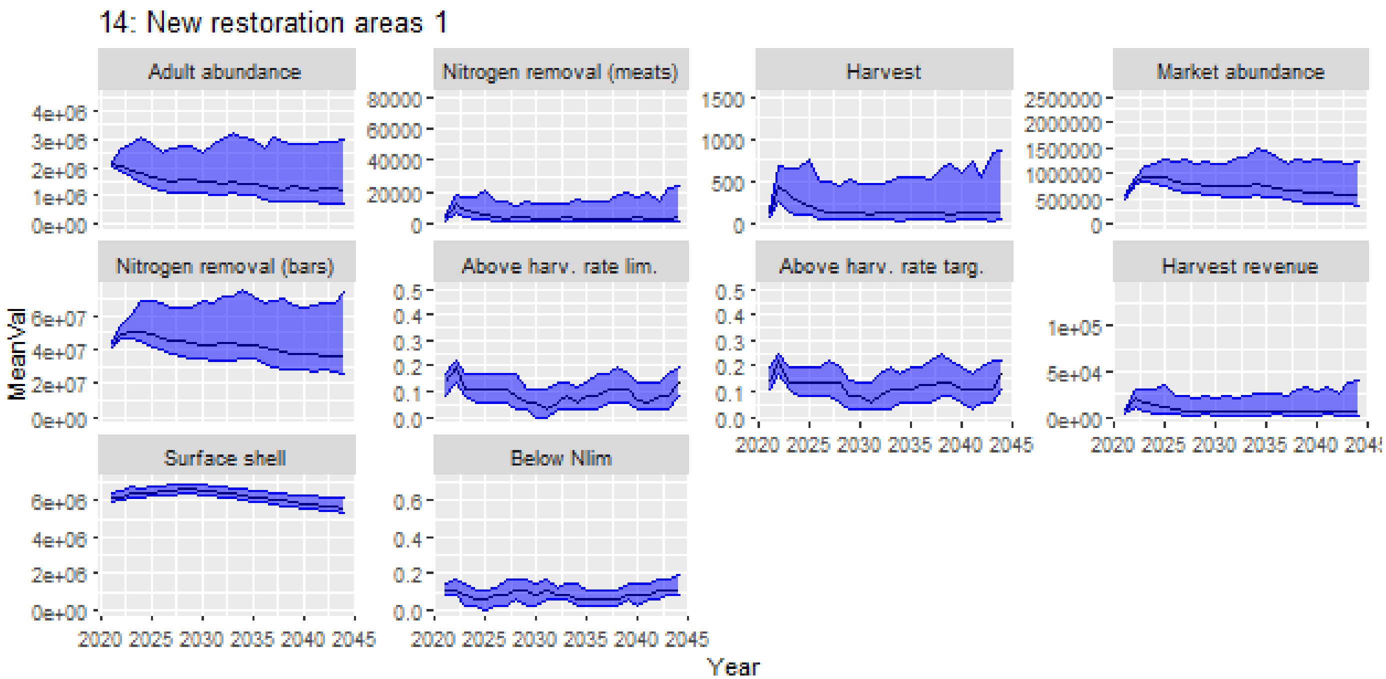

Fig. A158. Forecasted performance of Option 14 during 2022-2044. The solid lines indicate the medians and the shaded areas indicate the area between the upper 90th percentile and the lower 10th percentile.

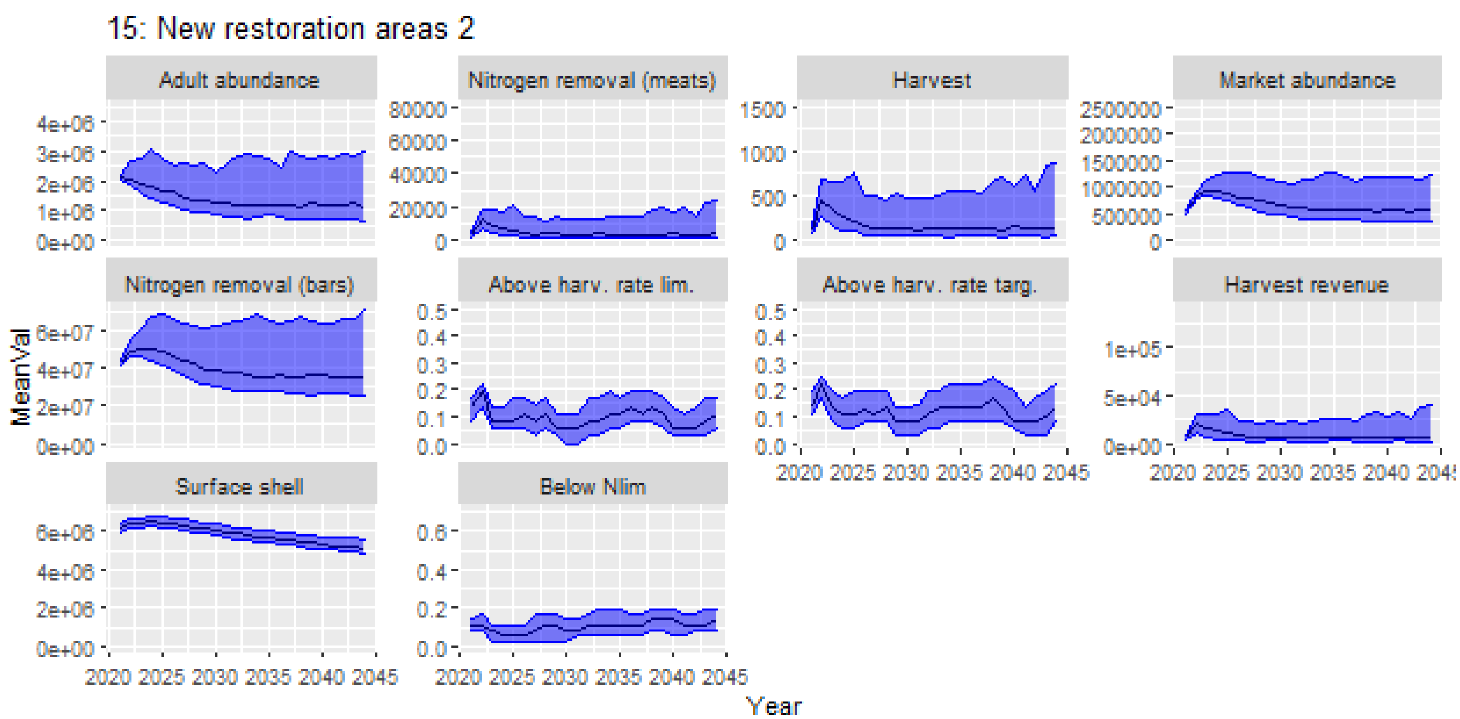

Fig. A159. Forecasted performance of Option 15 during 2022-2044. The solid lines indicate the medians and the shaded areas indicate the area between the upper 90th percentile and the lower 10th percentile.

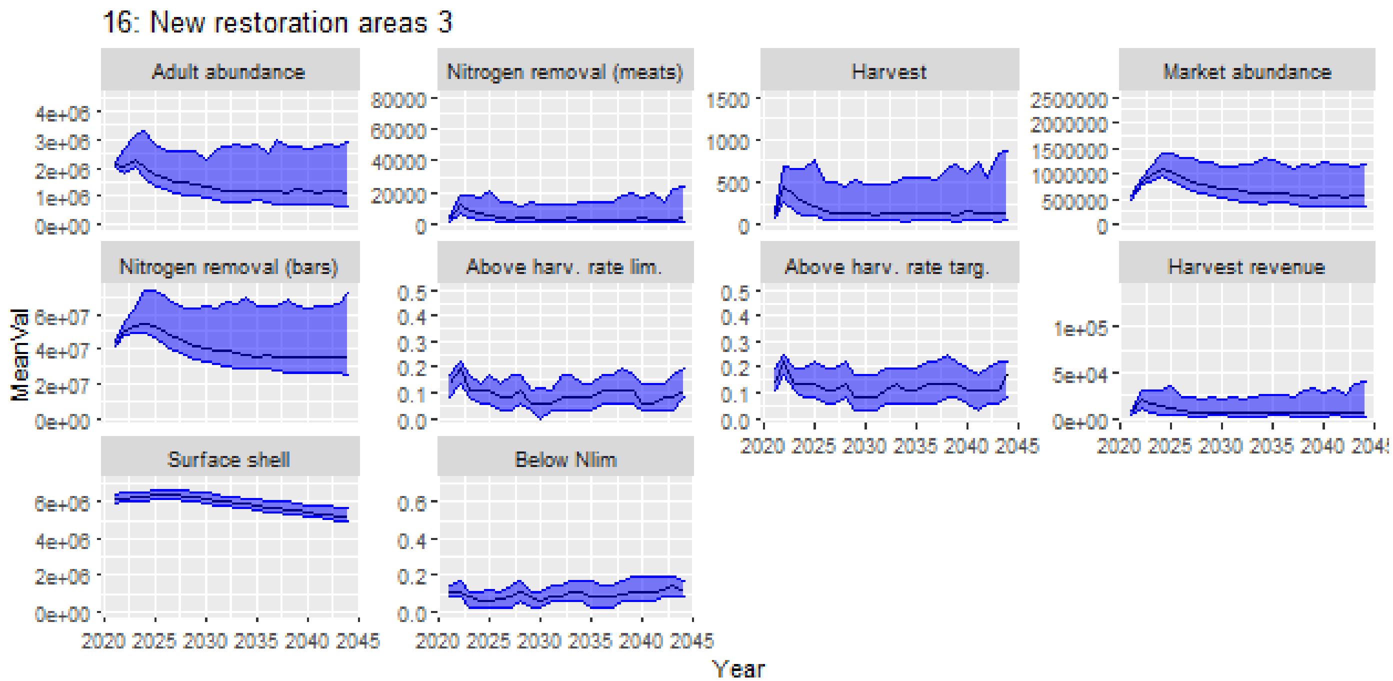

Fig. A160. Forecasted performance of Option 16 during 2022-2044. The solid lines indicate the medians and the shaded areas indicate the area between the upper 90th percentile and the lower 10th percentile.

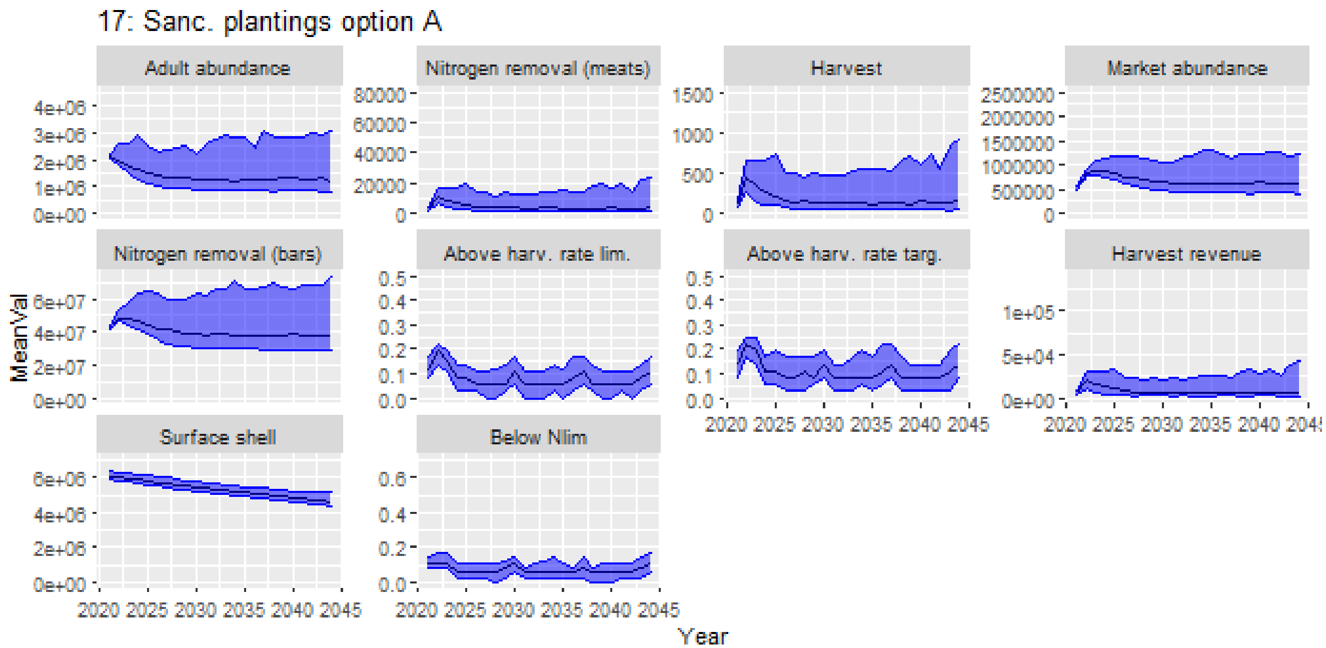

Fig. A161. Forecasted performance of Option 17 during 2022-2044. The solid lines indicate the medians and the shaded areas indicate the area between the upper 90th percentile and the lower 10th percentile.

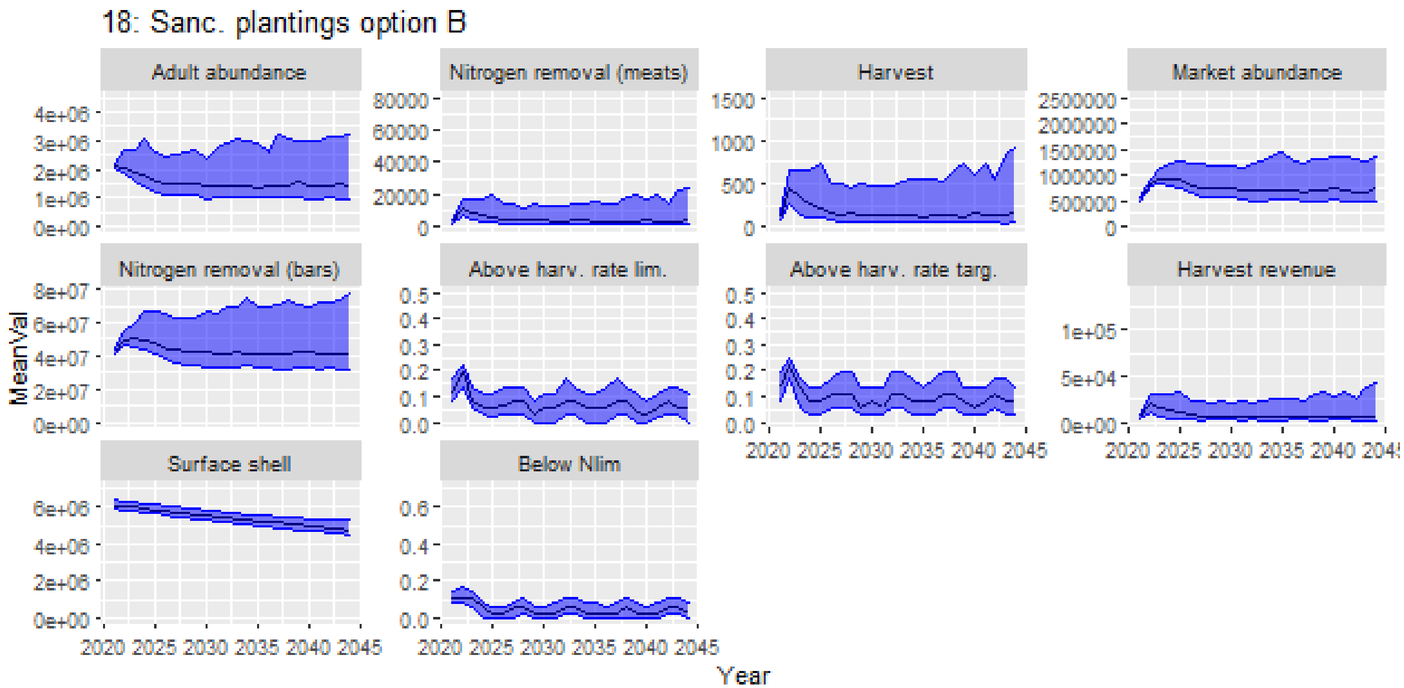

Fig. A162. Forecasted performance of Option 18 during 2022-2044. The solid lines indicate the medians and the shaded areas indicate the area between the upper 90th percentile and the lower 10th percentile.

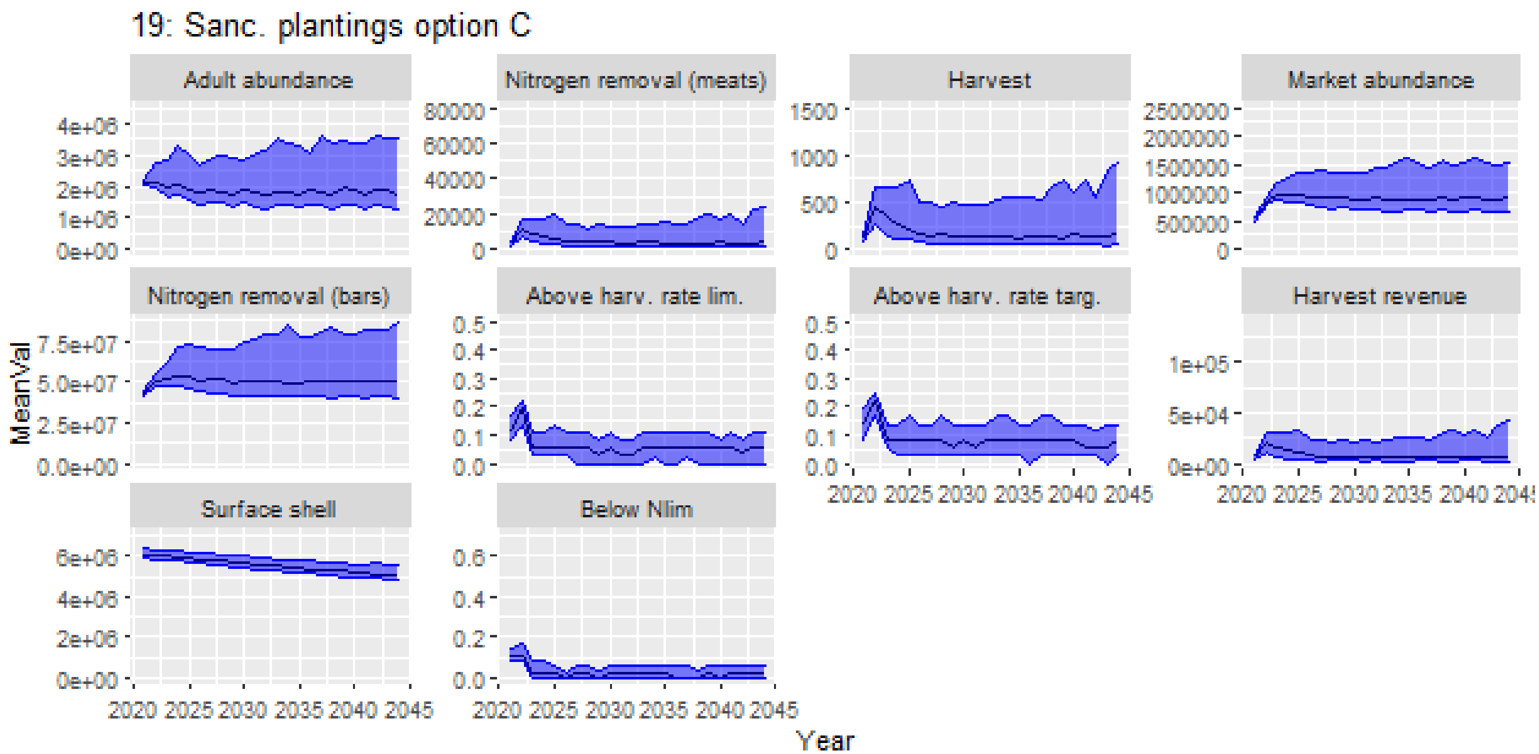

Fig. A163. Forecasted performance of Option 19 during 2022-2044. The solid lines indicate the medians and the shaded areas indicate the area between the upper 90th percentile and the lower 10th percentile.

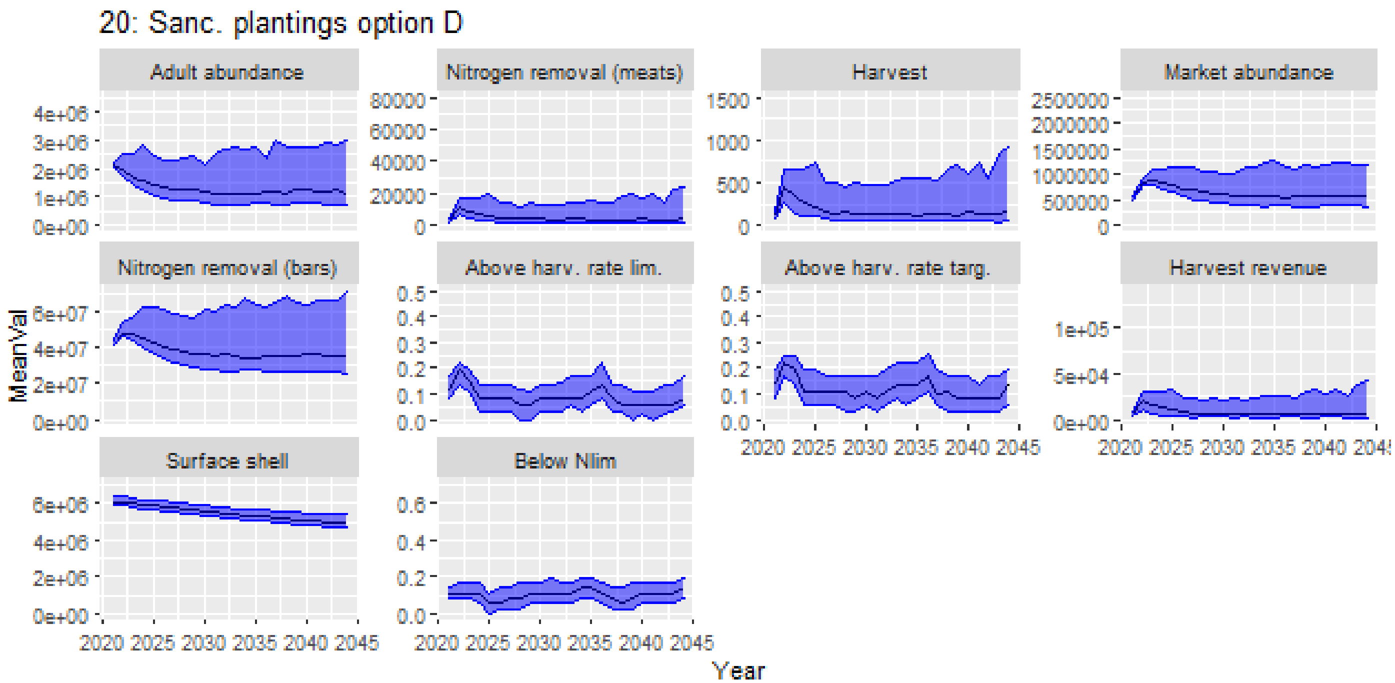

Fig. A164. Forecasted performance of Option 20 during 2022-2044. The solid lines indicate the medians and the shaded areas indicate the area between the upper 90th percentile and the lower 10th percentile.

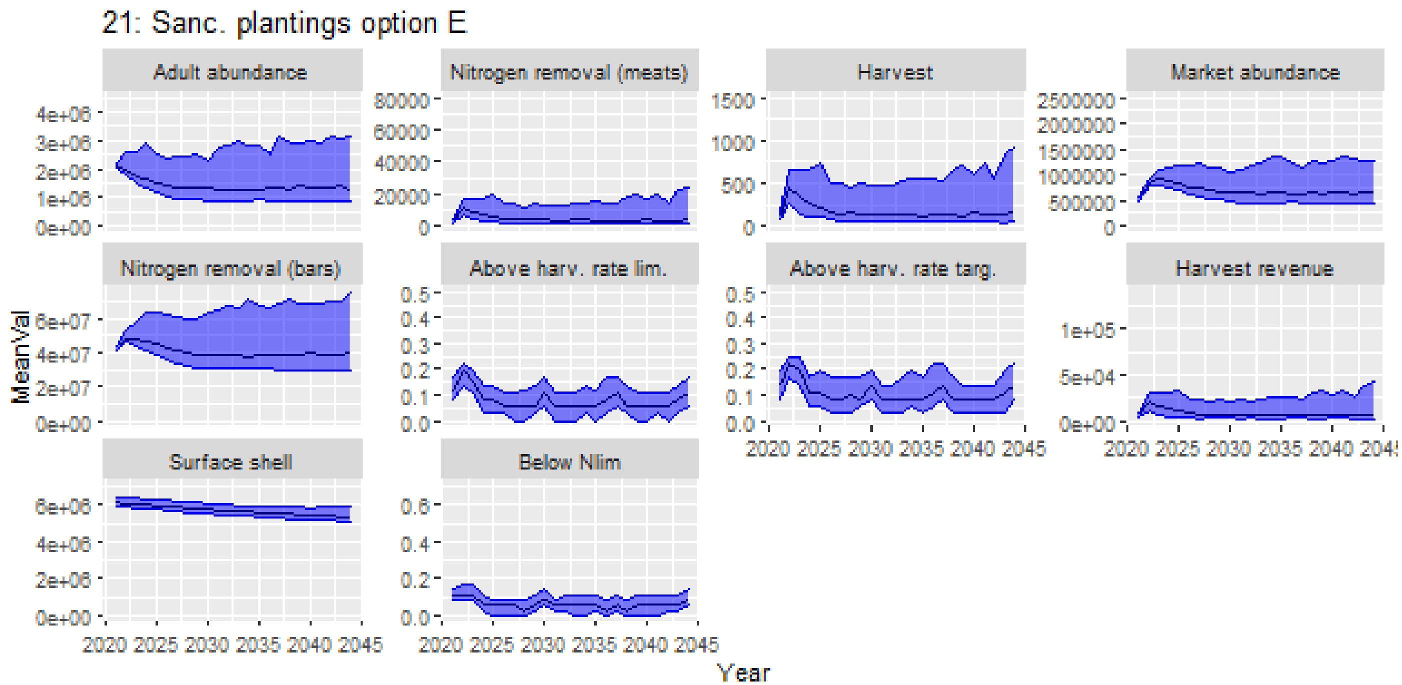

Fig. A165. Forecasted performance of Option 21 during 2022-2044. The solid lines indicate the medians and the shaded areas indicate the area between the upper 90th percentile and the lower 10th percentile.

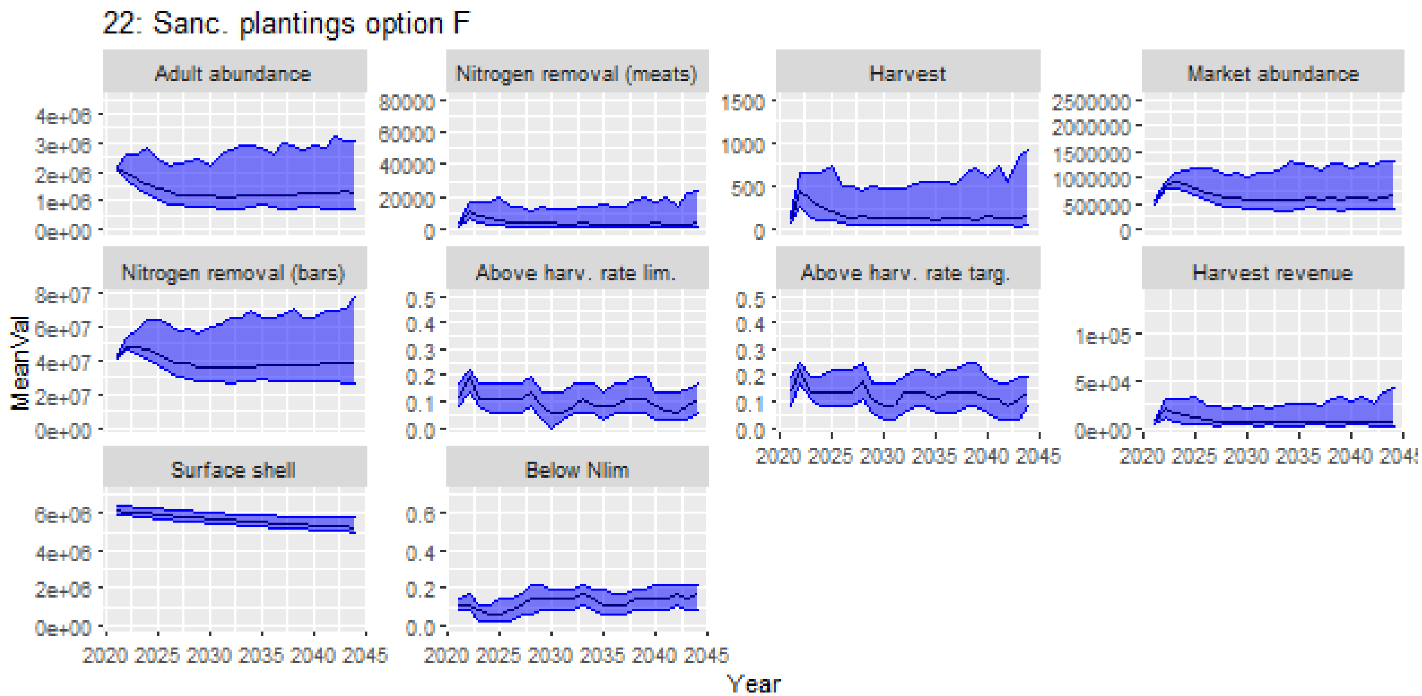

Fig. A166. Forecasted performance of Option 22 during 2022-2044. The solid lines indicate the medians and the shaded areas indicate the area between the upper 90th percentile and the lower 10th percentile.

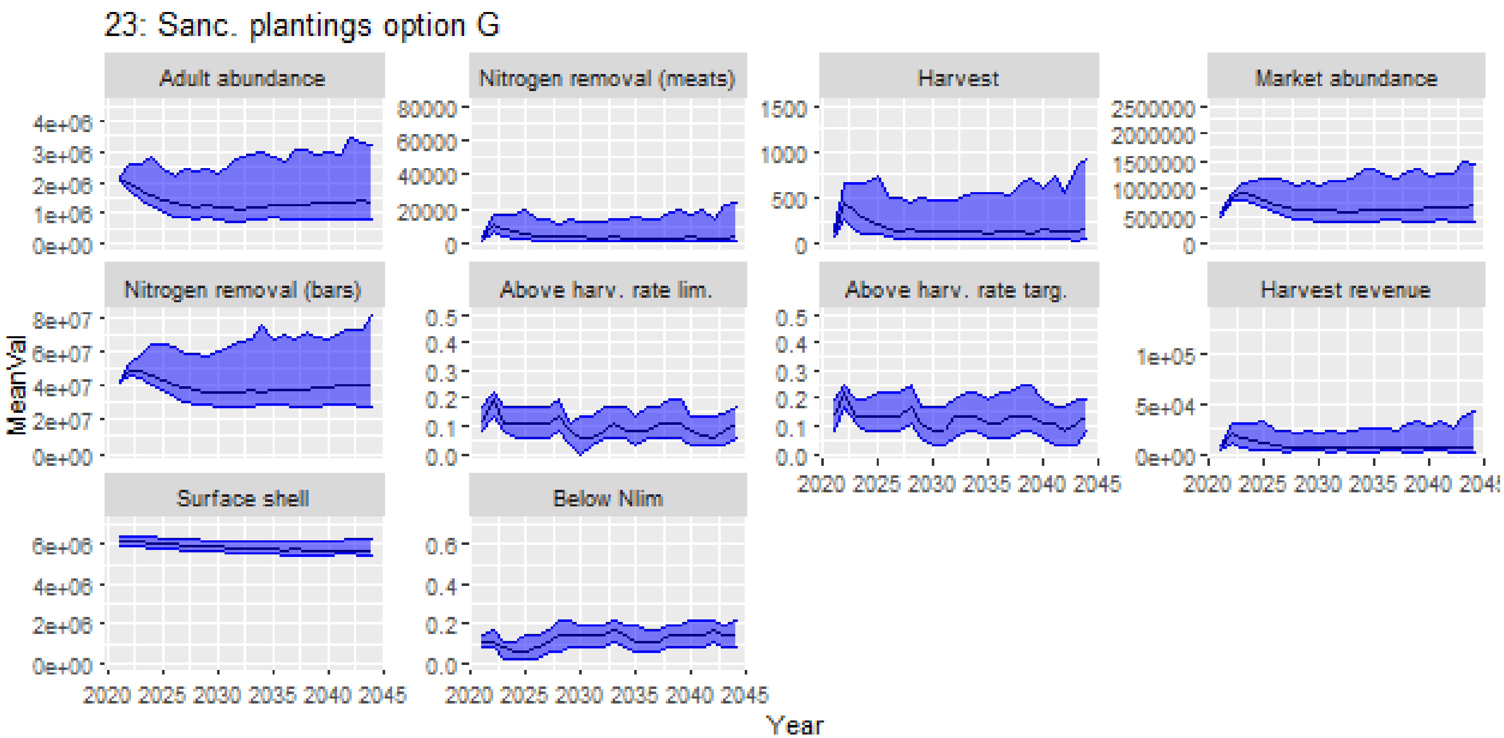

Fig. A167. Forecasted performance of Option 23 during 2022-2044. The solid lines indicate the medians and the shaded areas indicate the area between the upper 90th percentile and the lower 10th percentile.

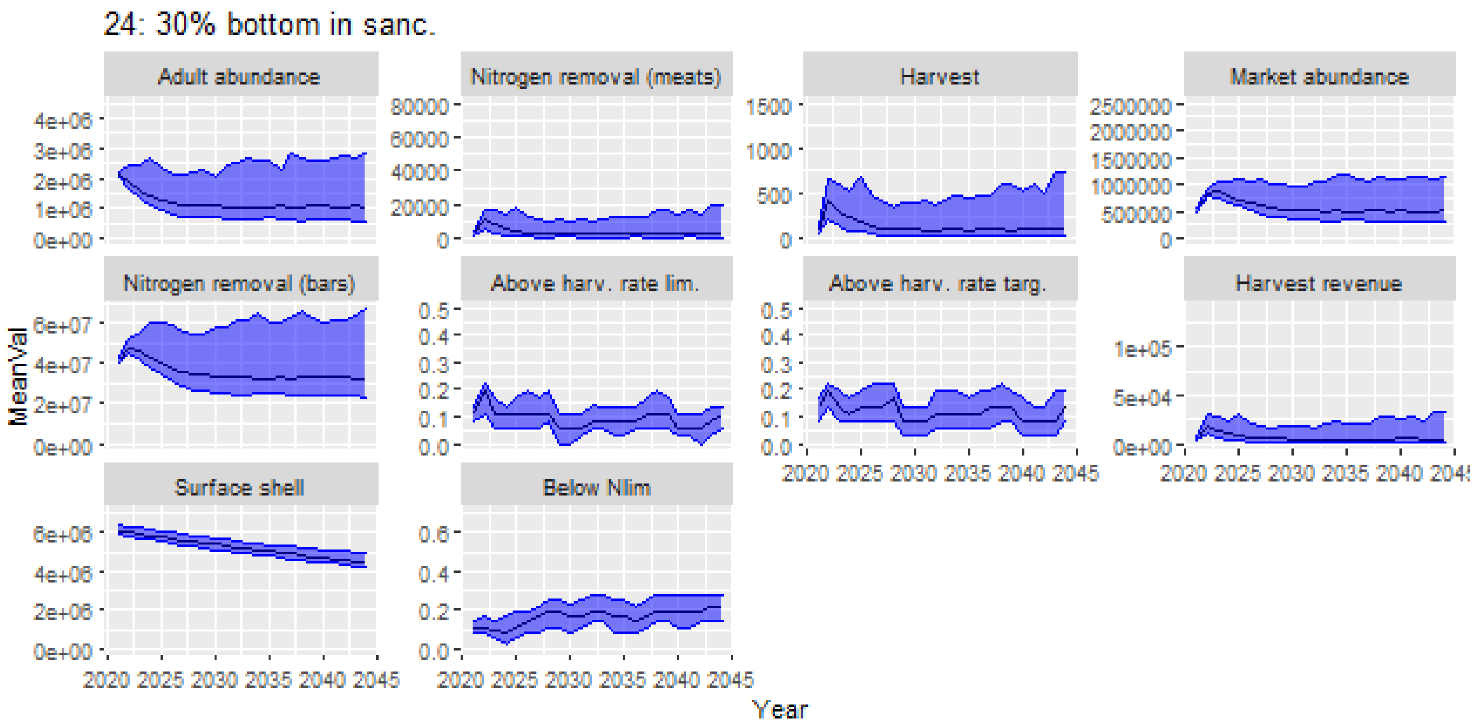

Fig. A168. Forecasted performance of Option 24 during 2022-2044. The solid lines indicate the medians and the shaded areas indicate the area between the upper 90th percentile and the lower 10th percentile.

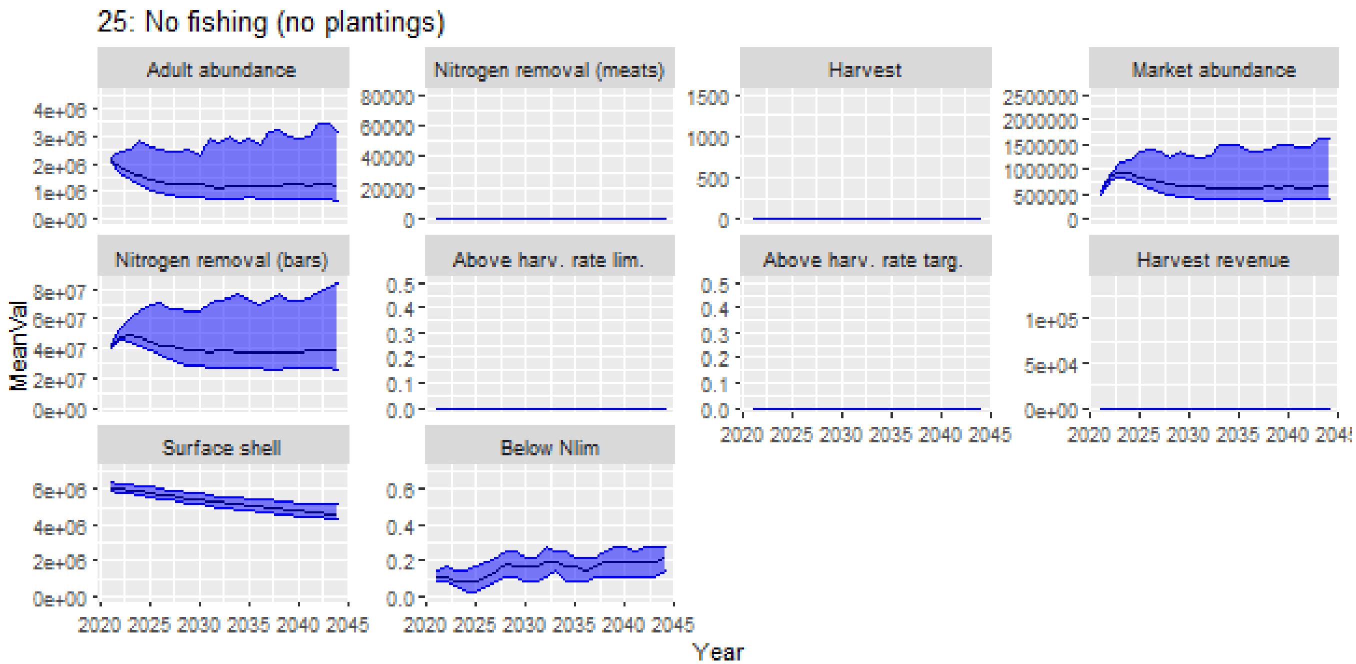

Fig. A169. Forecasted performance of Option 25 during 2022-2044. The solid lines indicate the medians and the shaded areas indicate the area between the upper 90th percentile and the lower 10th percentile.

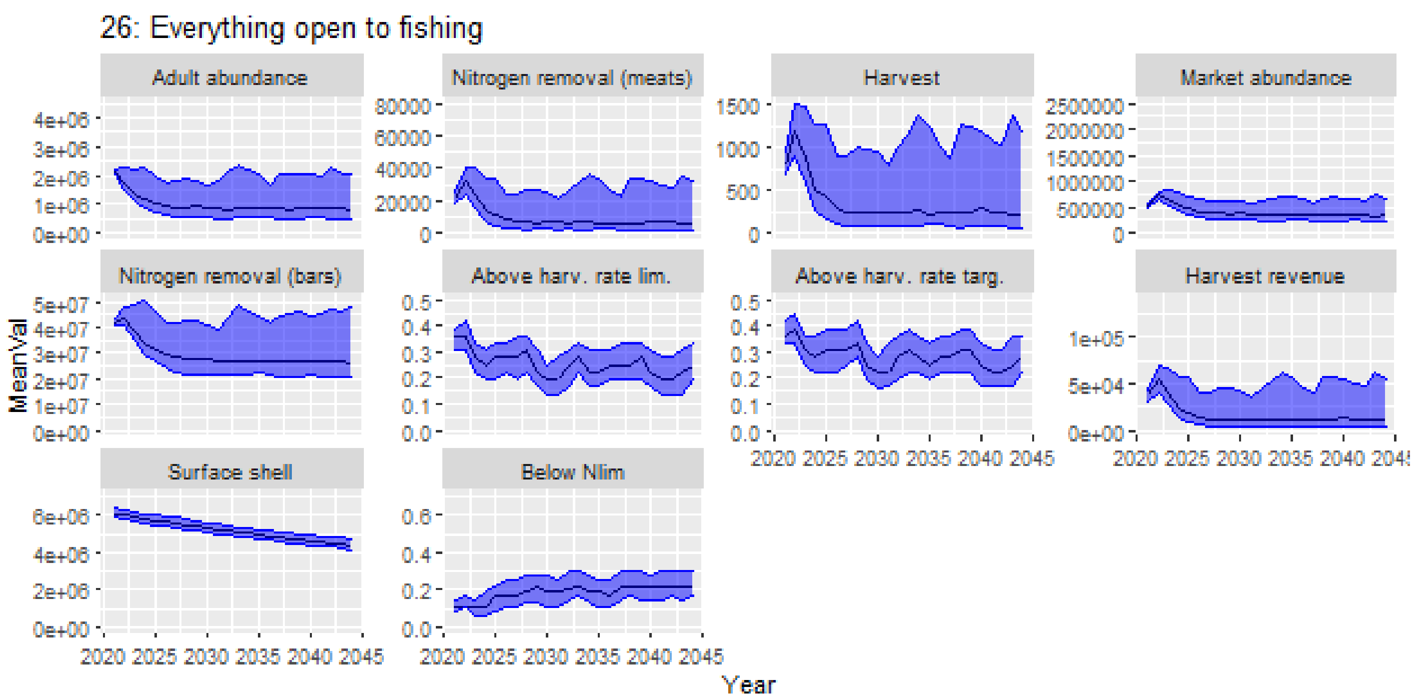

Fig. A170. Forecasted performance of Option 26 during 2022-2044. The solid lines indicate the medians and the shaded areas indicate the area between the upper 90th percentile and the lower 10th percentile.

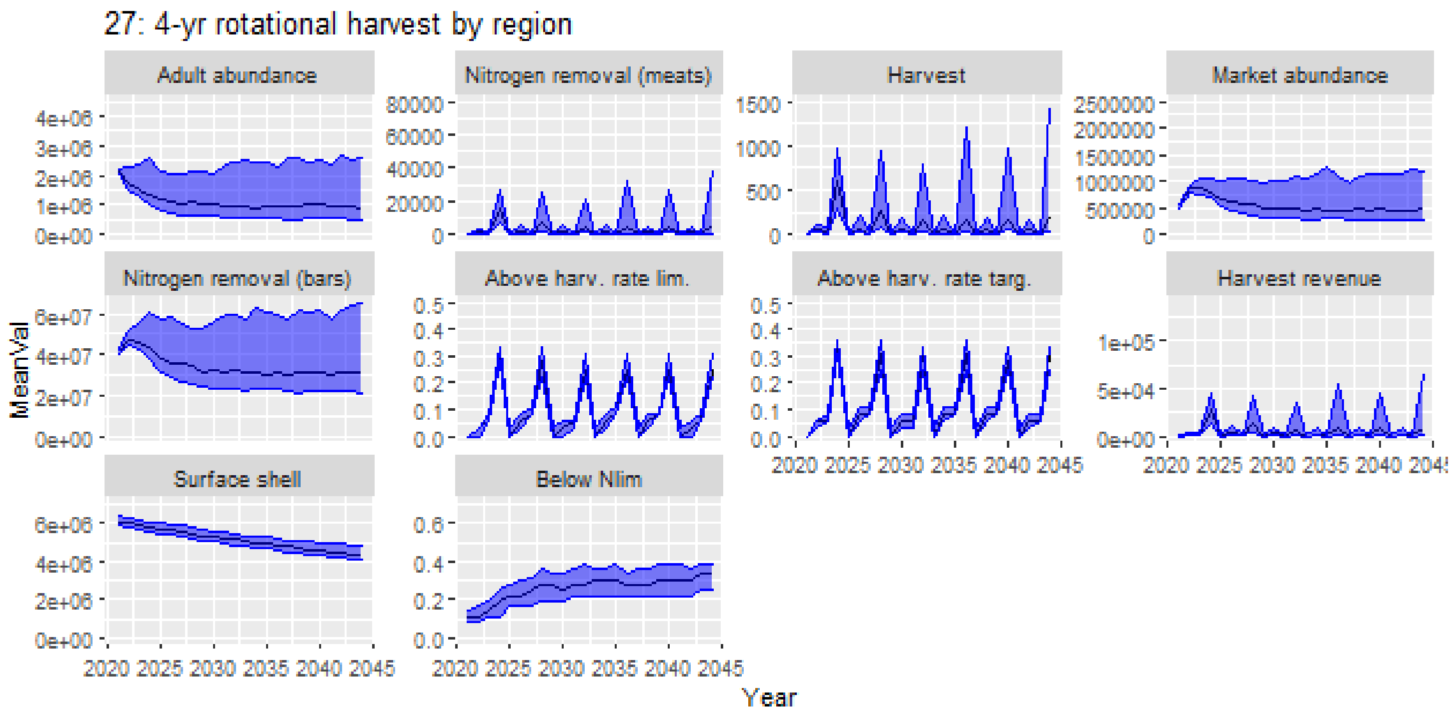

Fig. A171. Forecasted performance of Option 27 during 2022-2044. The solid lines indicate the medians and the shaded areas indicate the area between the upper 90th percentile and the lower 10th percentile.

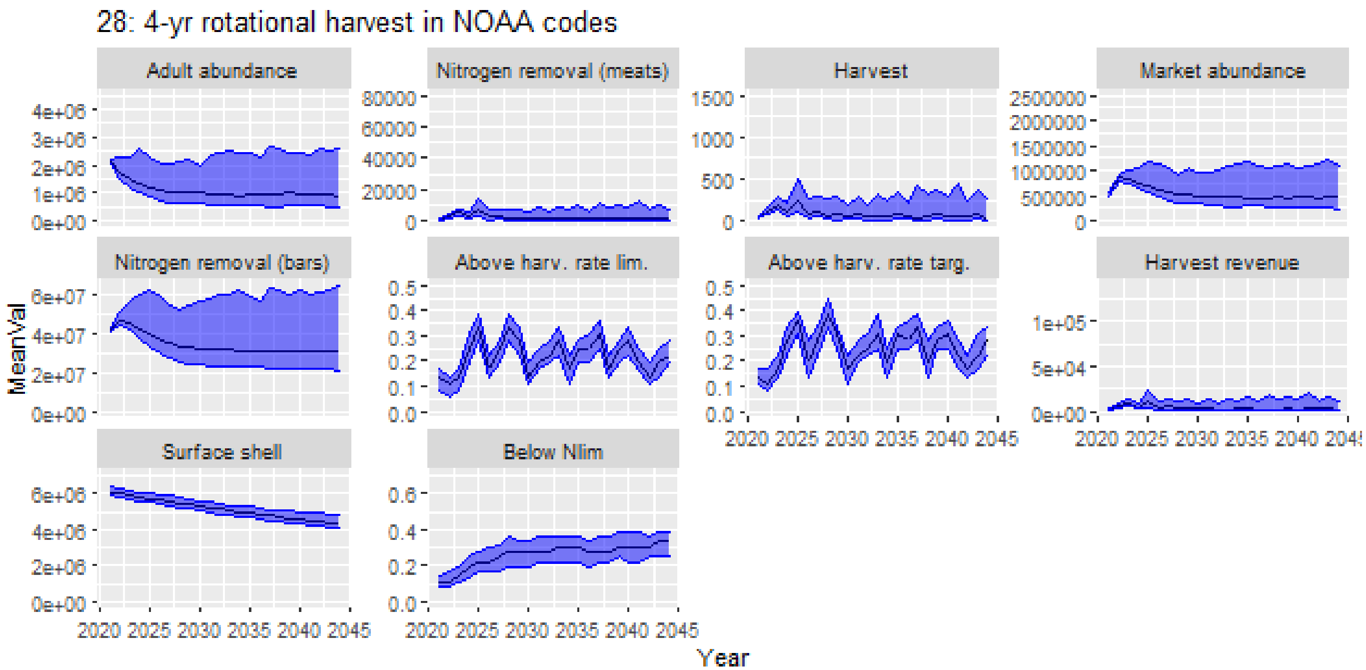

Fig. A172. Forecasted performance of Option 28 during 2022-2044. The solid lines indicate the medians and the shaded areas indicate the area between the upper 90th percentile and the lower 10th percentile.

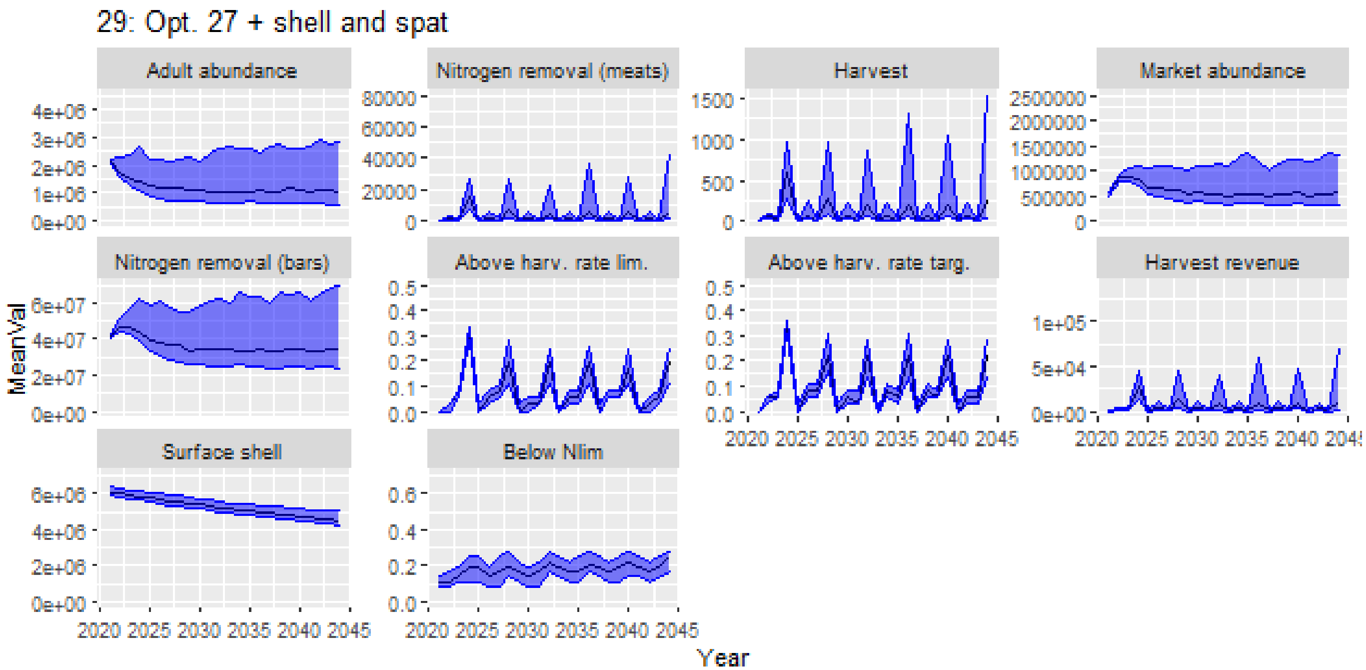

Fig. A173. Forecasted performance of Option 29 during 2022-2044. The solid lines indicate the medians and the shaded areas indicate the area between the upper 90th percentile and the lower 10th percentile.

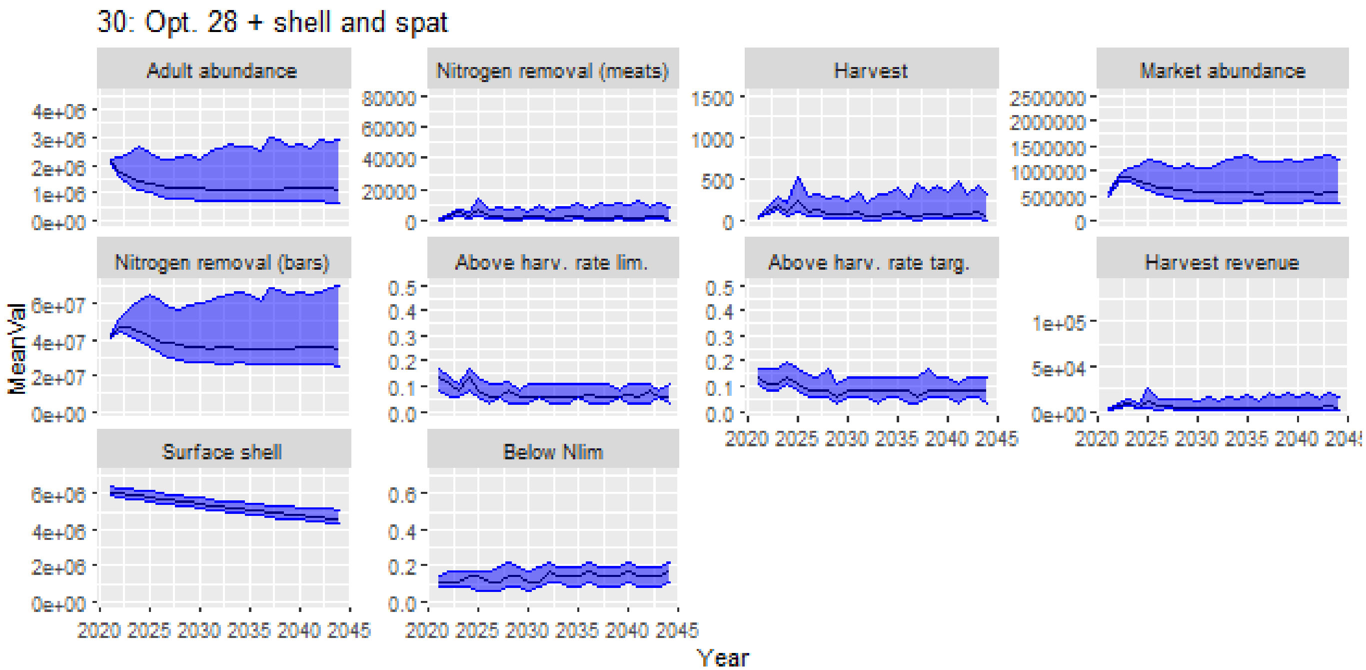

Fig. A174. Forecasted performance of Option 30 during 2022-2044. The solid lines indicate the medians and the shaded areas indicate the area between the upper 90th percentile and the lower 10th percentile.

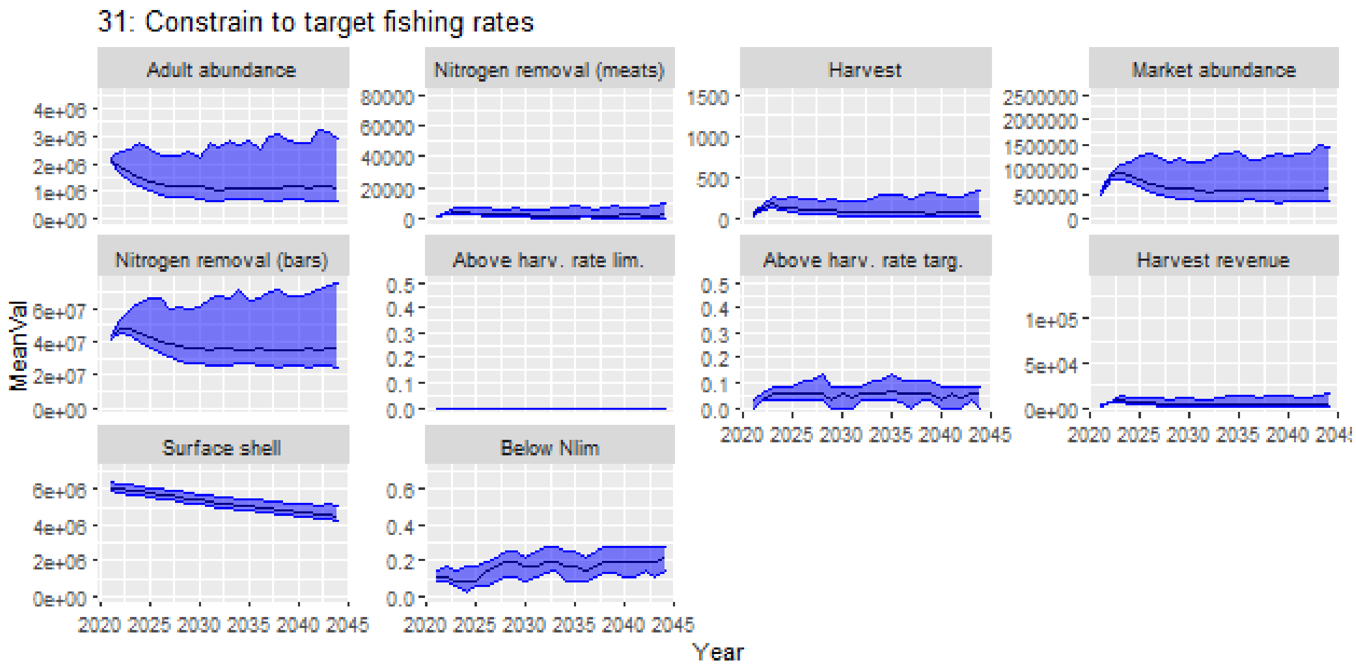

Fig. A175. Forecasted performance of Option 31 during 2022-2044. The solid lines indicate the medians and the shaded areas indicate the area between the upper 90th percentile and the lower 10th percentile.

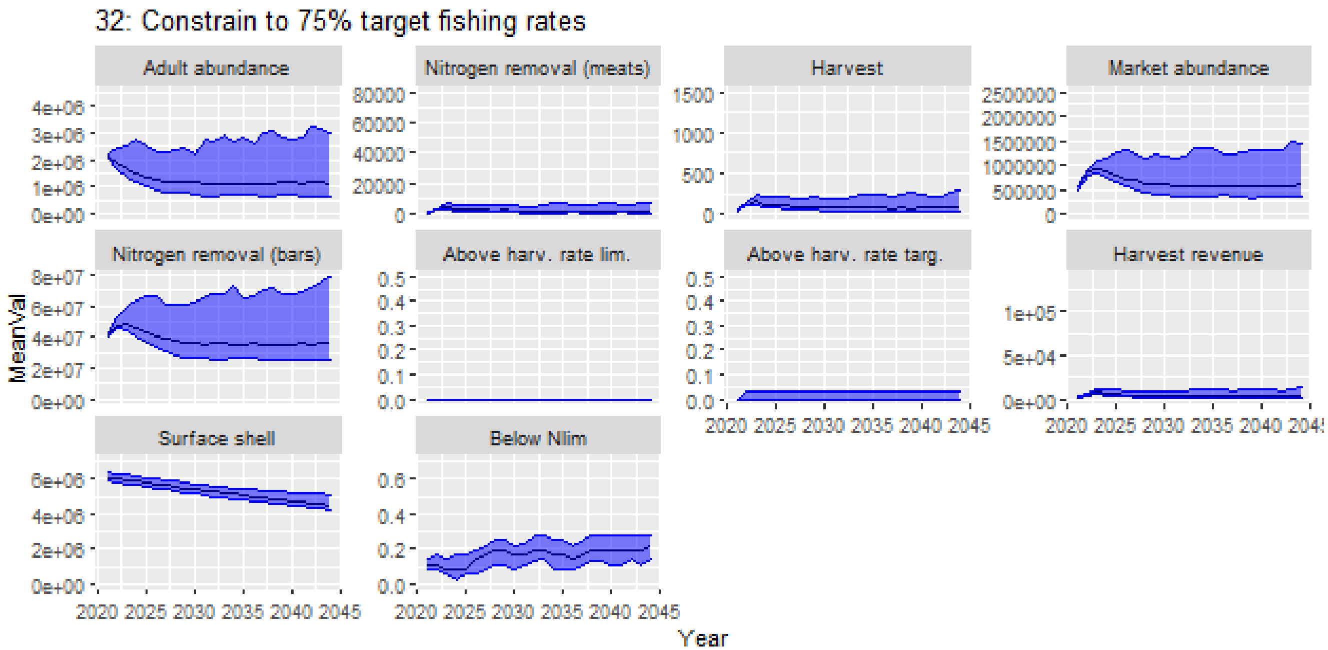

Fig. A176. Forecasted performance of Option 32 during 2022-2044. The solid lines indicate the medians and the shaded areas indicate the area between the upper 90th percentile and the lower 10th percentile.

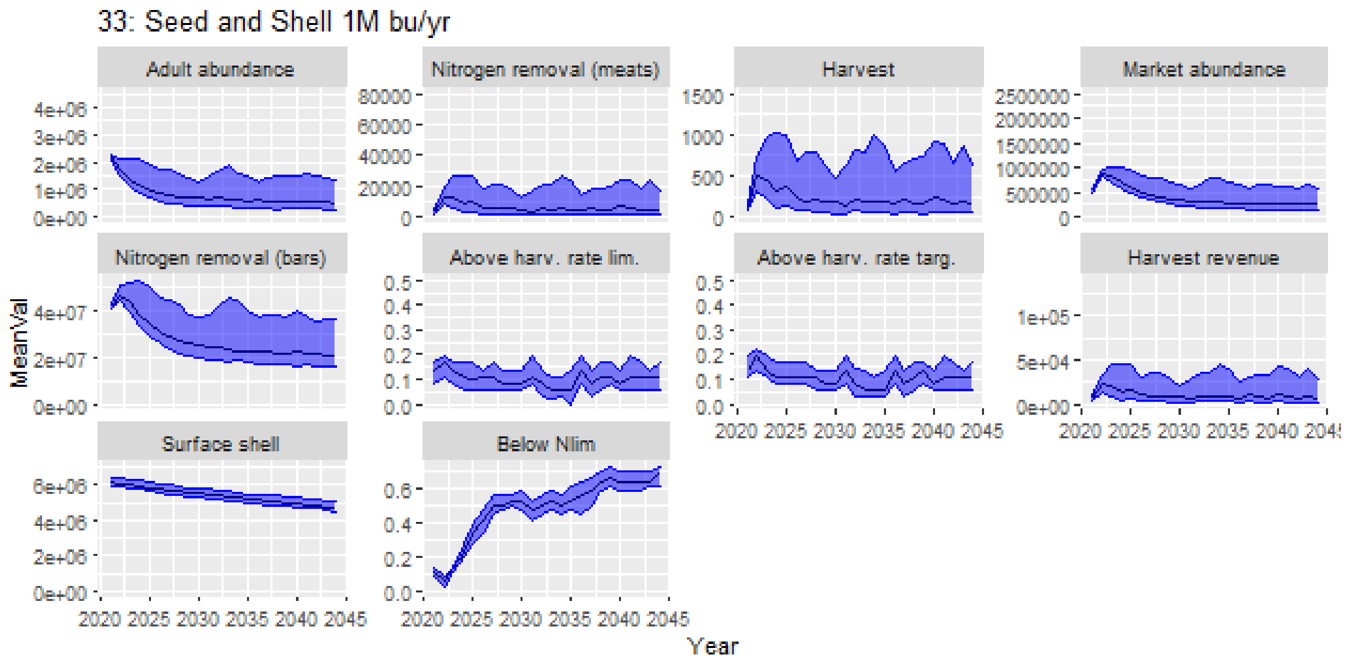

Fig. A177. Forecasted performance of Option 33 during 2022-2044. The solid lines indicate the medians and the shaded areas indicate the area between the upper 90th percentile and the lower 10th percentile.

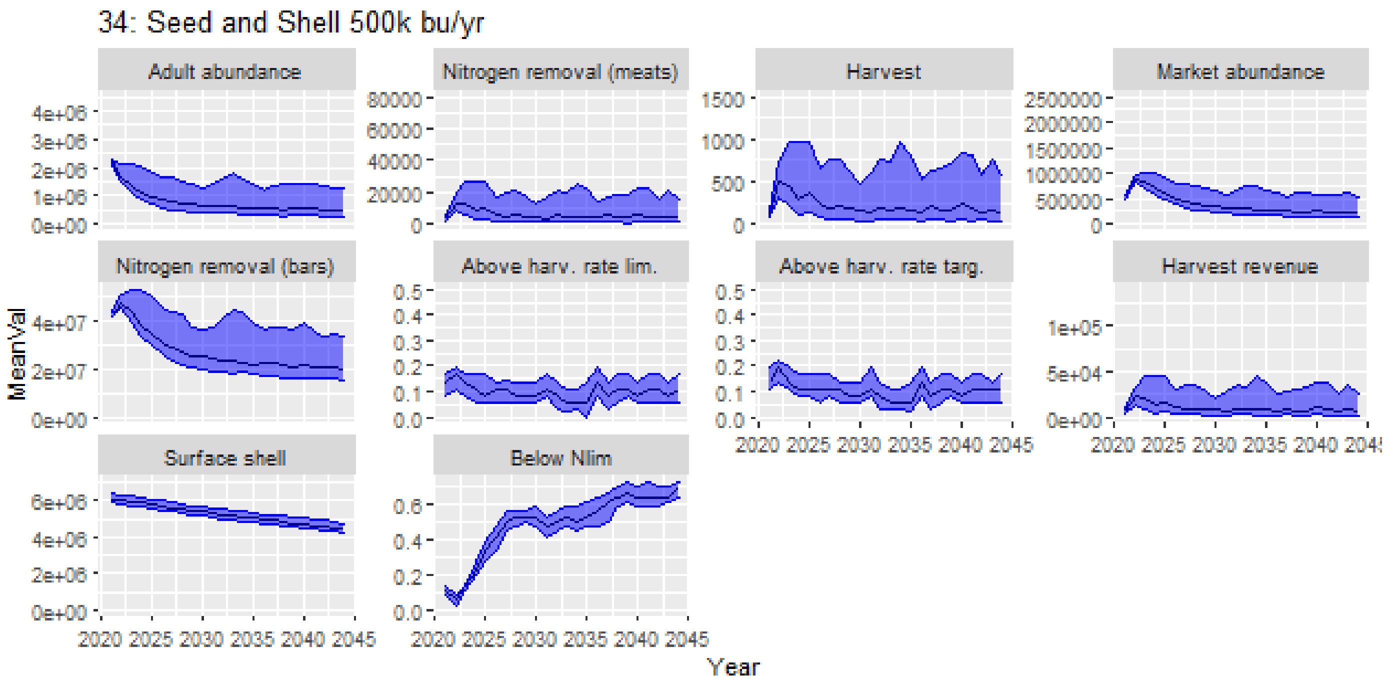

Fig. A178. Forecasted performance of Option 34 during 2022-2044. The solid lines indicate the medians and the shaded areas indicate the area between the upper 90th percentile and the lower 10th percentile.

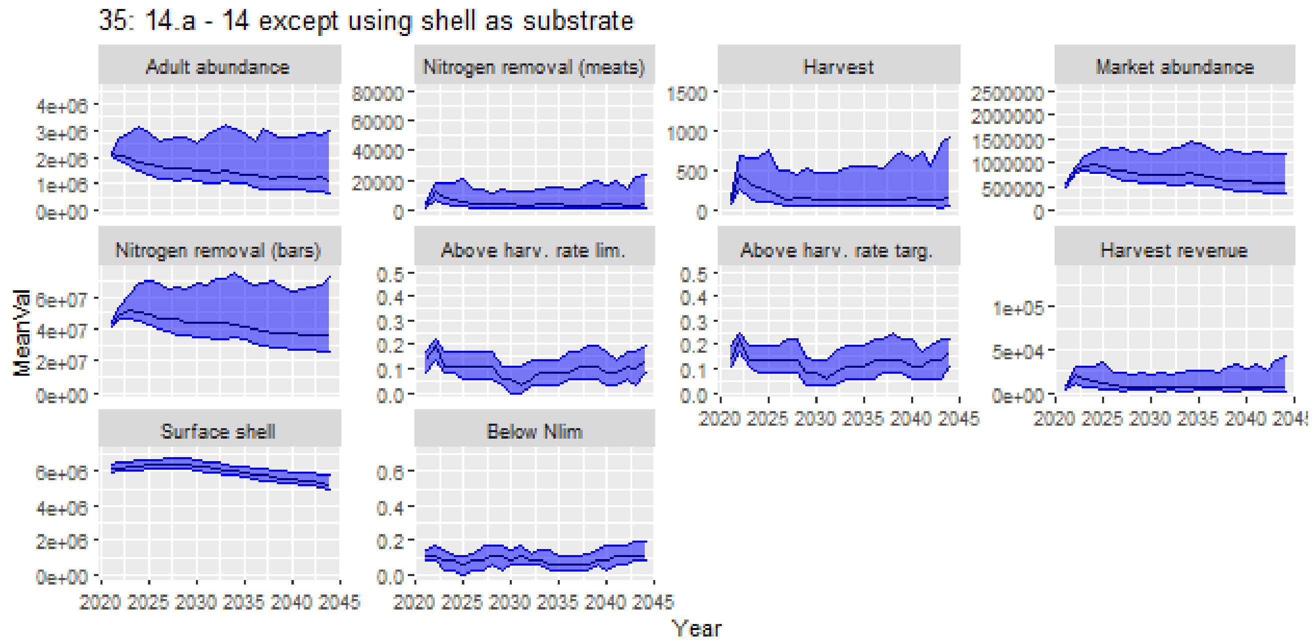

Fig. A179. Forecasted performance of Option 35 during 2022-2044. The solid lines indicate the medians and the shaded areas indicate the area between the upper 90th percentile and the lower 10th percentile.

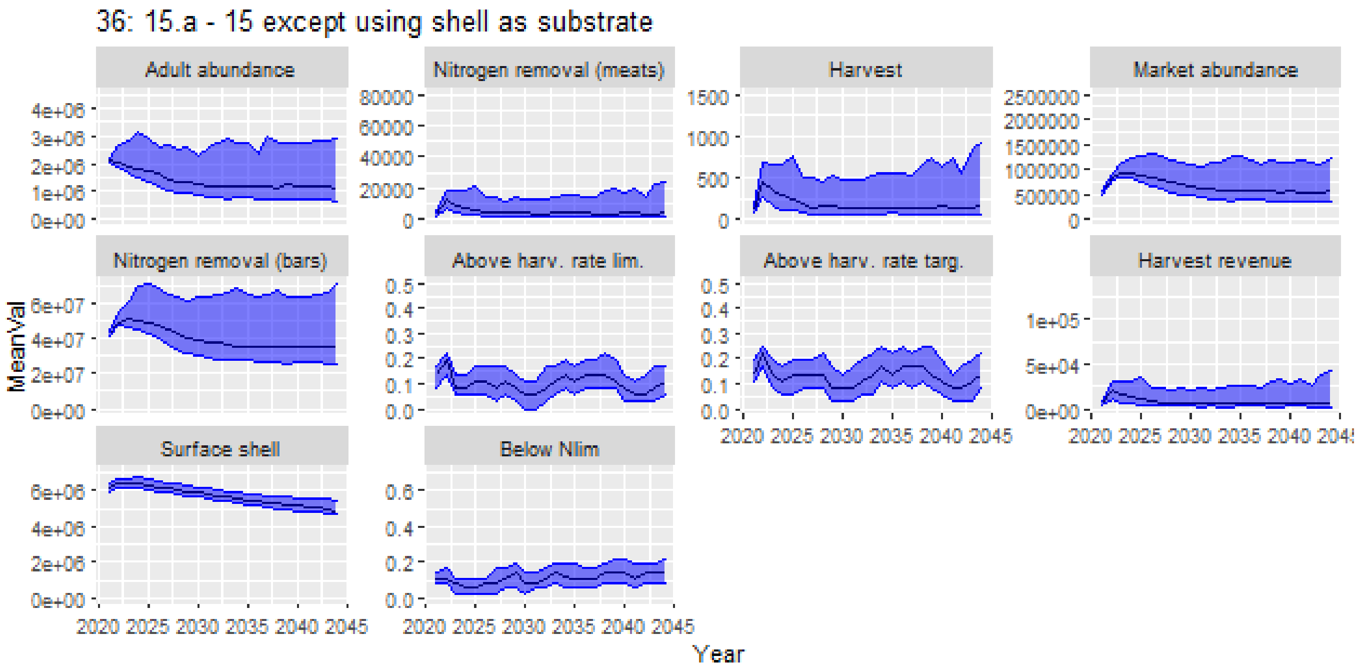

Fig. A180. Forecasted performance of Option 36 during 2022-2044. The solid lines indicate the medians and the shaded areas indicate the area between the upper 90th percentile and the lower 10th percentile.

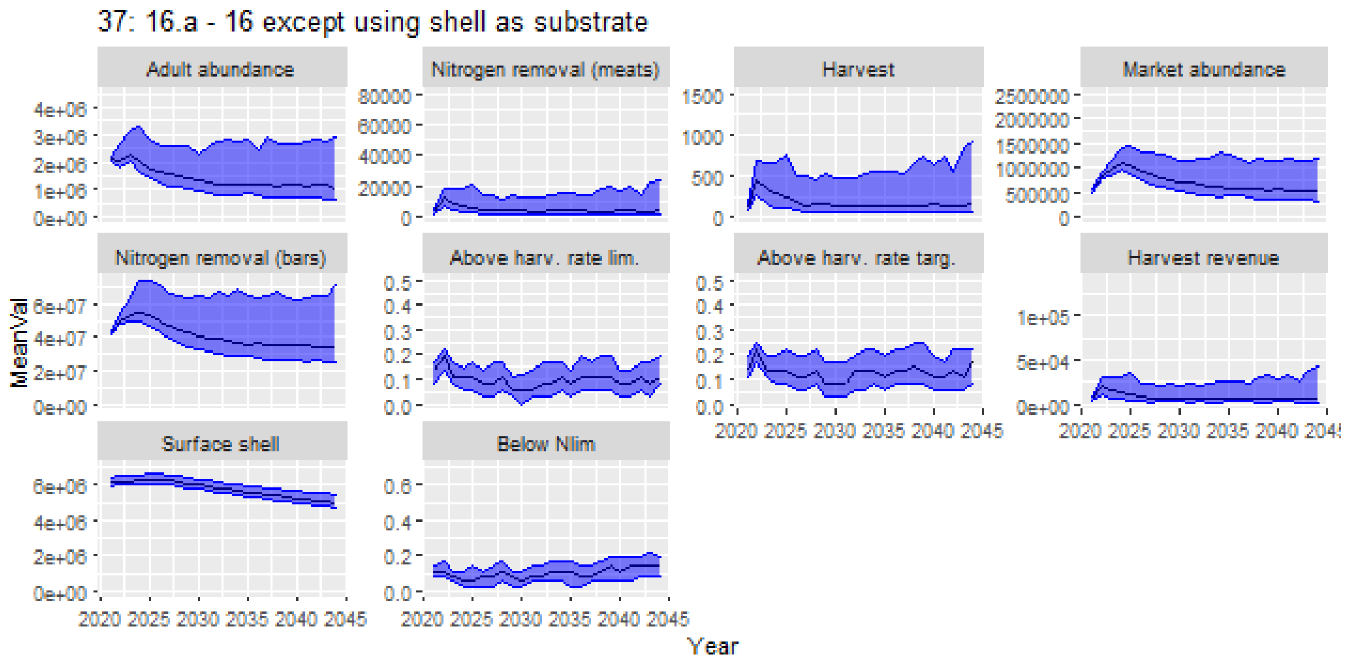

Fig. A181. Forecasted performance of Option 37 during 2022-2044. The solid lines indicate the medians and the shaded areas indicate the area between the upper 90th percentile and the lower 10th percentile.

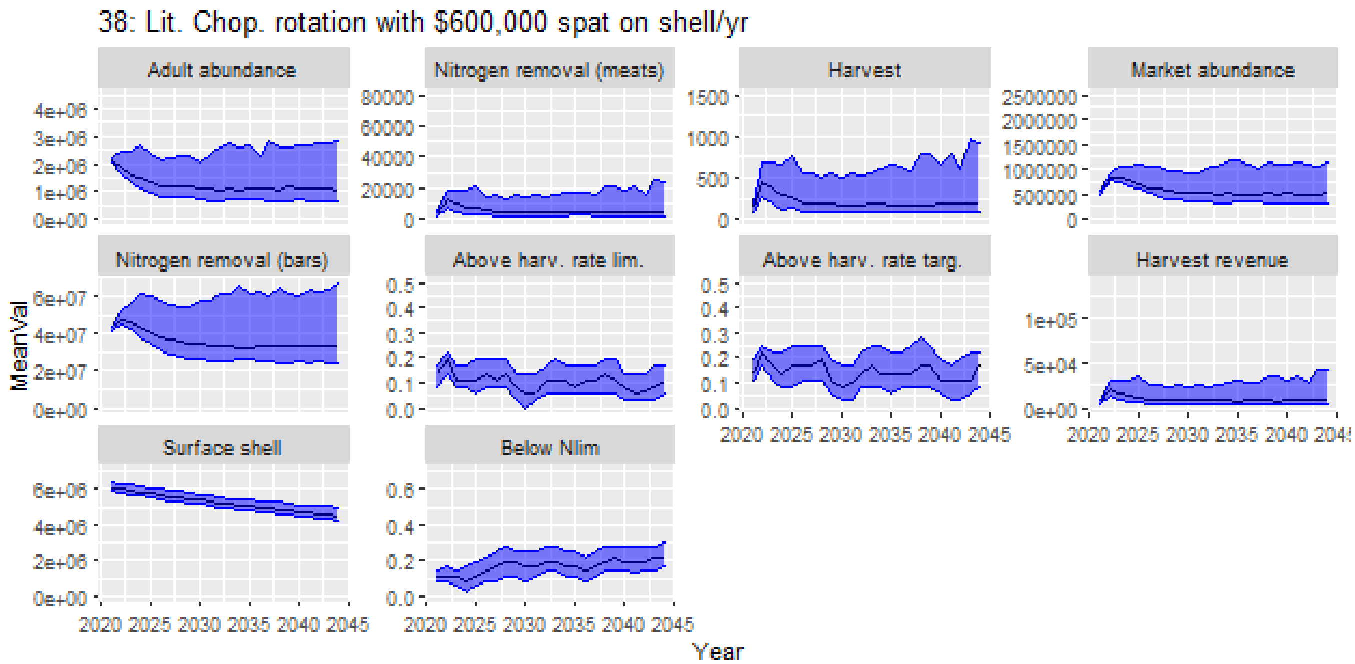

Fig. A182. Forecasted performance of Option 38 during 2022-2044. The solid lines indicate the medians and the shaded areas indicate the area between the upper 90th percentile and the lower 10th percentile.

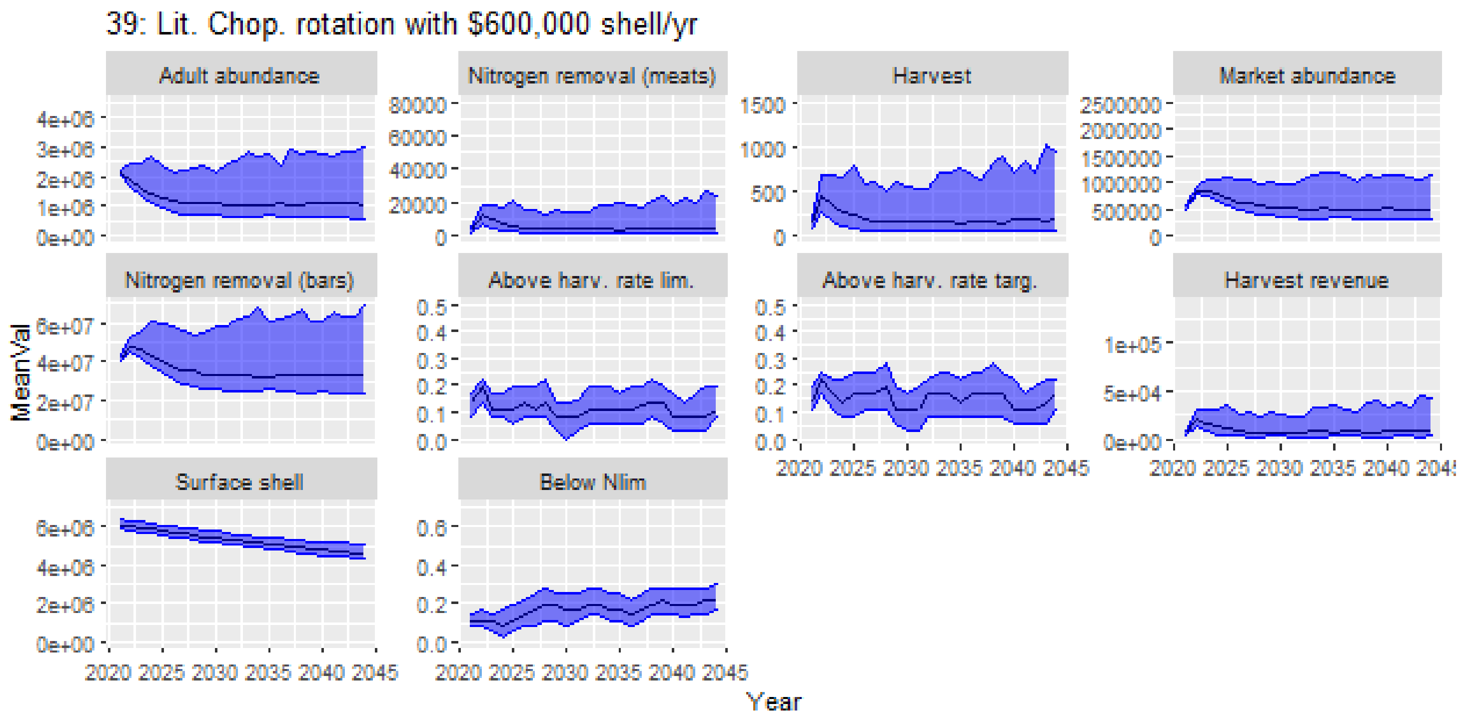

Fig. A183. Forecasted performance of Option 39 during 2022-2044. The solid lines indicate the medians and the shaded areas indicate the area between the upper 90th percentile and the lower 10th percentile.

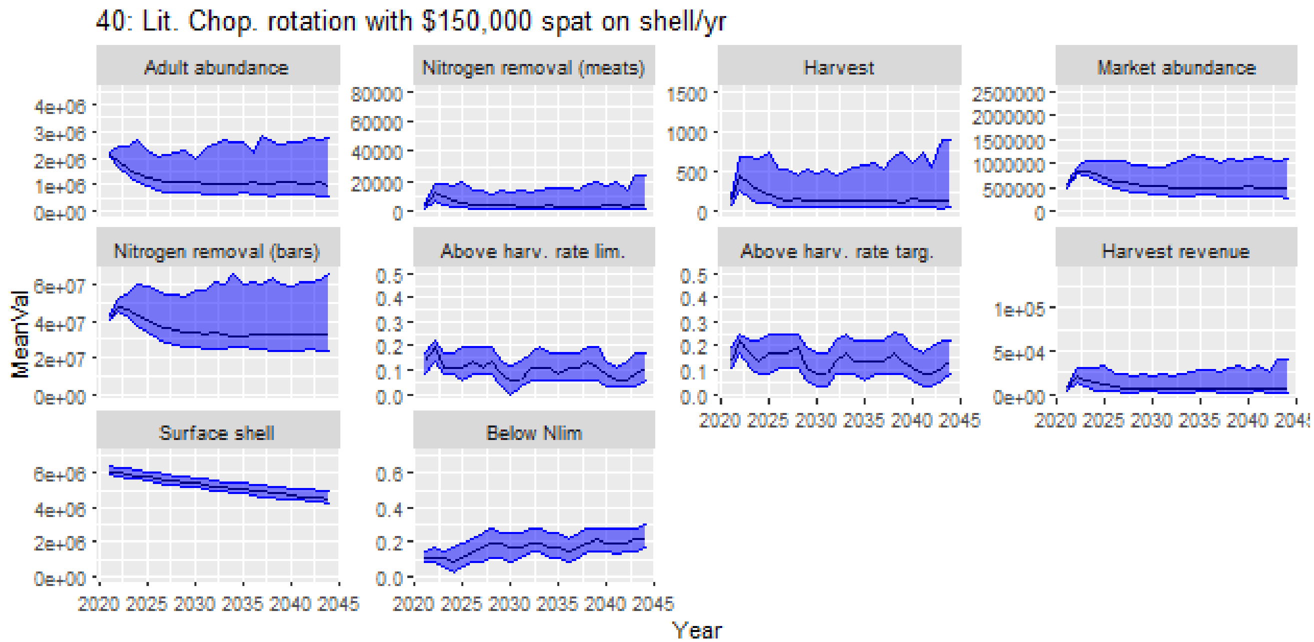

Fig. A184. Forecasted performance of Option 40 during 2022-2044. The solid lines indicate the medians and the shaded areas indicate the area between the upper 90th percentile and the lower 10th percentile.

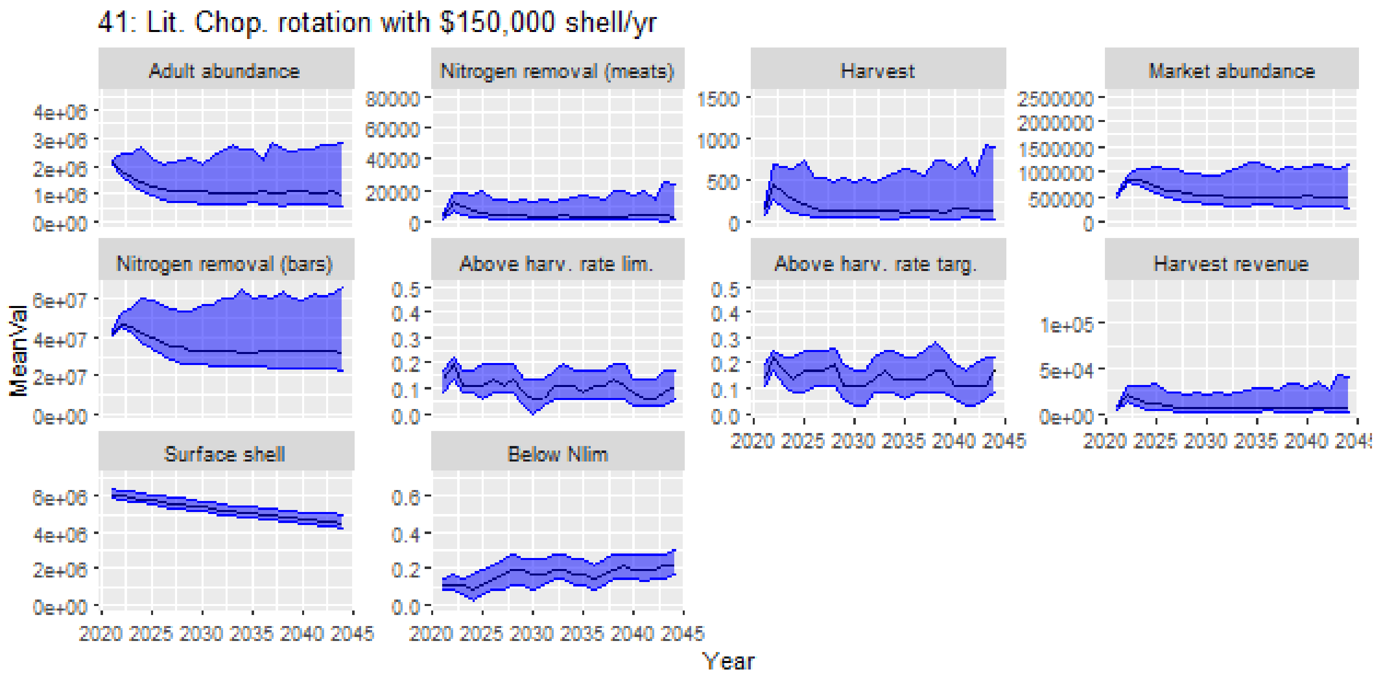

Fig. A185. Forecasted performance of Option 41 during 2022-2044. The solid lines indicate the medians and the shaded areas indicate the area between the upper 90th percentile and the lower 10th percentile.

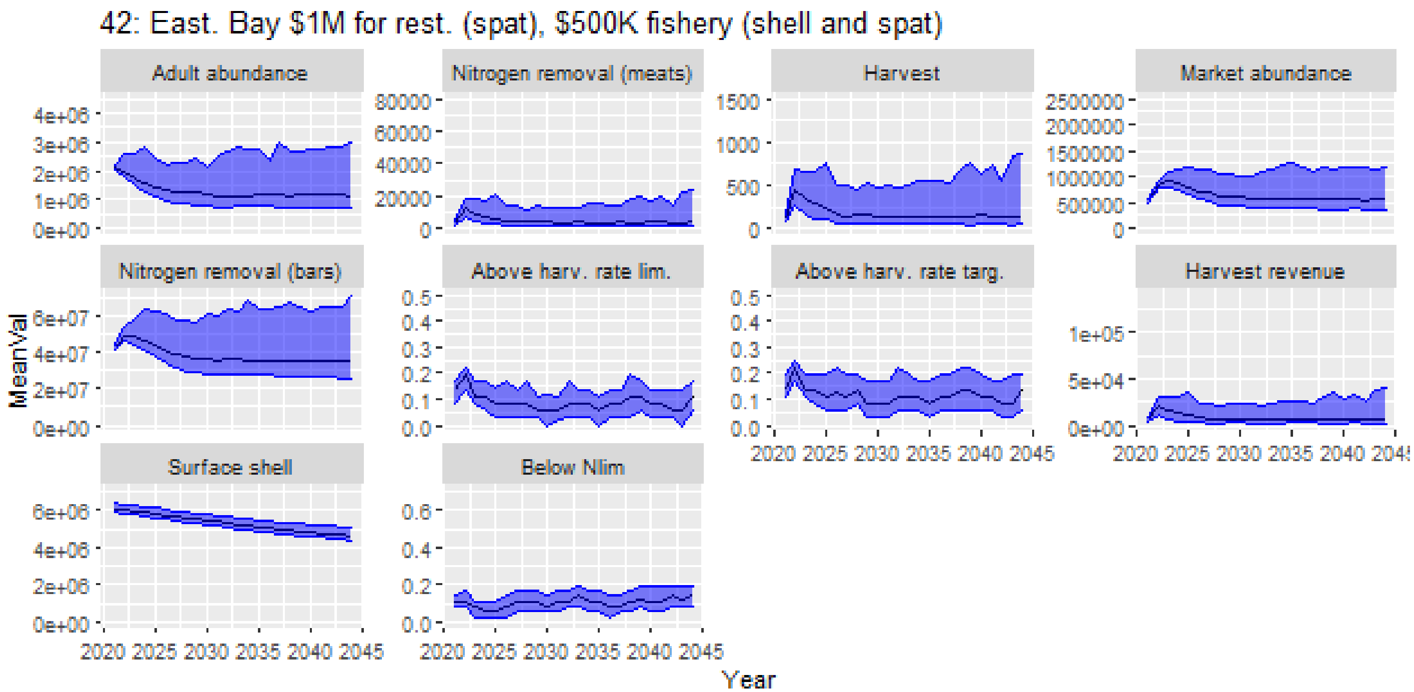

Fig. A186. Forecasted performance of Option 42 during 2022-2044. The solid lines indicate the medians and the shaded areas indicate the area between the upper 90th percentile and the lower 10th percentile.

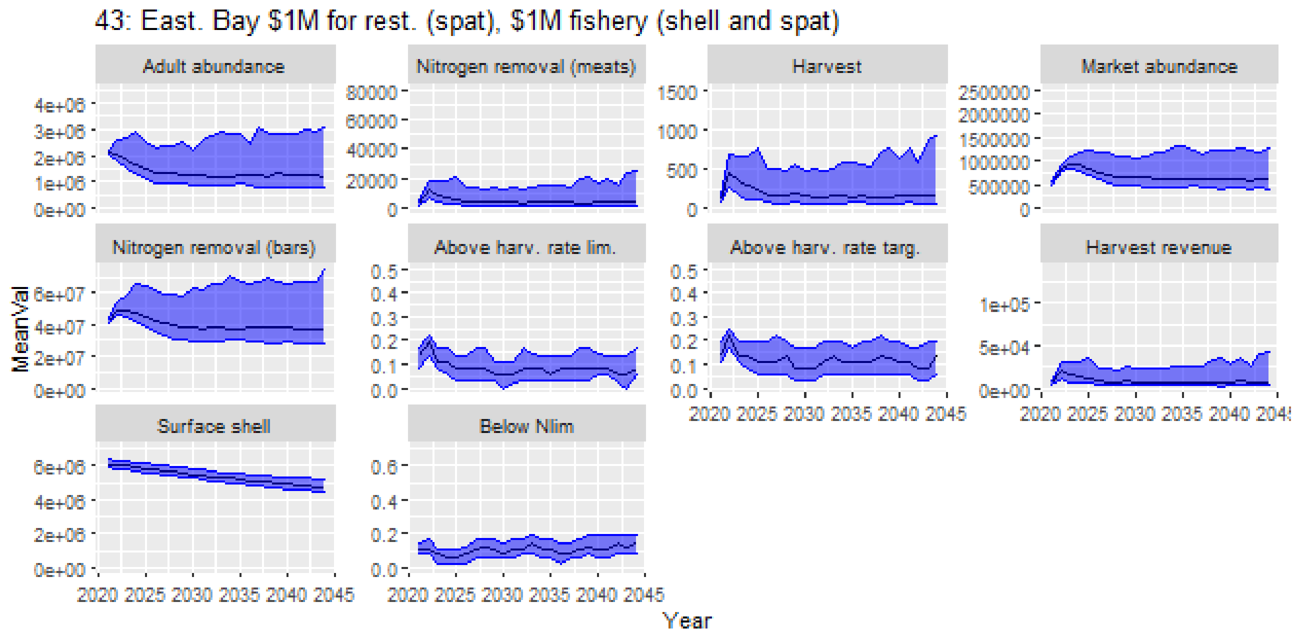

Fig. A187. Forecasted performance of Option 43 during 2022-2044. The solid lines indicate the medians and the shaded areas indicate the area between the upper 90th percentile and the lower 10th percentile.

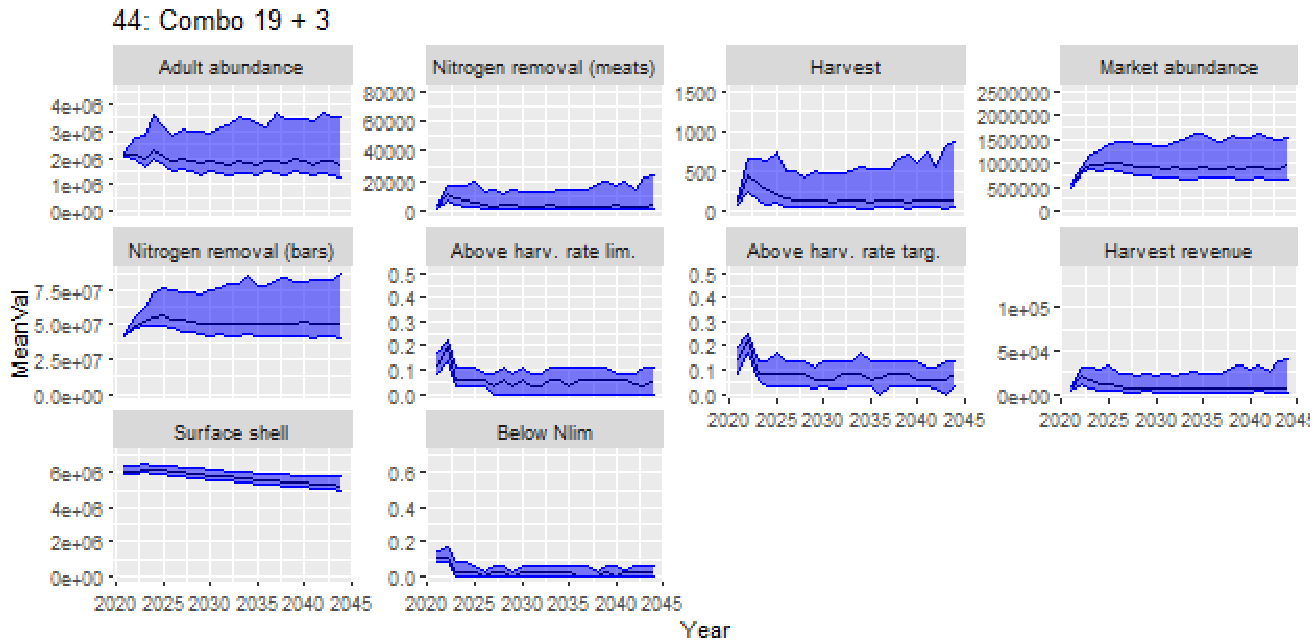

Fig. A188. Forecasted performance of Option 44 during 2022-2044. The solid lines indicate the medians and the shaded areas indicate the area between the upper 90th percentile and the lower 10th percentile.

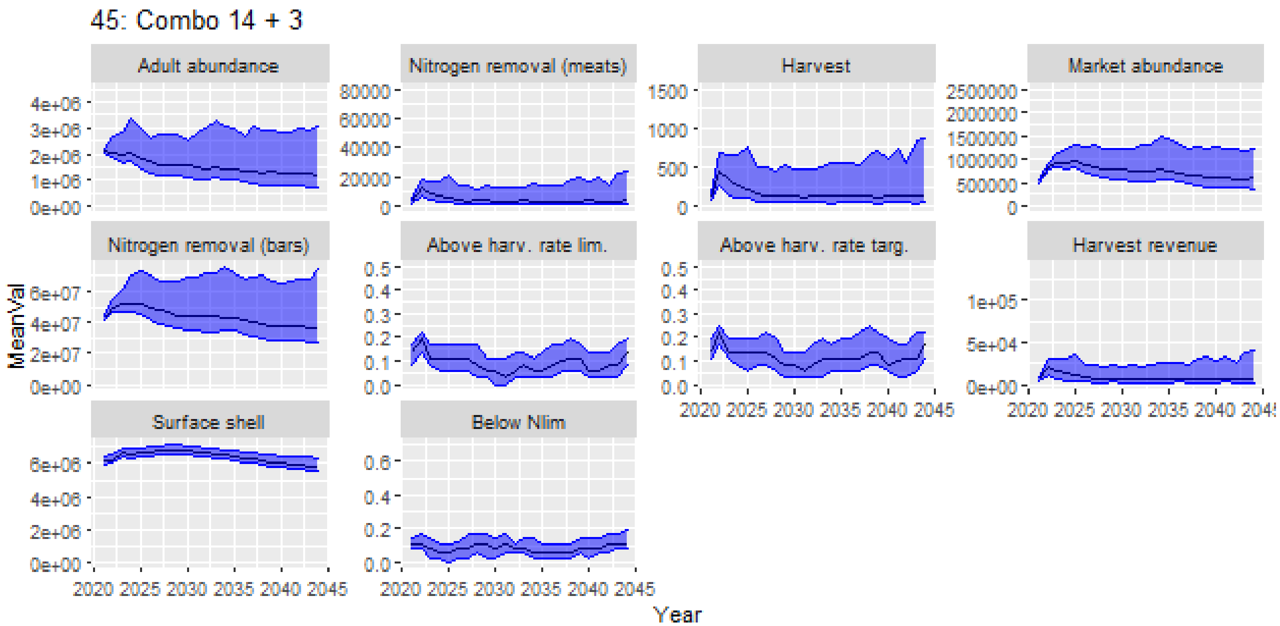

Fig. A189. Forecasted performance of Option 45 during 2022-2044. The solid lines indicate the medians and the shaded areas indicate the area between the upper 90th percentile and the lower 10th percentile.

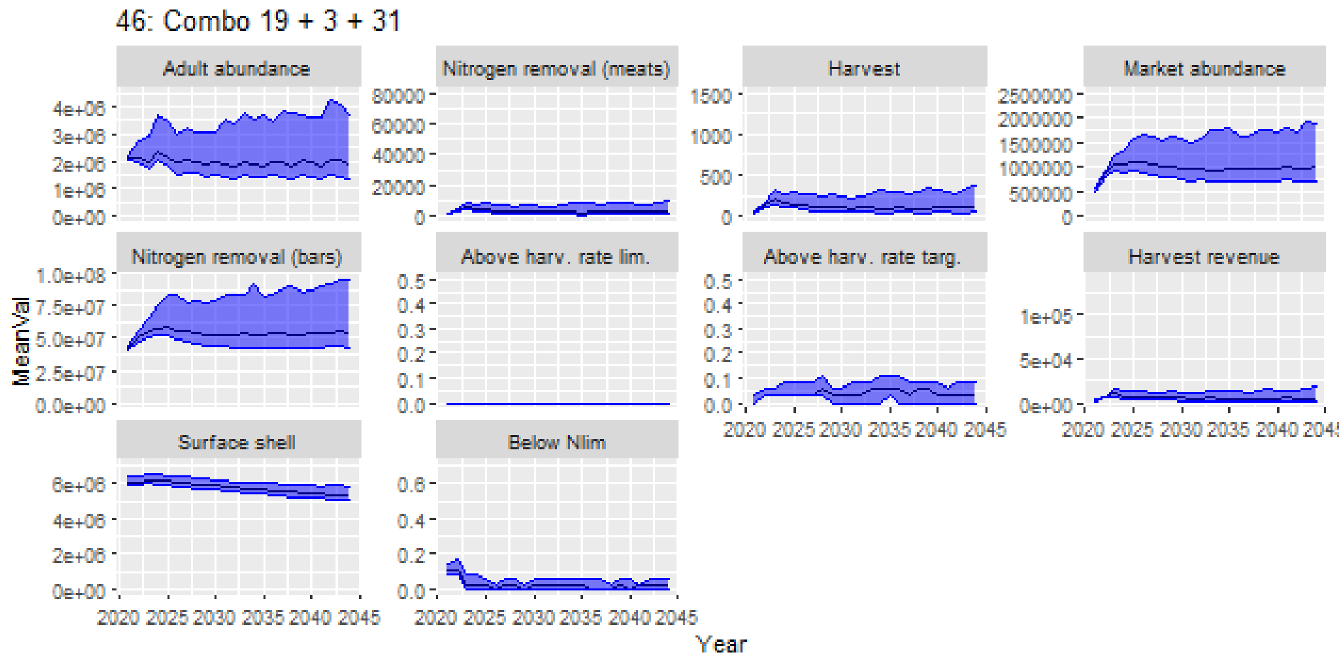

Fig. A190. Forecasted performance of Option 46 during 2022-2044. The solid lines indicate the medians and the shaded areas indicate the area between the upper 90th percentile and the lower 10th percentile.

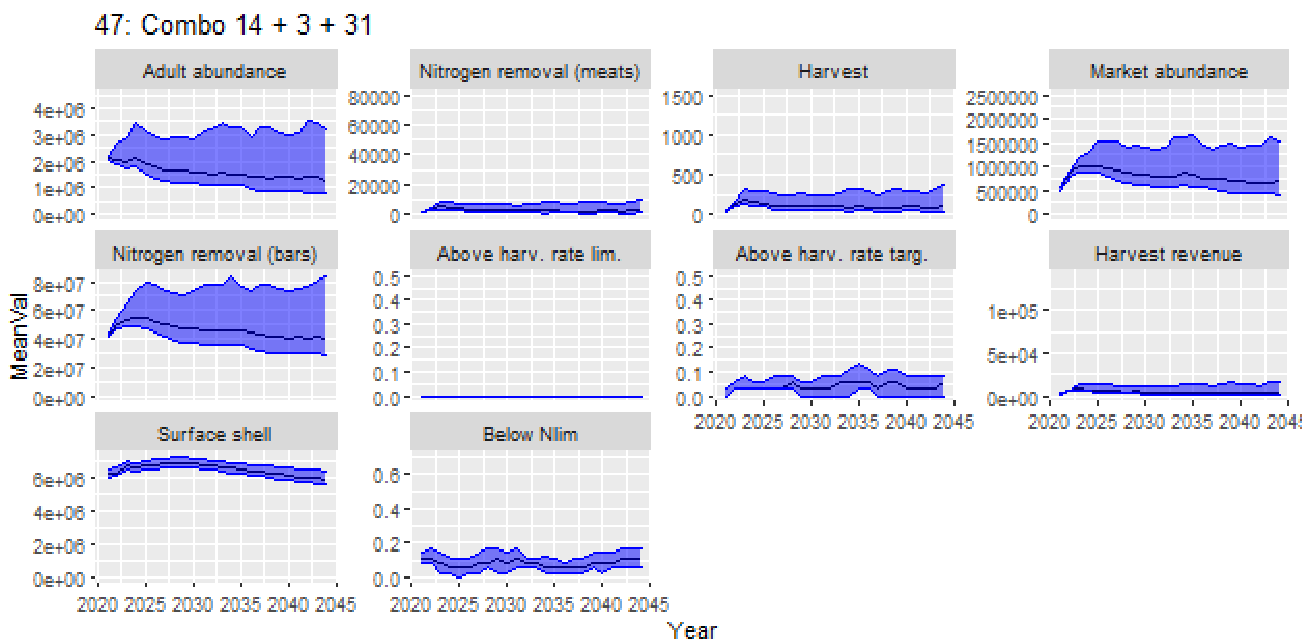

Fig. A191. Forecasted performance of Option 47 during 2022-2044. The solid lines indicate the medians and the shaded areas indicate the area between the upper 90th percentile and the lower 10th percentile.

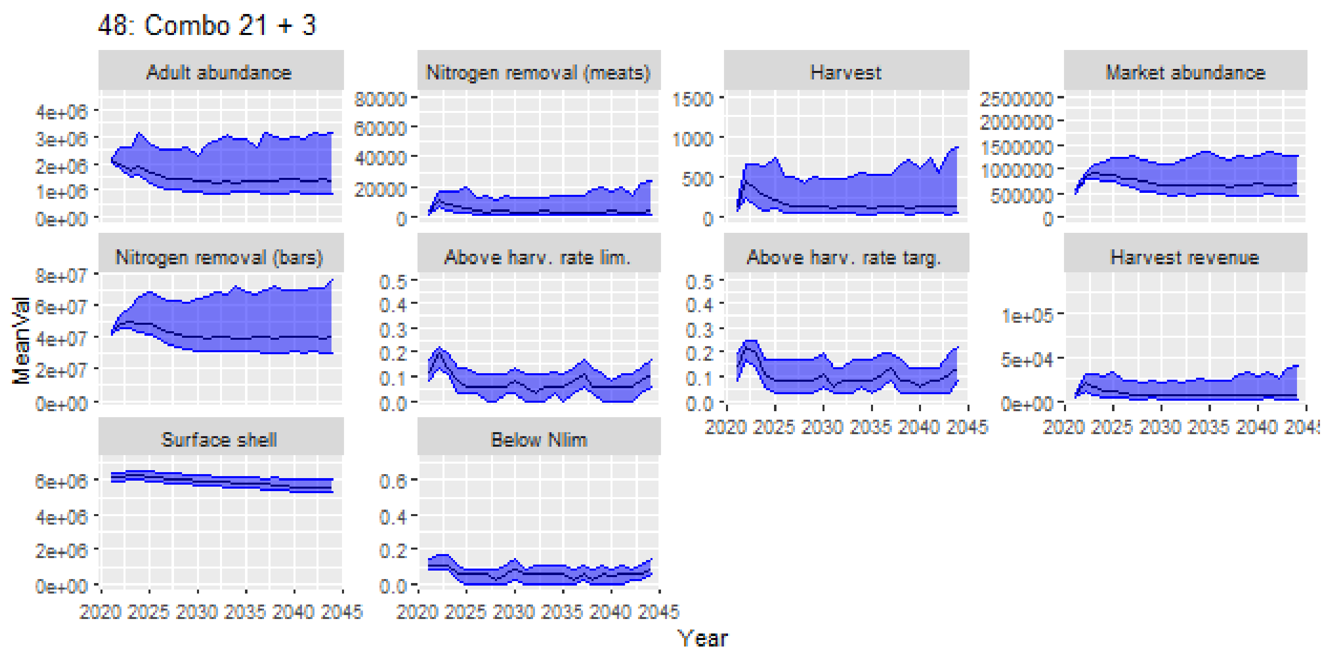

Fig. A192. Forecasted performance of Option 48 during 2022-2044. The solid lines indicate the medians and the shaded areas indicate the area between the upper 90th percentile and the lower 10th percentile.

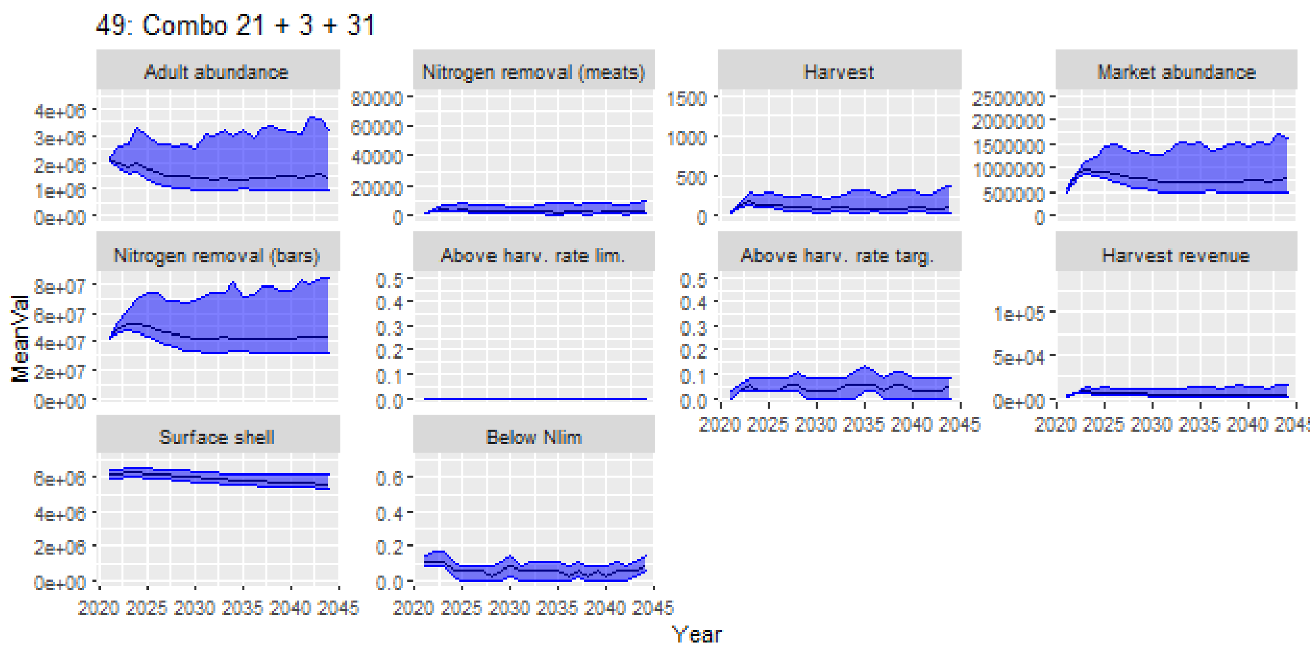

Fig. A193. Forecasted performance of Option 49 during 2022-2044. The solid lines indicate the medians and the shaded areas indicate the area between the upper 90th percentile and the lower 10th percentile.

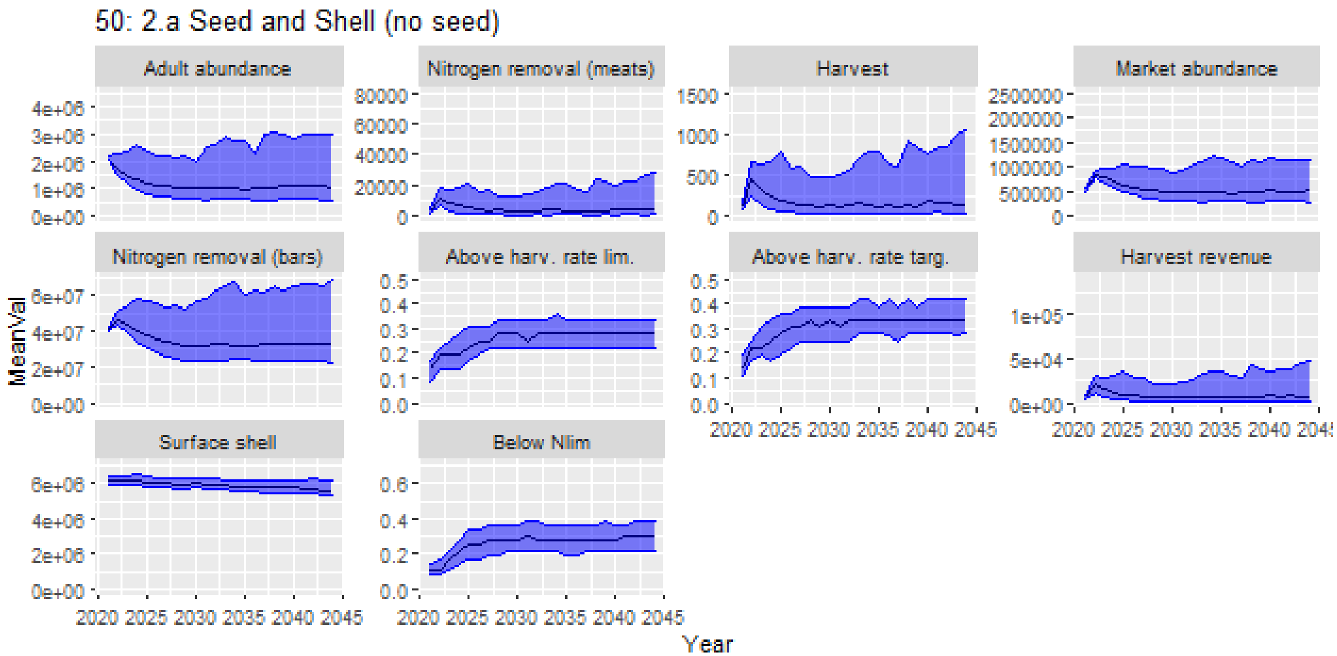

Fig. A194. Forecasted performance of Option 50 during 2022-2044. The solid lines indicate the medians and the shaded areas indicate the area between the upper 90th percentile and the lower 10th percentile.

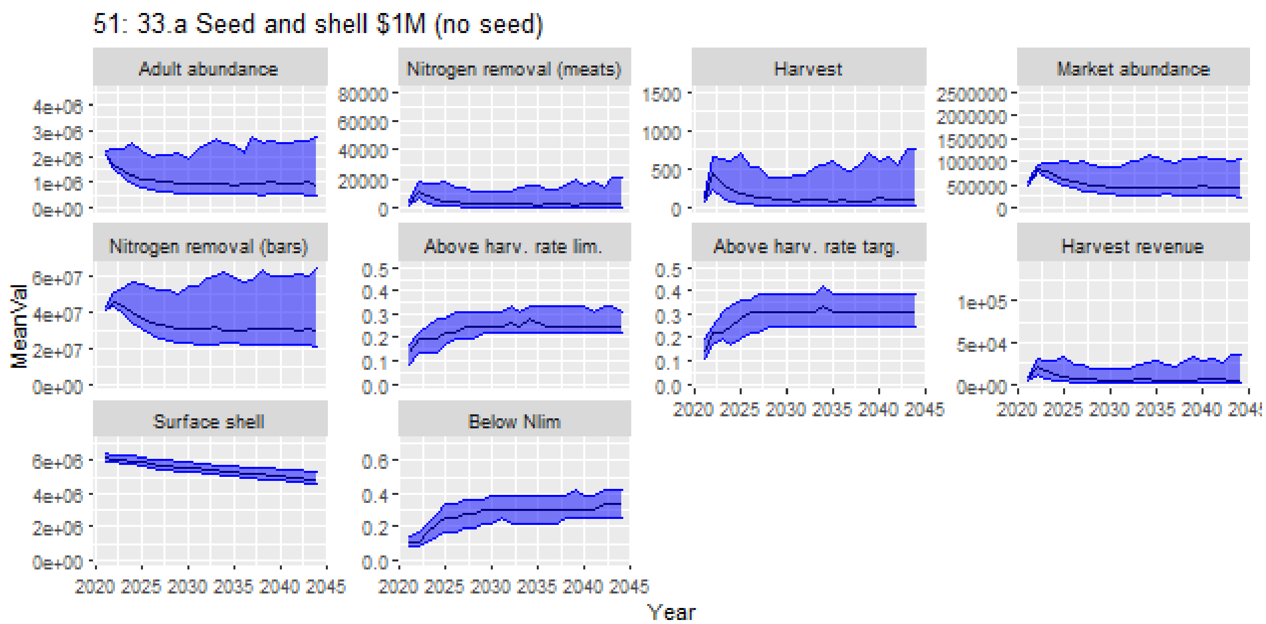

Fig. A195. Forecasted performance of Option 51 during 2022-2044. The solid lines indicate the medians and the shaded areas indicate the area between the upper 90th percentile and the lower 10th percentile.

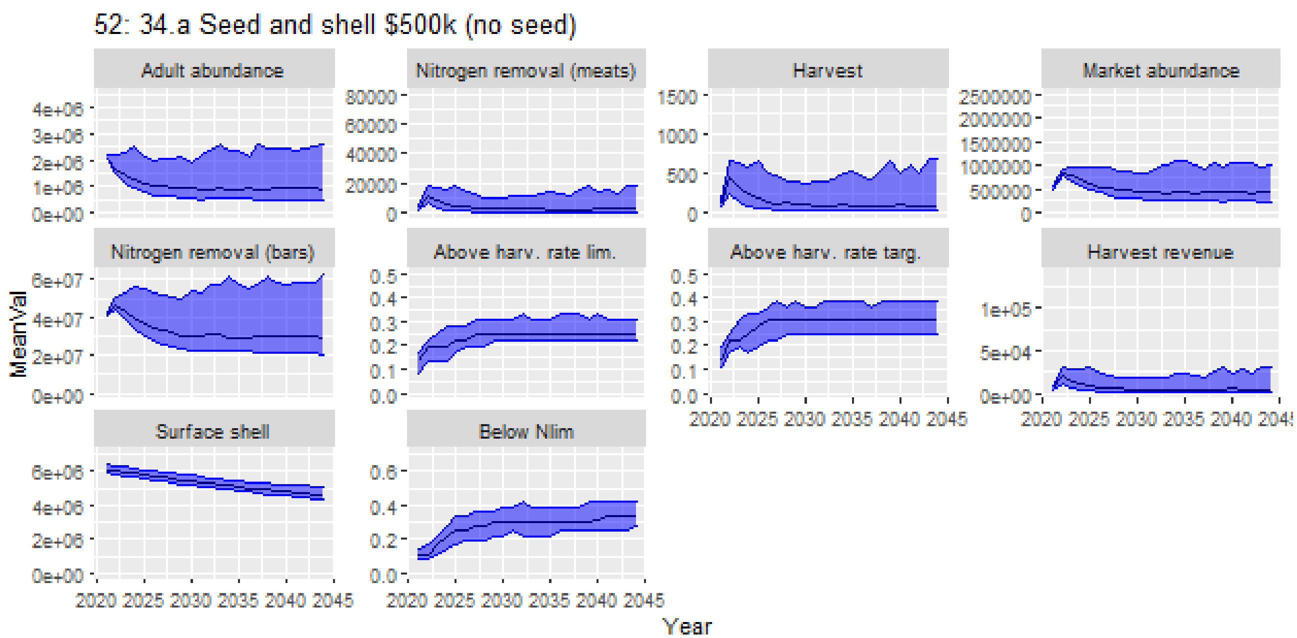

Fig. A196. Forecasted performance of Option 52 during 2022-2044. The solid lines indicate the medians and the shaded areas indicate the area between the upper 90th percentile and the lower 10th percentile.

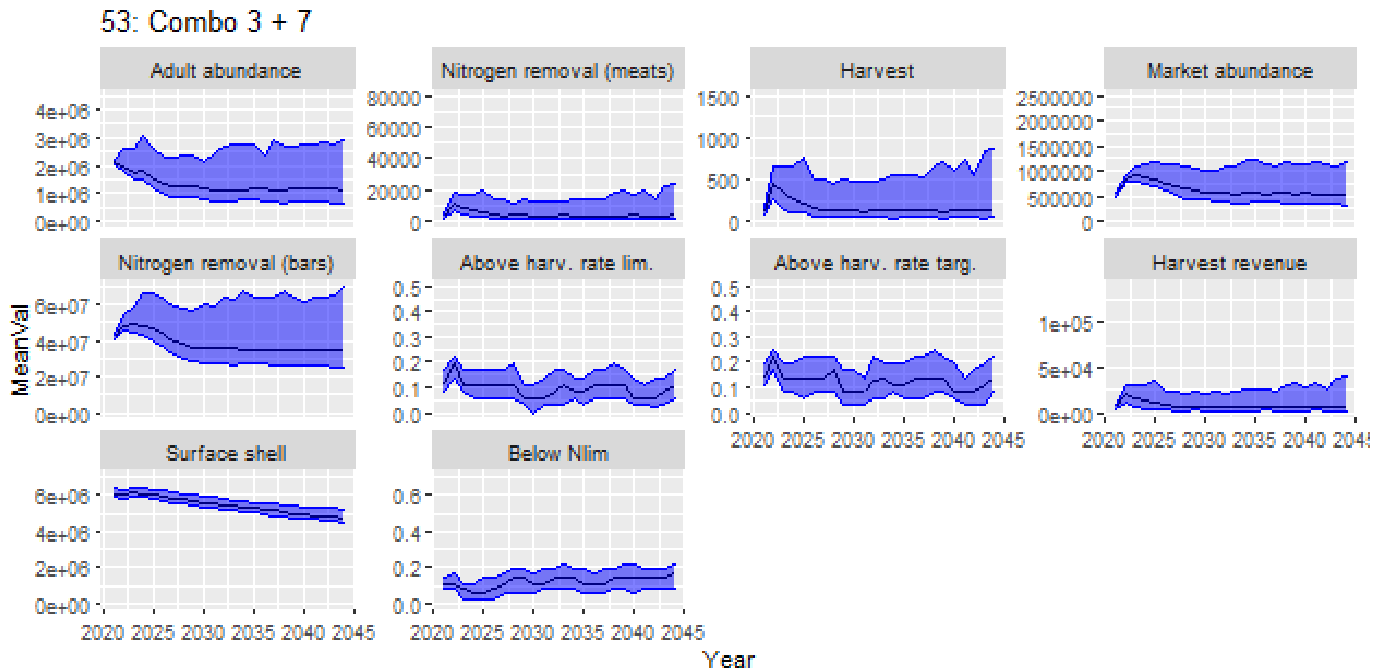

Fig. A197. Forecasted performance of Option 53 during 2022-2044. The solid lines indicate the medians and the shaded areas indicate the area between the upper 90th percentile and the lower 10th percentile.

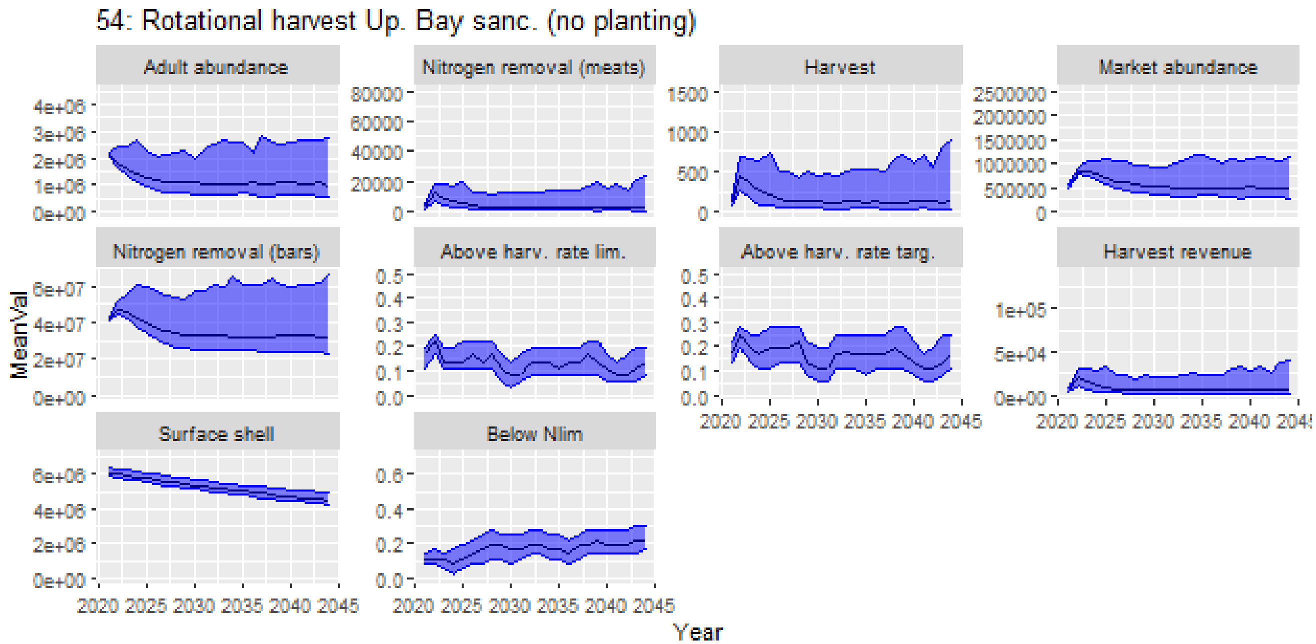

Fig. A198. Forecasted performance of Option 54 during 2022-2044. The solid lines indicate the medians and the shaded areas indicate the area between the upper 90th percentile and the lower 10th percentile.

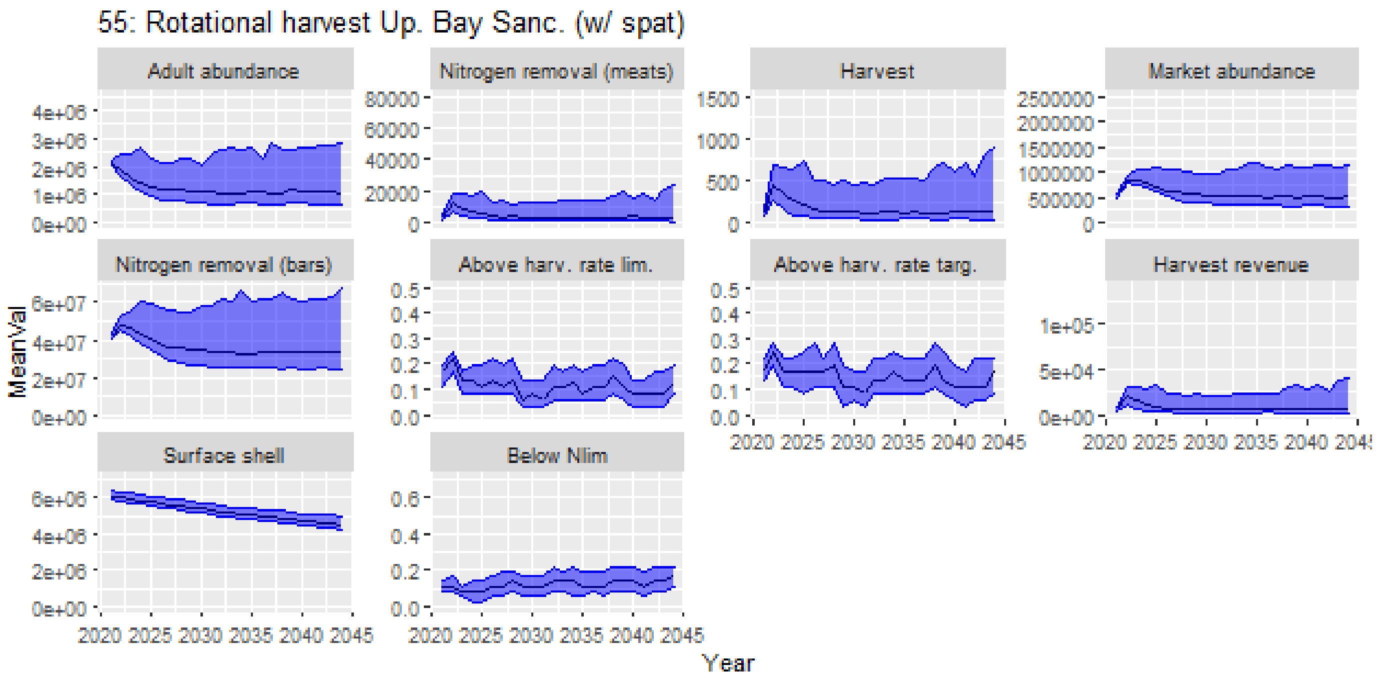

Fig. A199. Forecasted performance of Option 55 during 2022-2044. The solid lines indicate the medians and the shaded areas indicate the area between the upper 90th percentile and the lower 10th percentile.

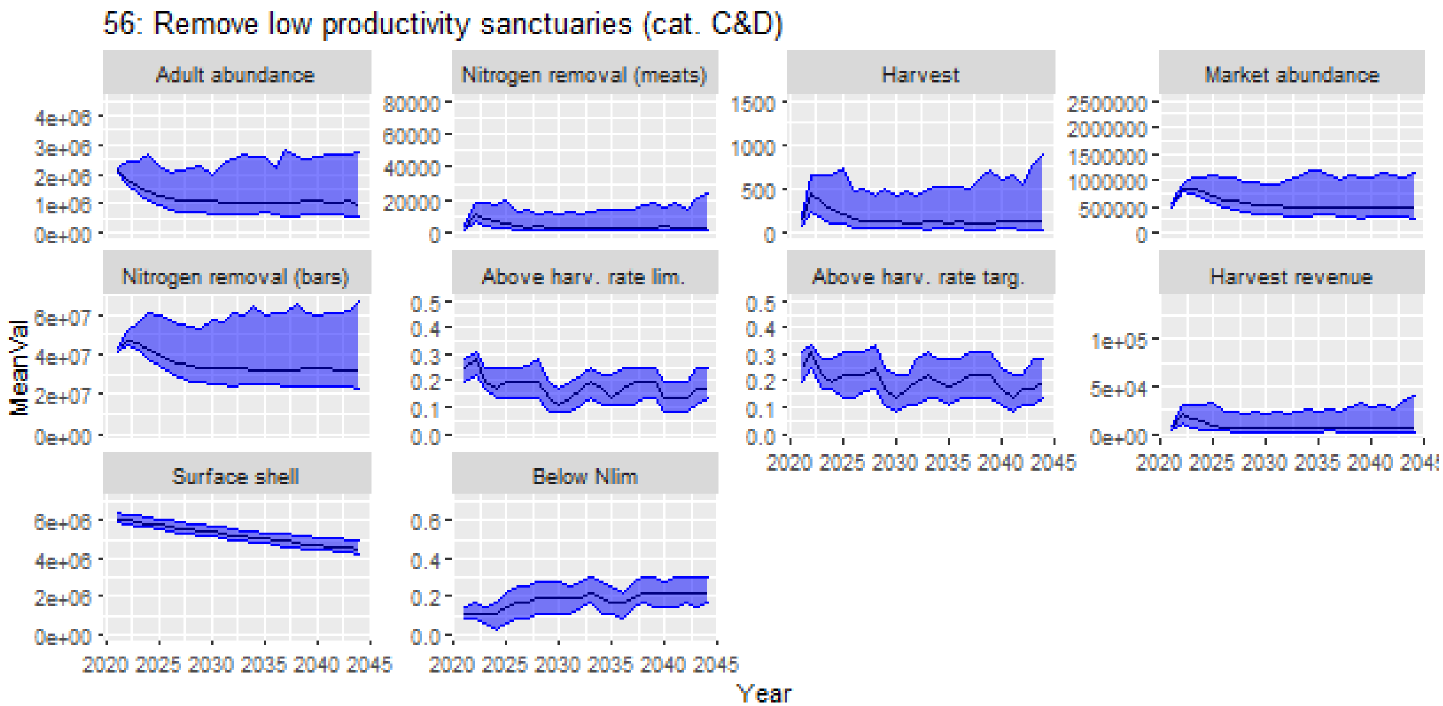

Fig. A200. Forecasted performance of Option 56 during 2022-2044. The solid lines indicate the medians and the shaded areas indicate the area between the upper 90th percentile and the lower 10th percentile.

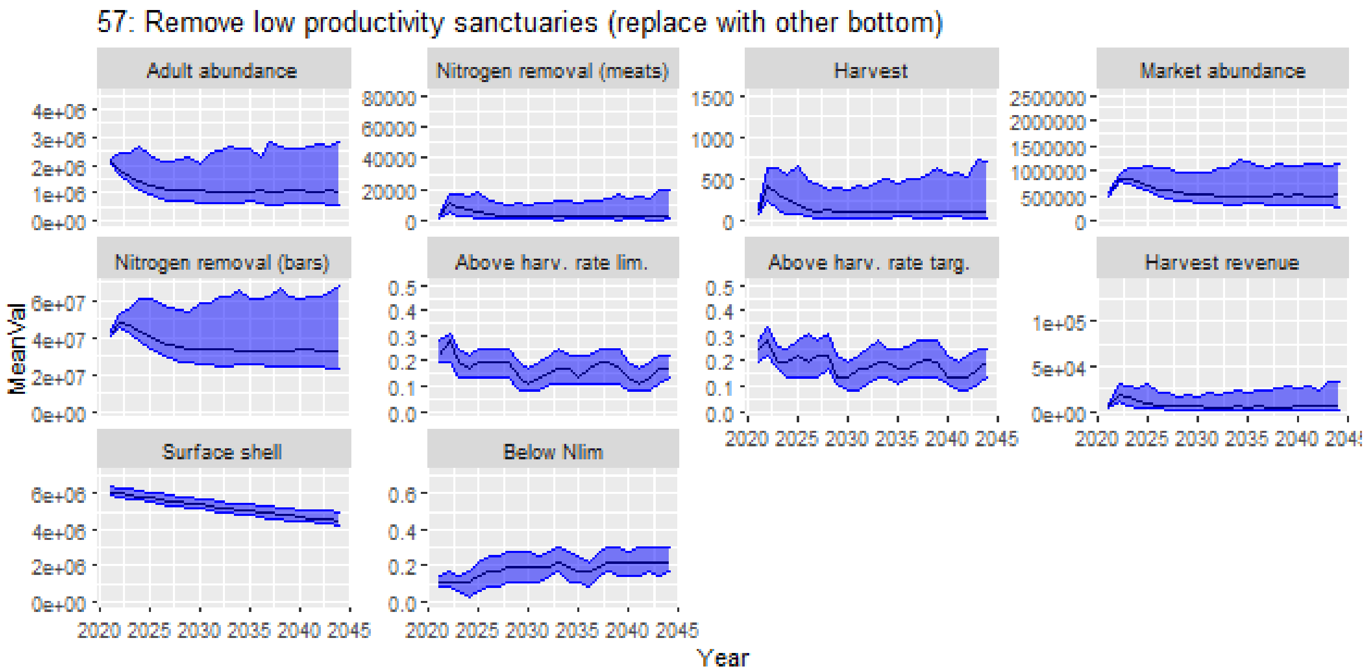

Fig. A201. Forecasted performance of Option 57 during 2022-2044. The solid lines indicate the medians and the shaded areas indicate the area between the upper 90th percentile and the lower 10th percentile.

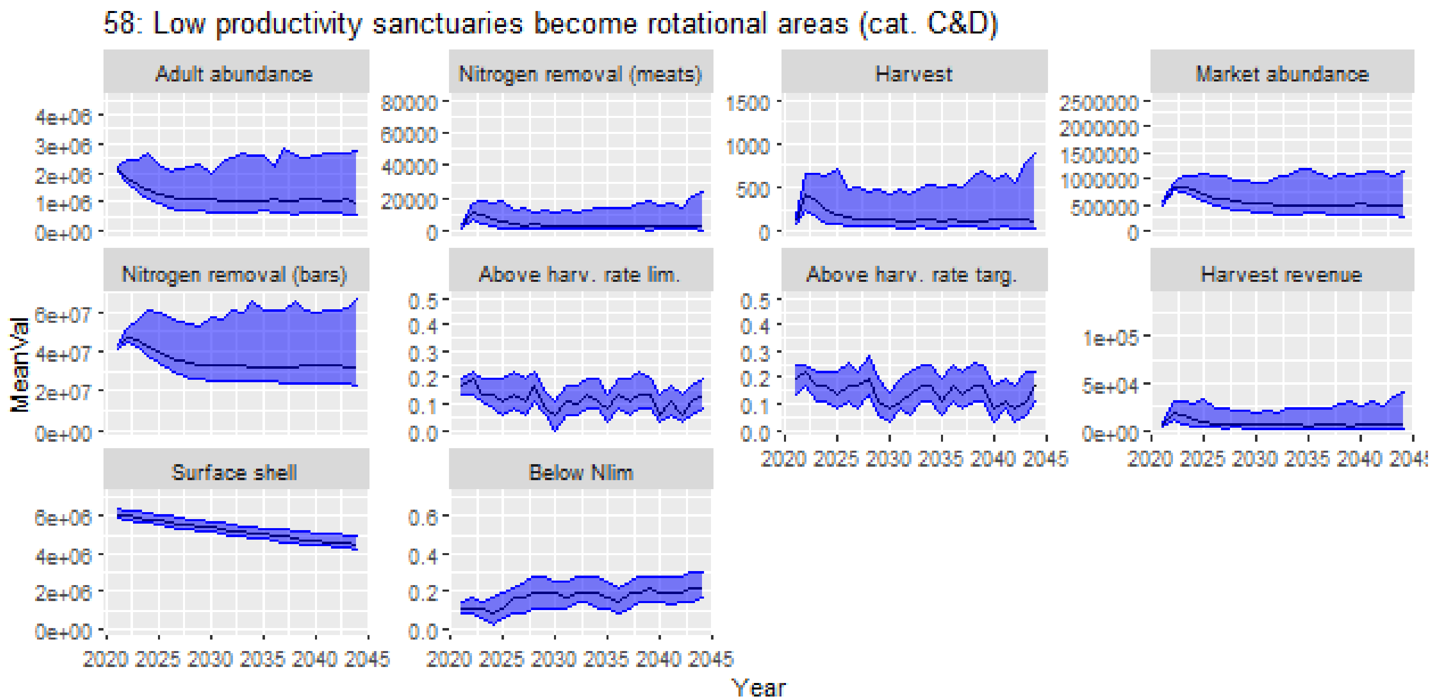

Fig. A202. Forecasted performance of Option 58 during 2022-2044. The solid lines indicate the medians and the shaded areas indicate the area between the upper 90th percentile and the lower 10th percentile.

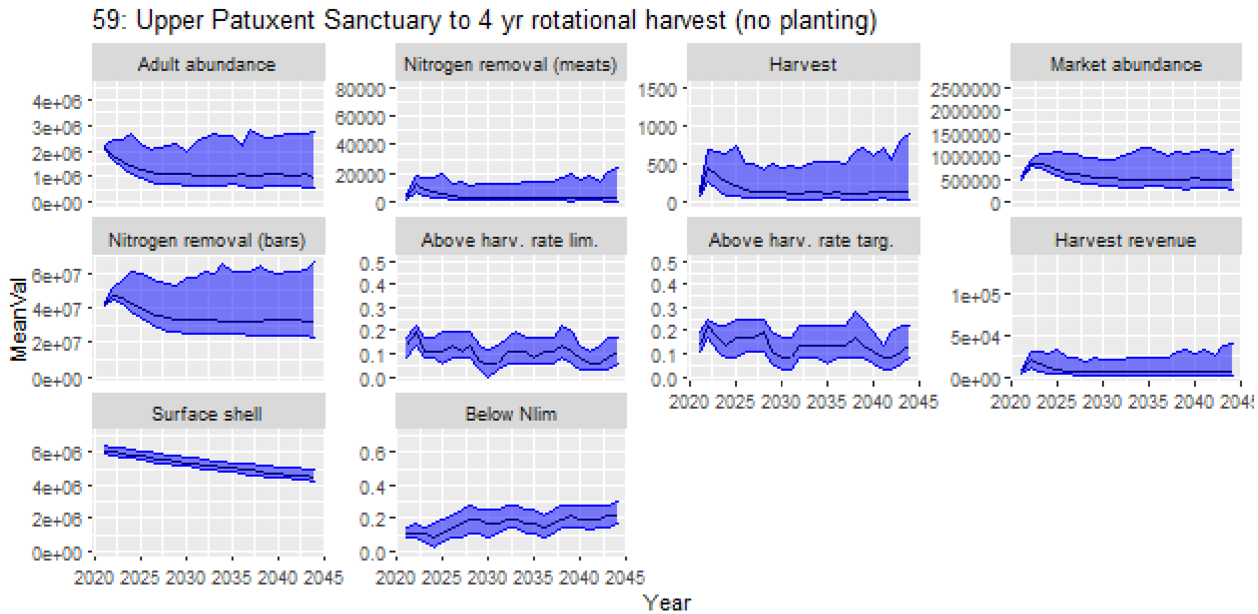

Fig. A203. Forecasted performance of Option 59 during 2022-2044. The solid lines indicate the medians and the shaded areas indicate the area between the upper 90th percentile and the lower 10th percentile.

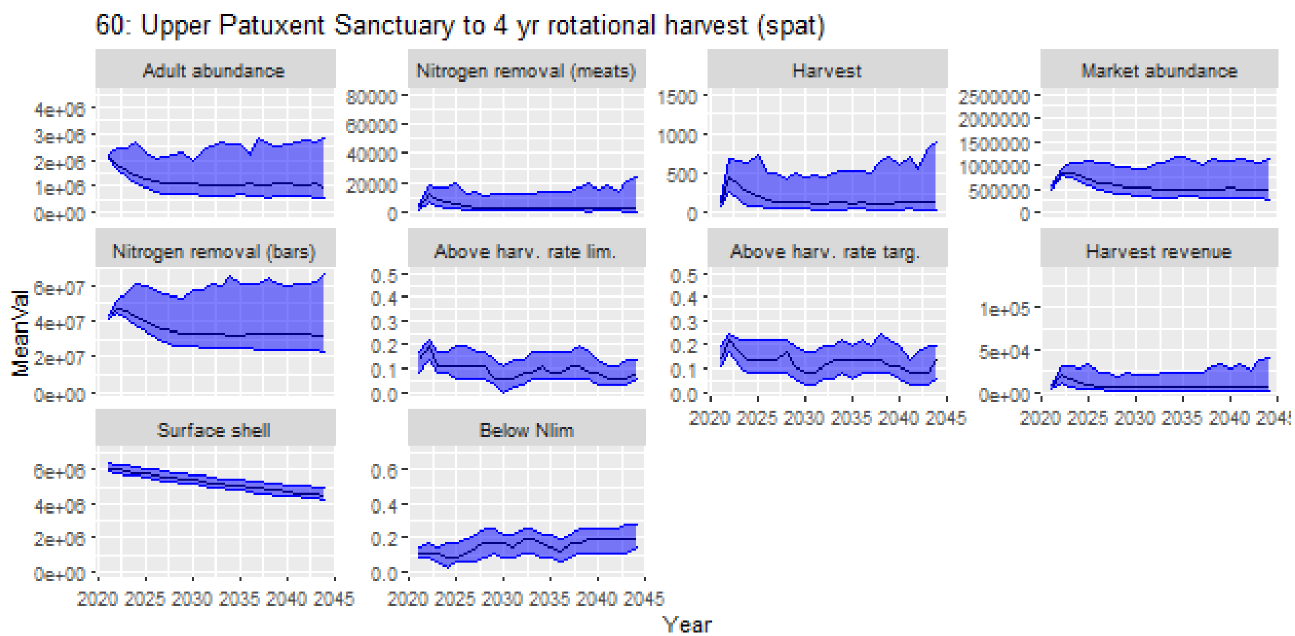

Fig. A204. Forecasted performance of Option 60 during 2022-2044. The solid lines indicate the medians and the shaded areas indicate the area between the upper 90th percentile and the lower 10th percentile.

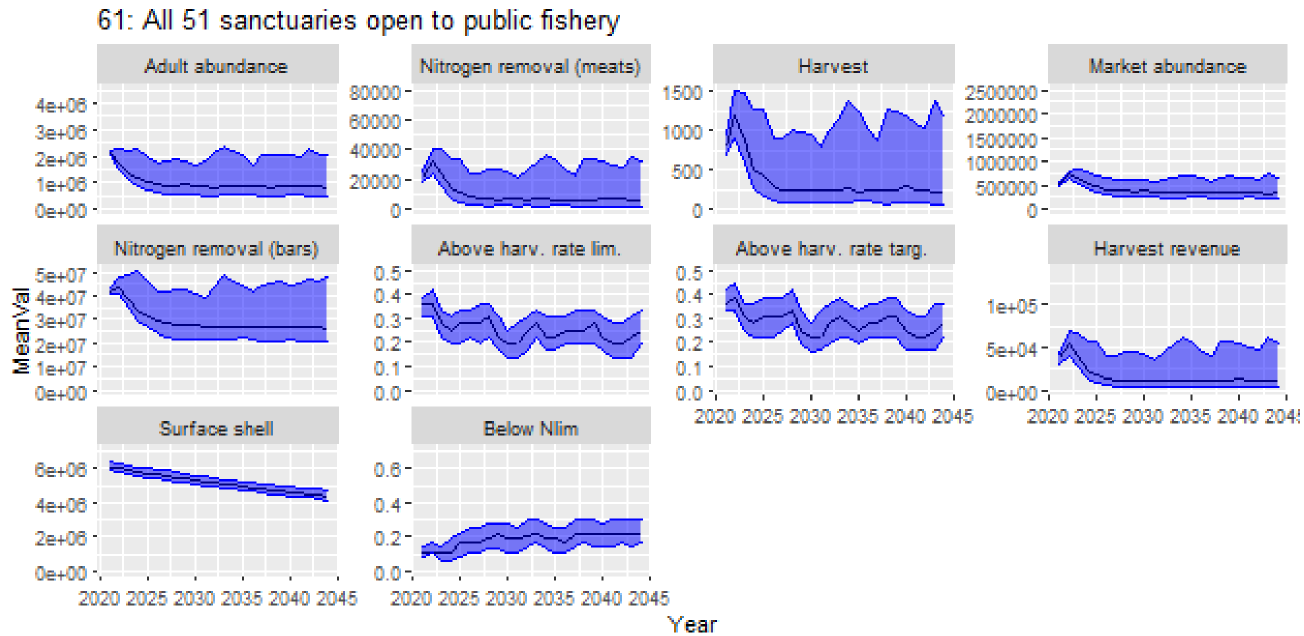

Fig. A205. Forecasted performance of Option 61 during 2022-2044. The solid lines indicate the medians and the shaded areas indicate the area between the upper 90th percentile and the lower 10th percentile.

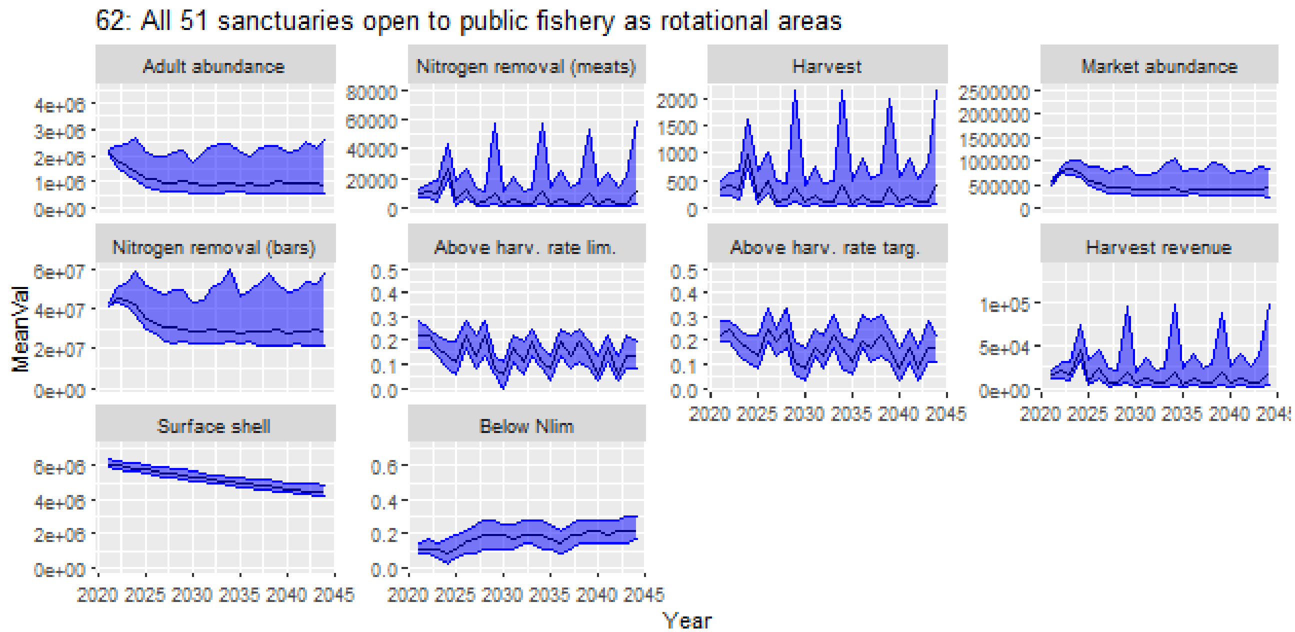

Fig. A206. Forecasted performance of Option 62 during 2022-2044. The solid lines indicate the medians and the shaded areas indicate the area between the upper 90th percentile and the lower 10th percentile.

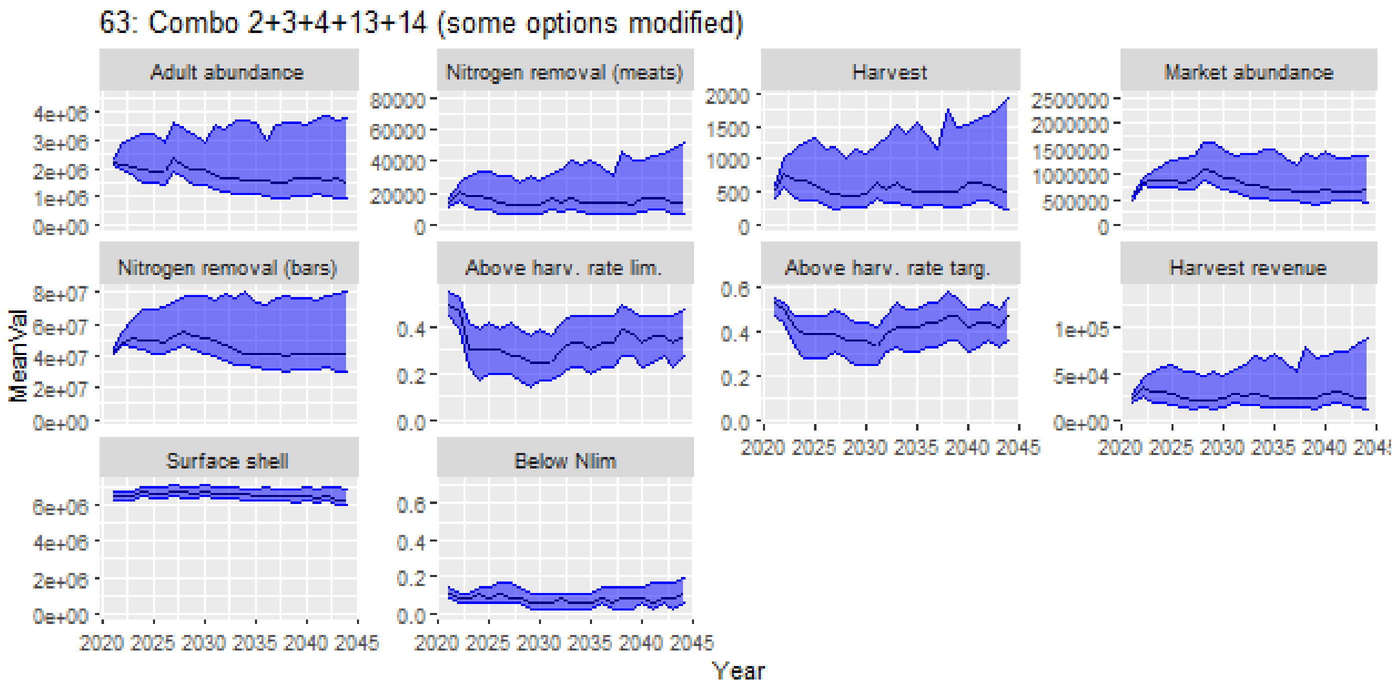

Fig. A207. Forecasted performance of Option 63 during 2022-2044. The solid lines indicate the medians and the shaded areas indicate the area between the upper 90th percentile and the lower 10th percentile.

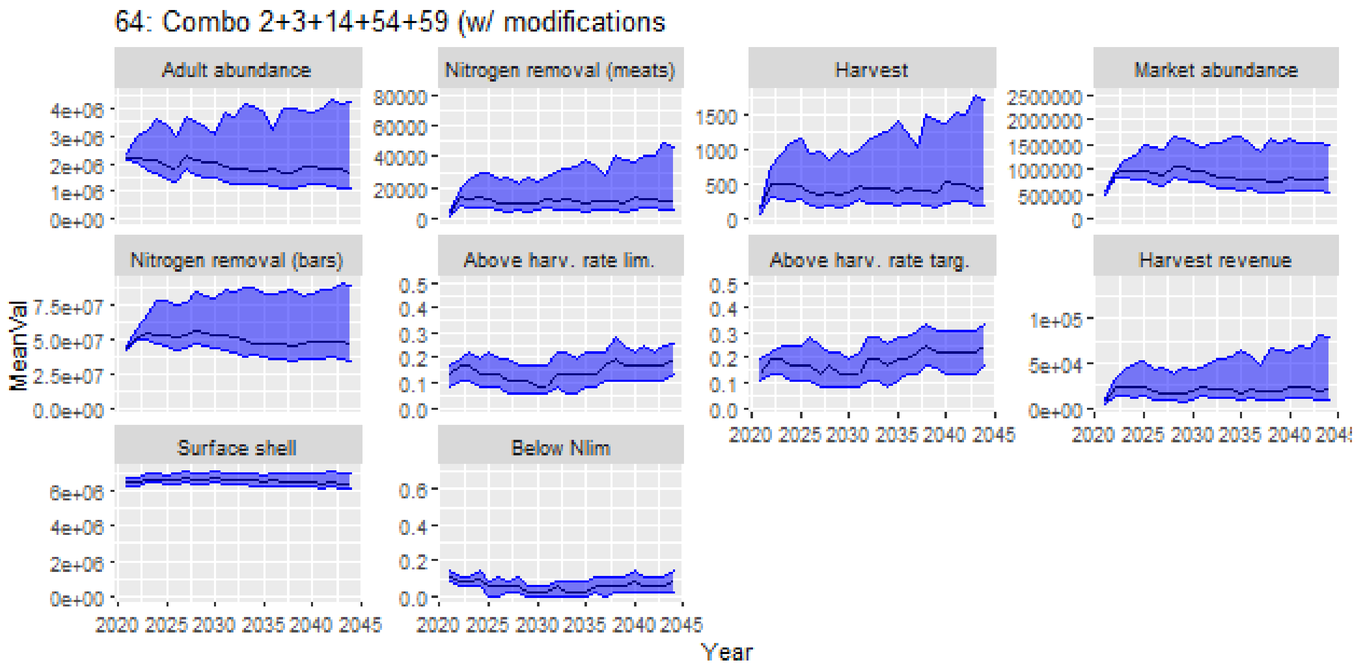

Fig. A208. Forecasted performance of Option 64 during 2022-2044. The solid lines indicate the medians and the shaded areas indicate the area between the upper 90th percentile and the lower 10th percentile.

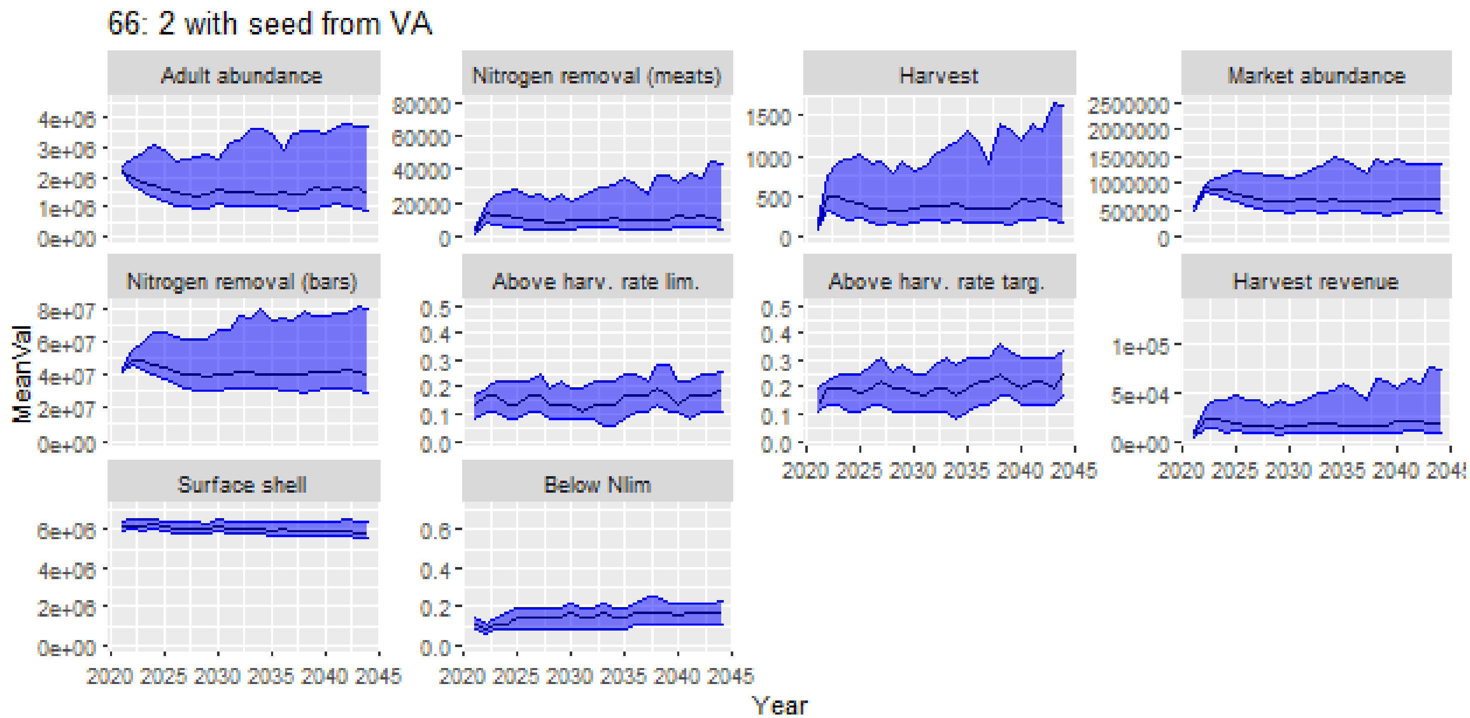

Fig. A209. Forecasted performance of Option 66 during 2022-2044. The solid lines indicate the medians and the shaded areas indicate the area between the upper 90th percentile and the lower 10th percentile.

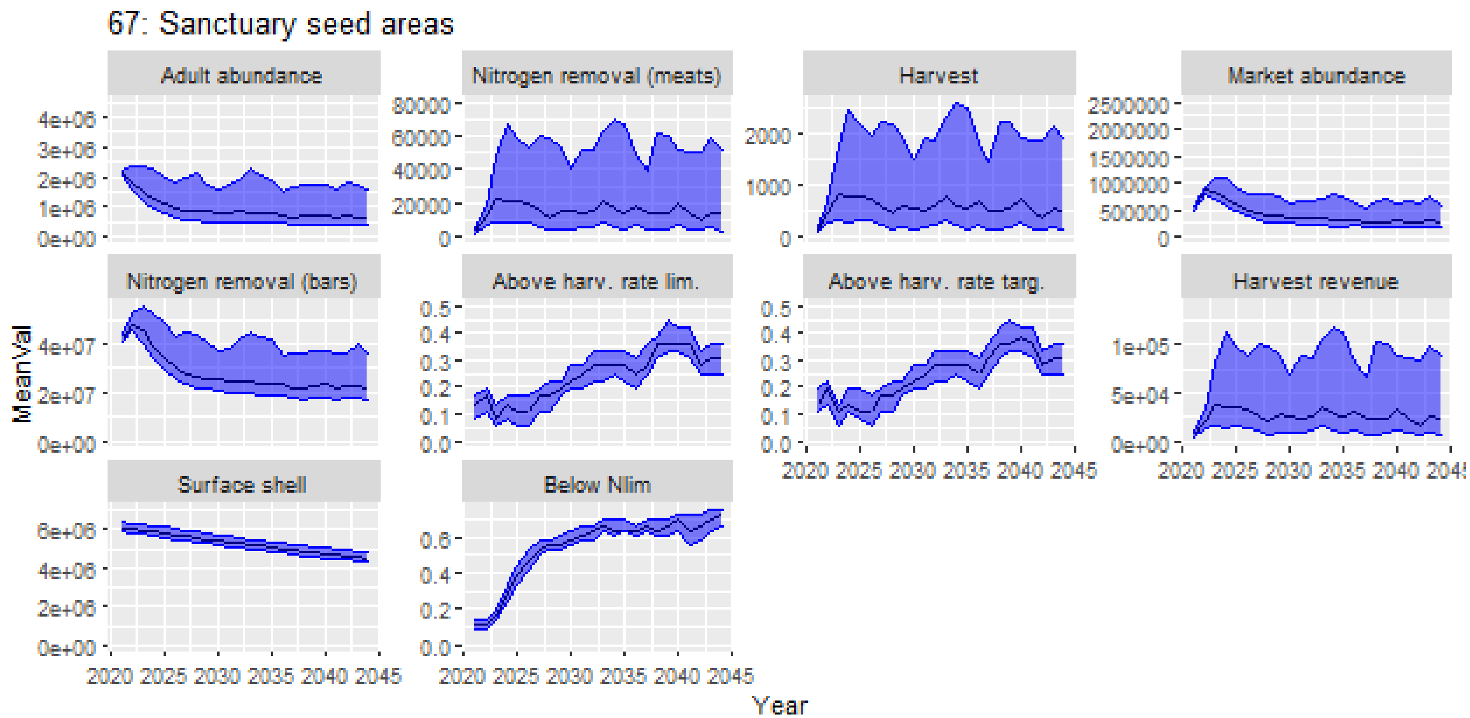

Fig. A210. Forecasted performance of Option 67 during 2022-2044. The solid lines indicate the medians and the shaded areas indicate the area between the upper 90th percentile and the lower 10th percentile.

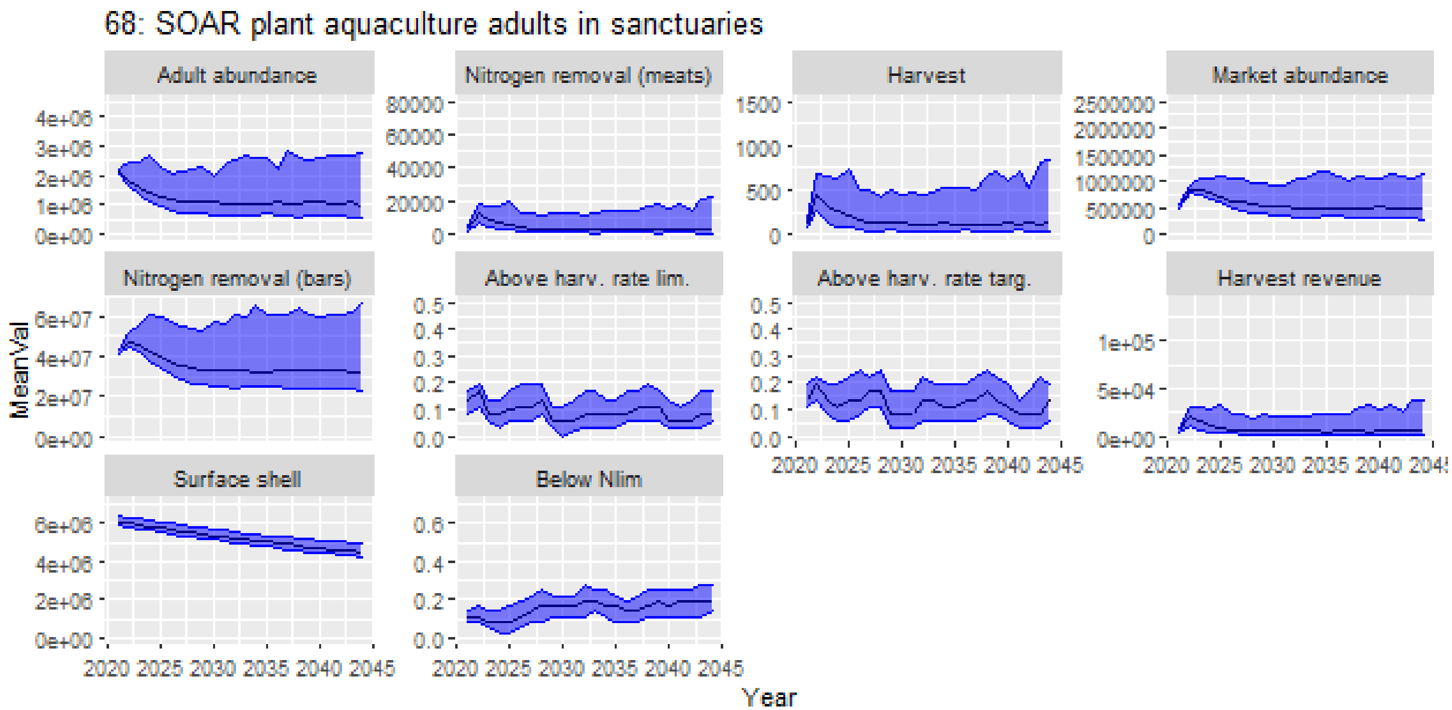

Fig. A211. Forecasted performance of Option 68 during 2022-2044. The solid lines indicate the medians and the shaded areas indicate the area between the upper 90th percentile and the lower 10th percentile.

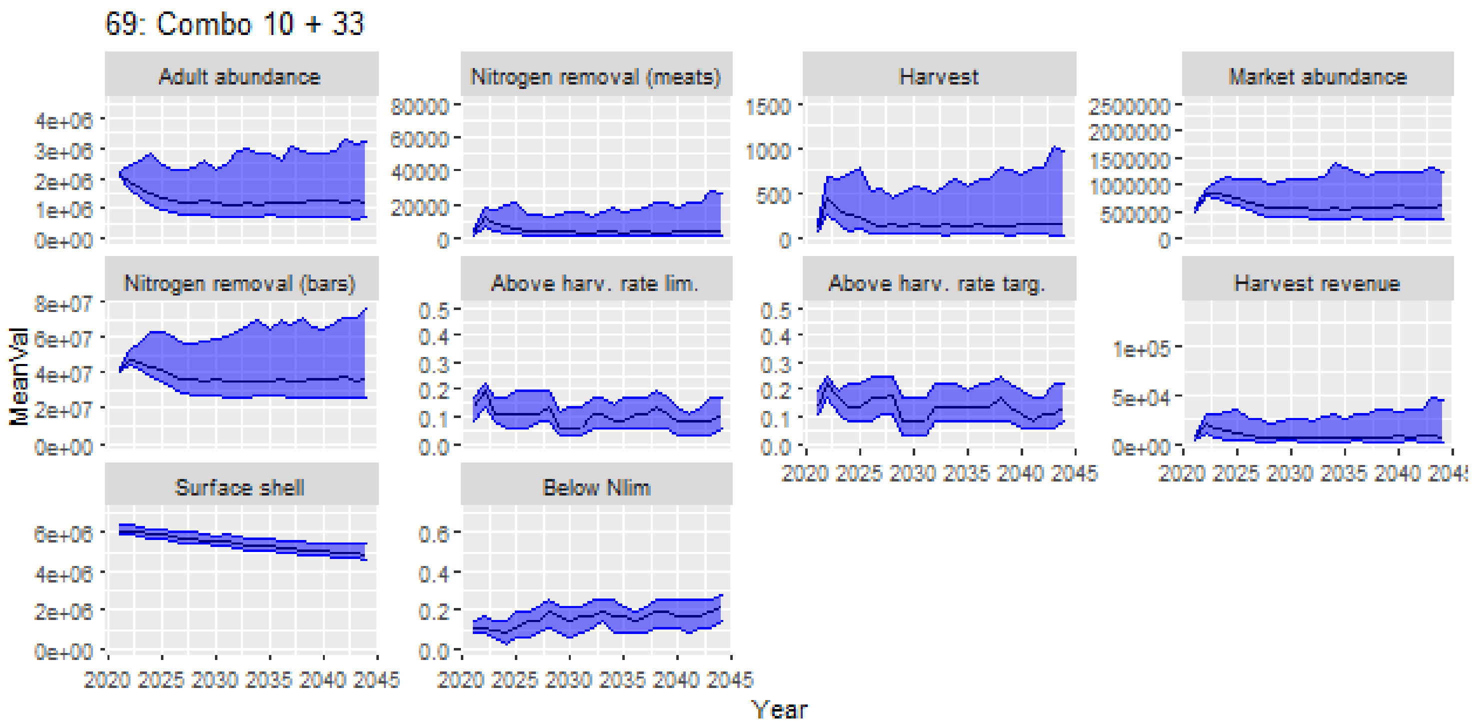

Fig. A212. Forecasted performance of Option 69 during 2022-2044. The solid lines indicate the medians and the shaded areas indicate the area between the upper 90th percentile and the lower 10th percentile.

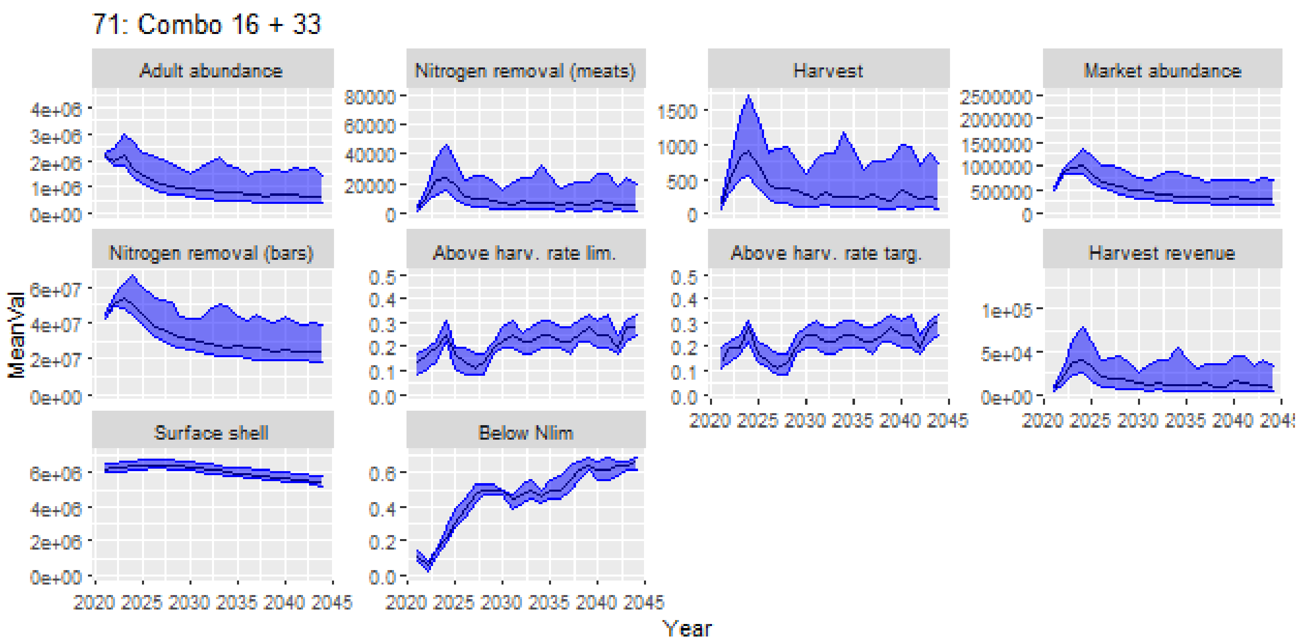

Fig. A213. Forecasted performance of Option 71 during 2022-2044. The solid lines indicate the medians and the shaded areas indicate the area between the upper 90th percentile and the lower 10th percentile.

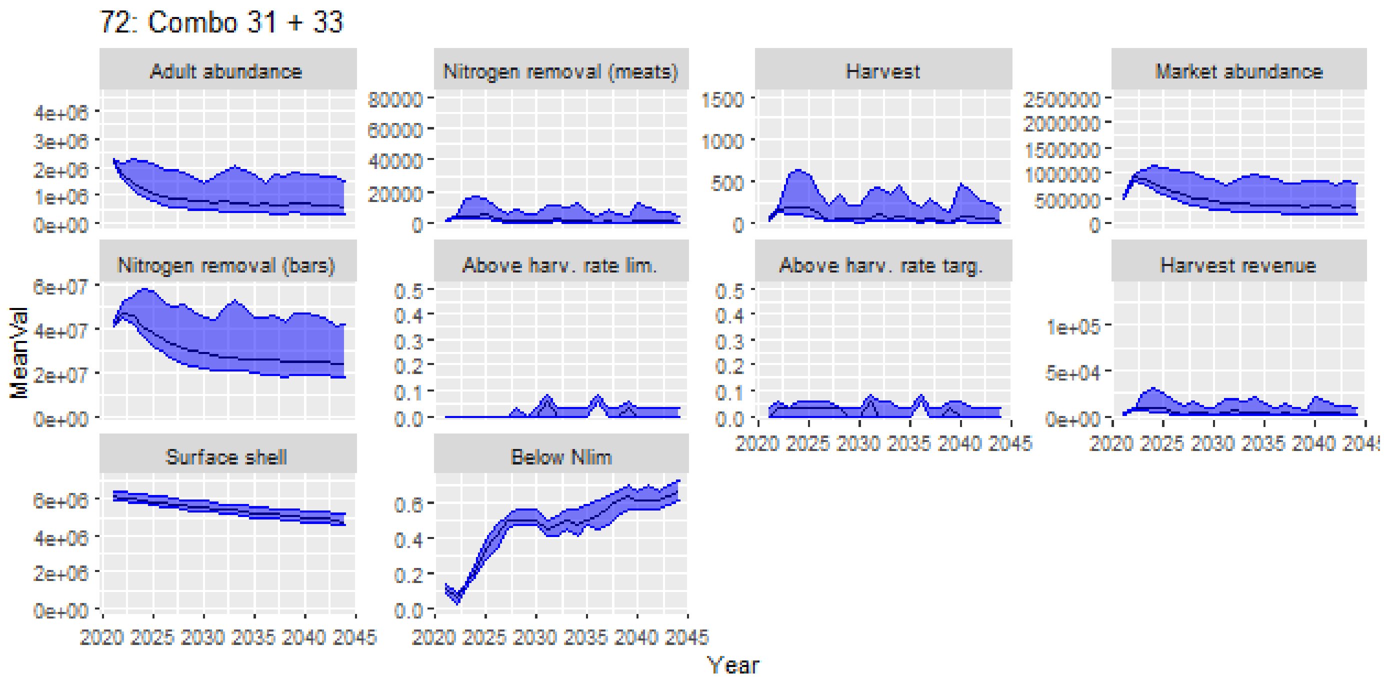

Fig. A214. Forecasted performance of Option 72 during 2022-2044. The solid lines indicate the medians and the shaded areas indicate the area between the upper 90th percentile and the lower 10th percentile.

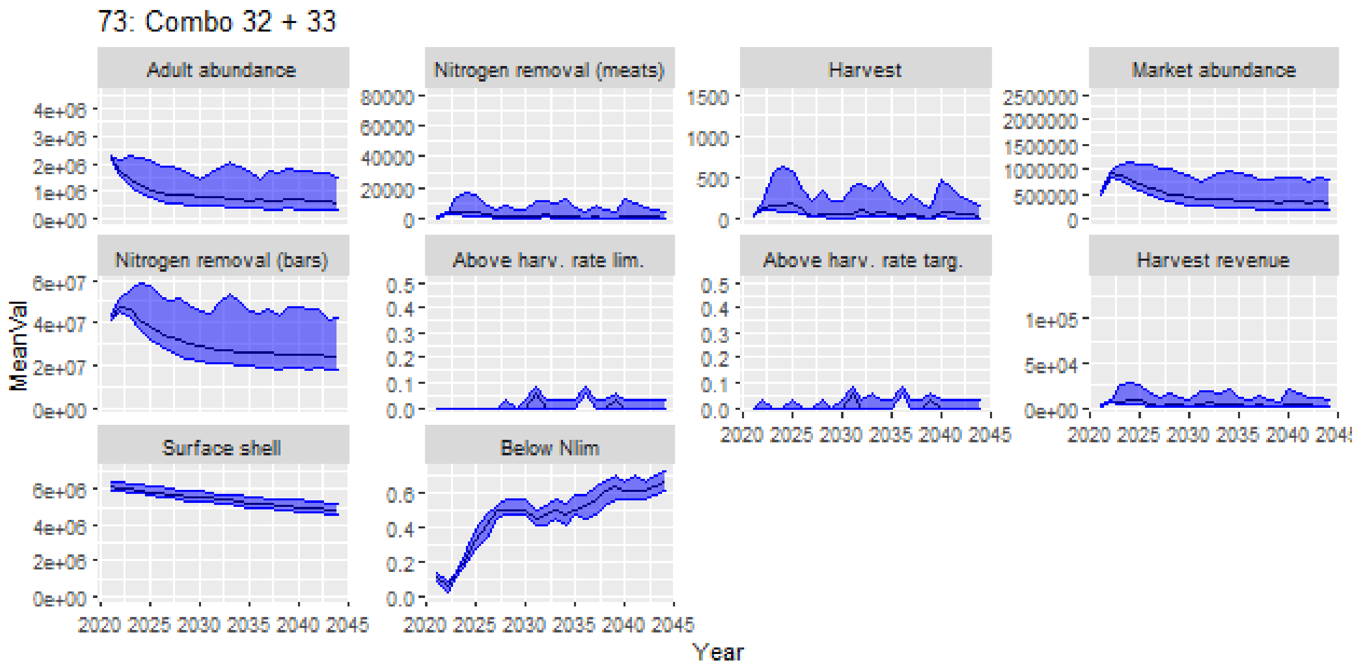

Fig. A215. Forecasted performance of Option 73 during 2022-2044. The solid lines indicate the medians and the shaded areas indicate the area between the upper 90th percentile and the lower 10th percentile.

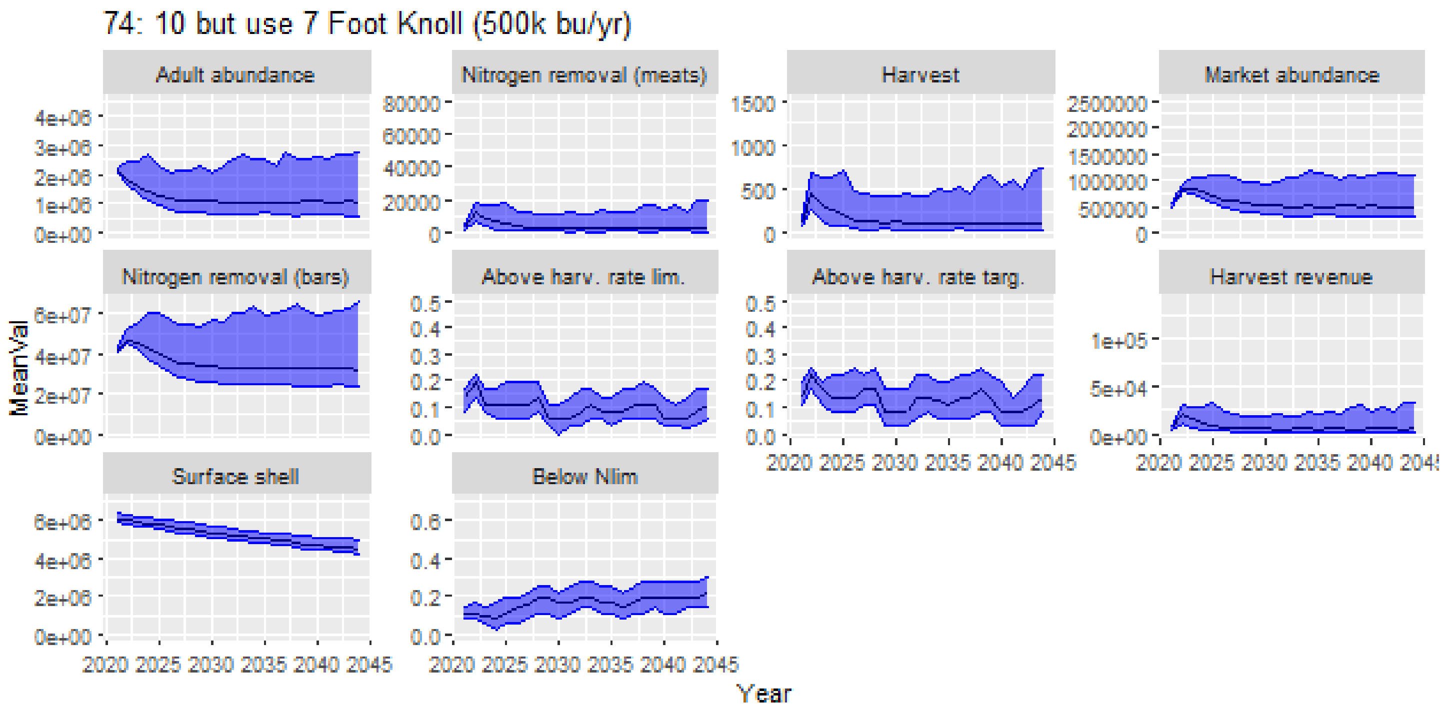

Fig. A216. Forecasted performance of Option 74 during 2022-2044. The solid lines indicate the medians and the shaded areas indicate the area between the upper 90th percentile and the lower 10th percentile.

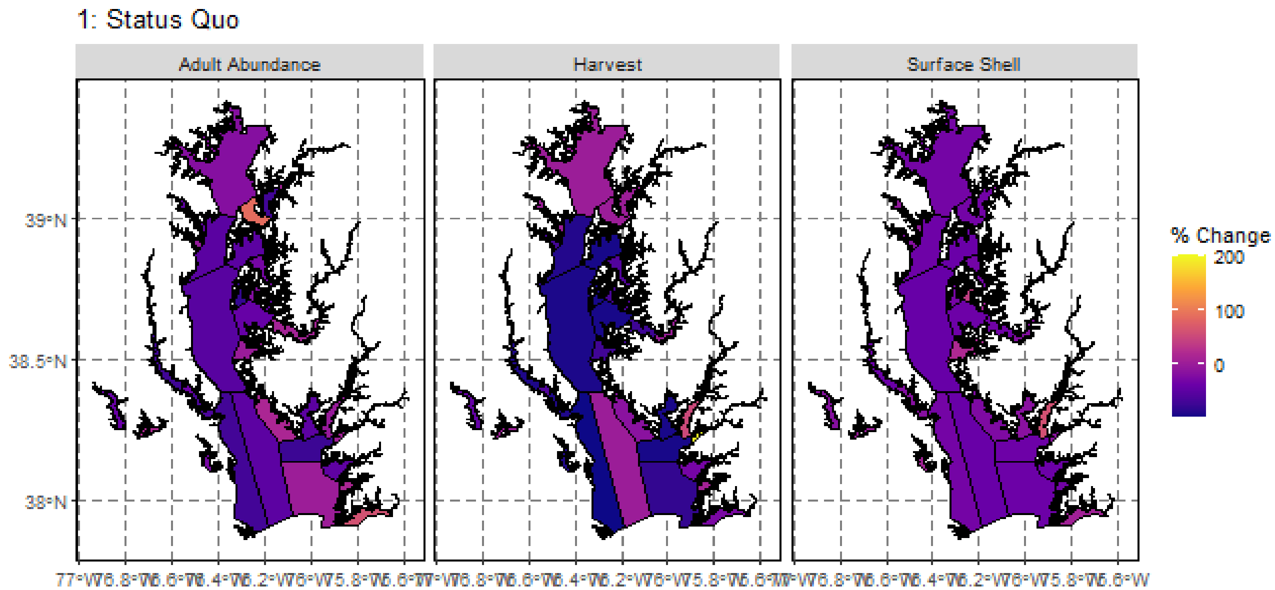

Fig. A217. Median percent change in adult abundance, harvest, and surface shell from 2019 to last year of simulations for Option 1.

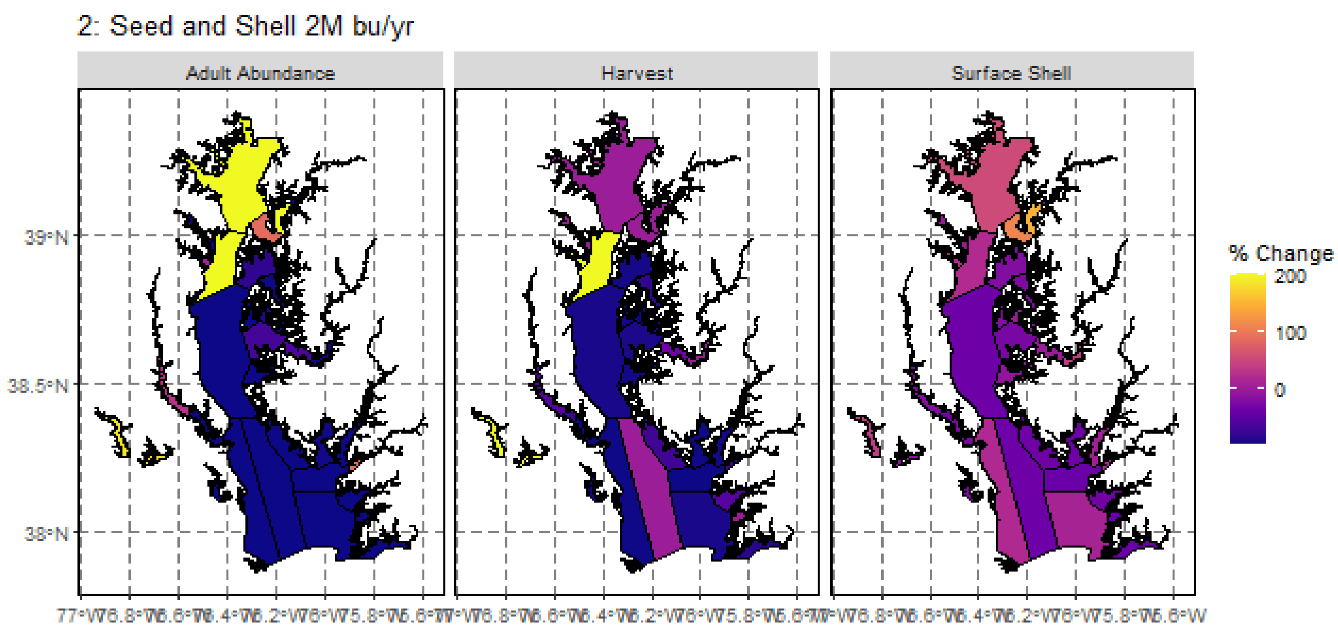

Fig. A218. Median percent change in adult abundance, harvest, and surface shell from 2019 to last year of simulations for Option 2.

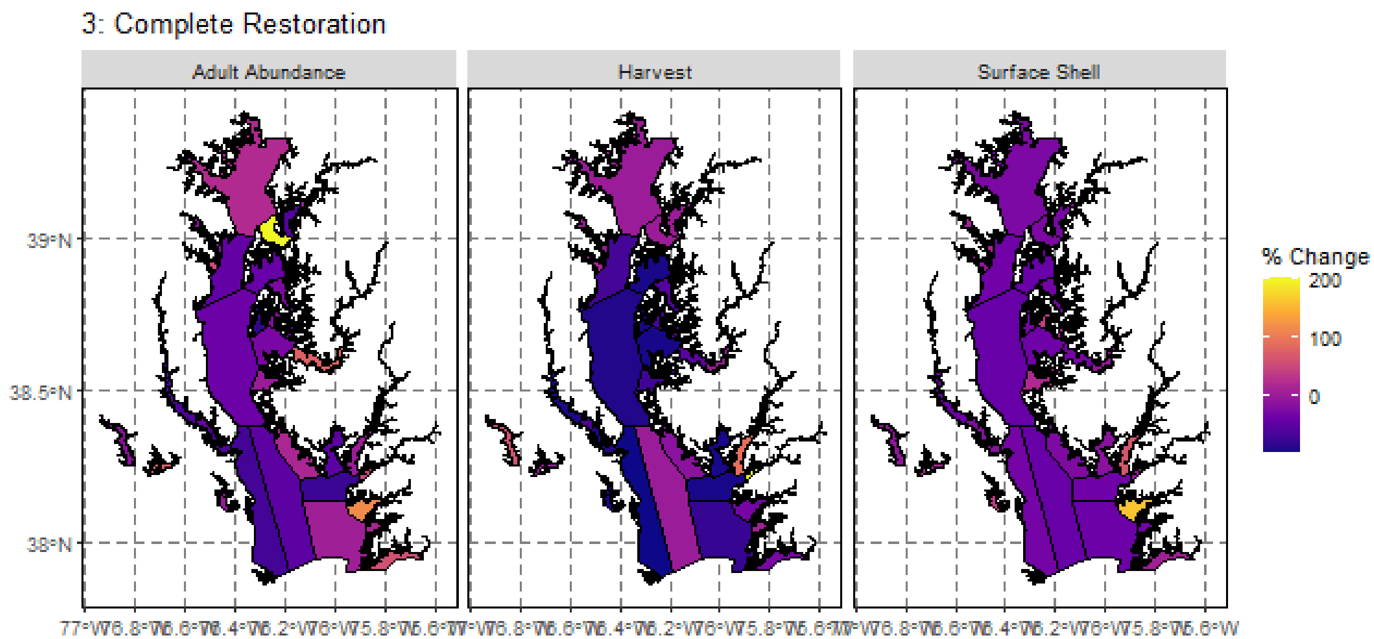

Fig. A219. Median percent change in adult abundance, harvest, and surface shell from 2019 to last year of simulations for Option 3.

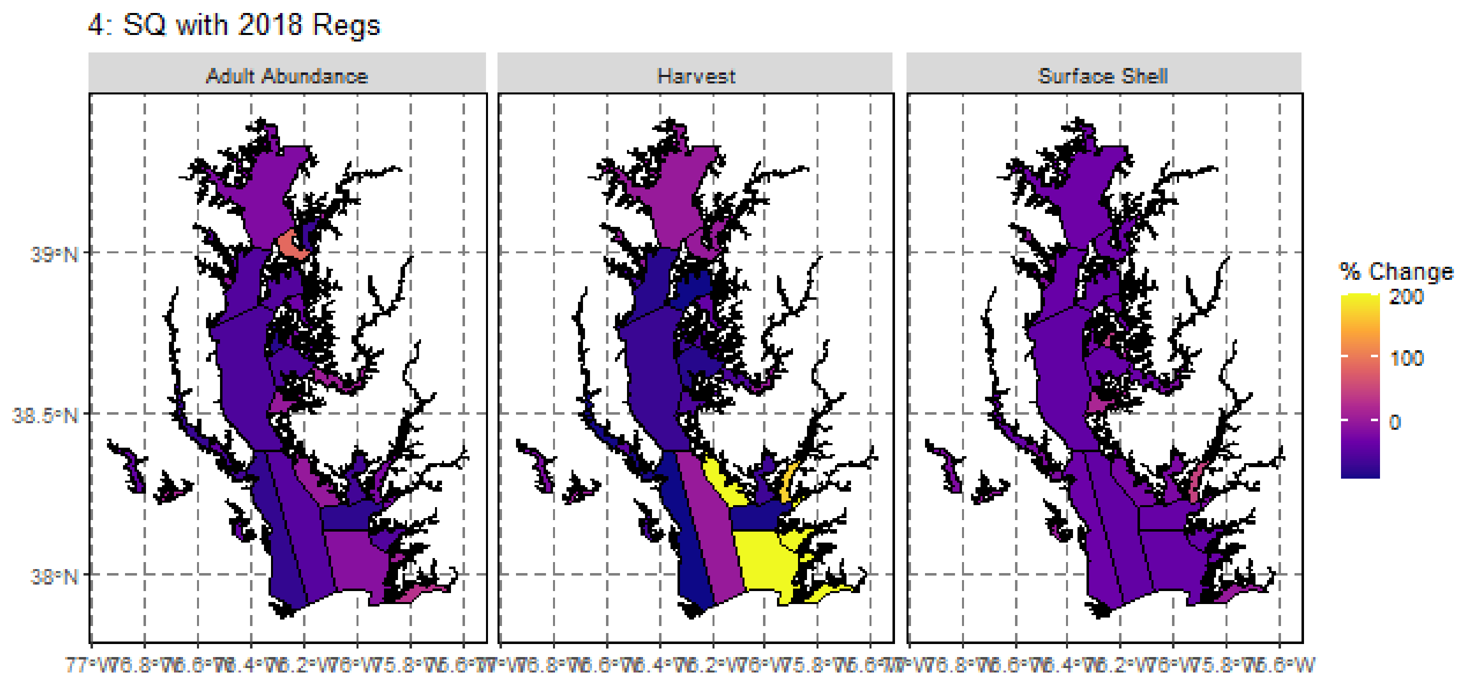

Fig. A220. Median percent change in adult abundance, harvest, and surface shell from 2019 to last year of simulations for Option 4.

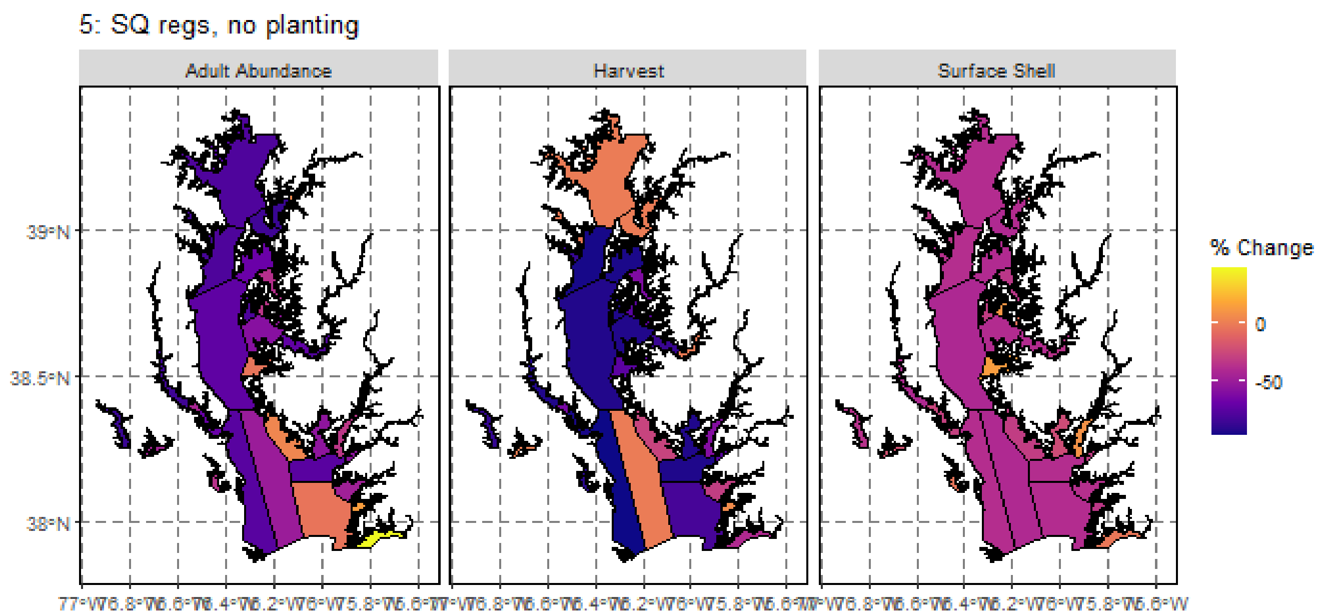

Fig. A221. Median percent change in adult abundance, harvest, and surface shell from 2019 to last year of simulations for Option 5.

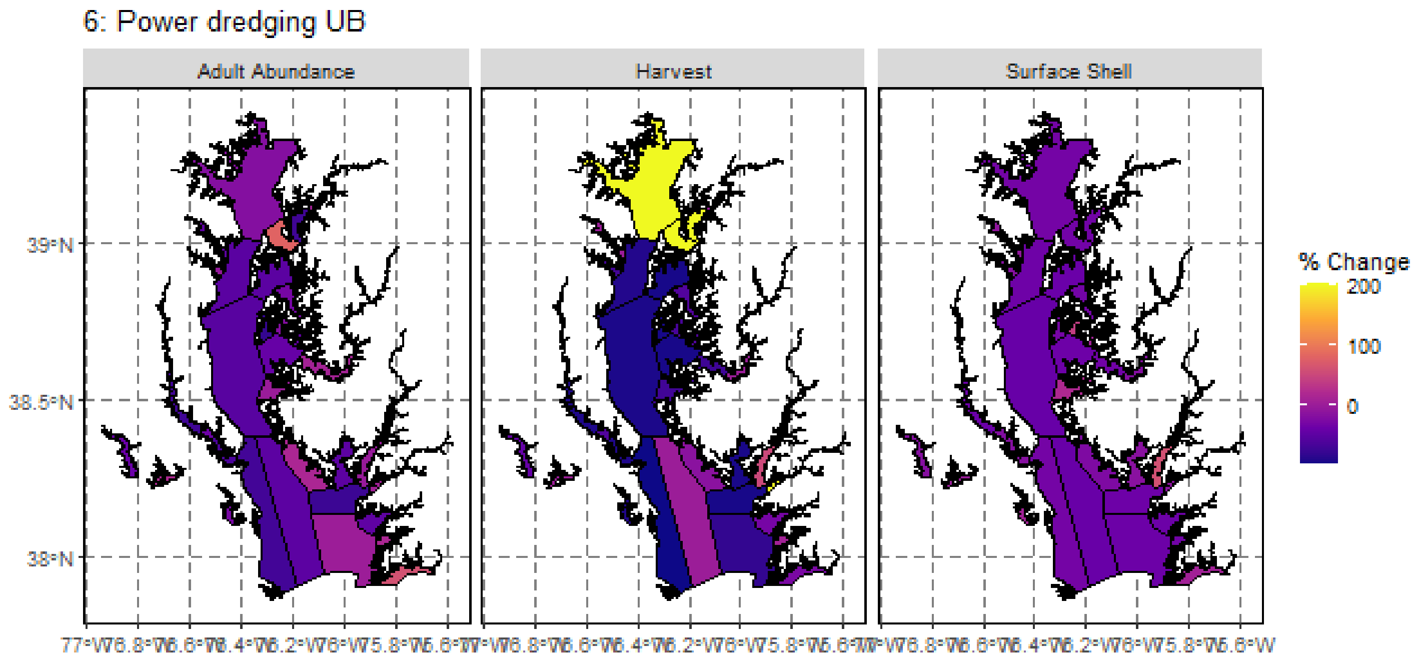

Fig. A222. Median percent change in adult abundance, harvest, and surface shell from 2019 to last year of simulations for Option 6.

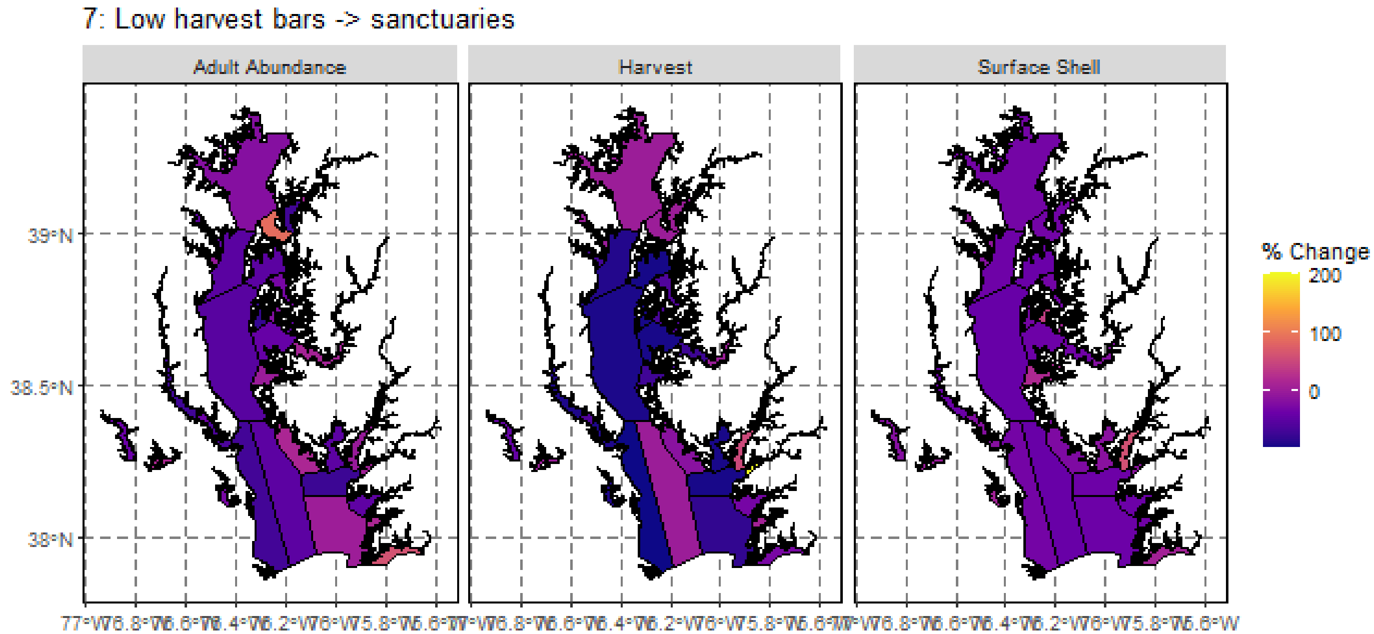

Fig. A223. Median percent change in adult abundance, harvest, and surface shell from 2019 to last year of simulations for Option 7.

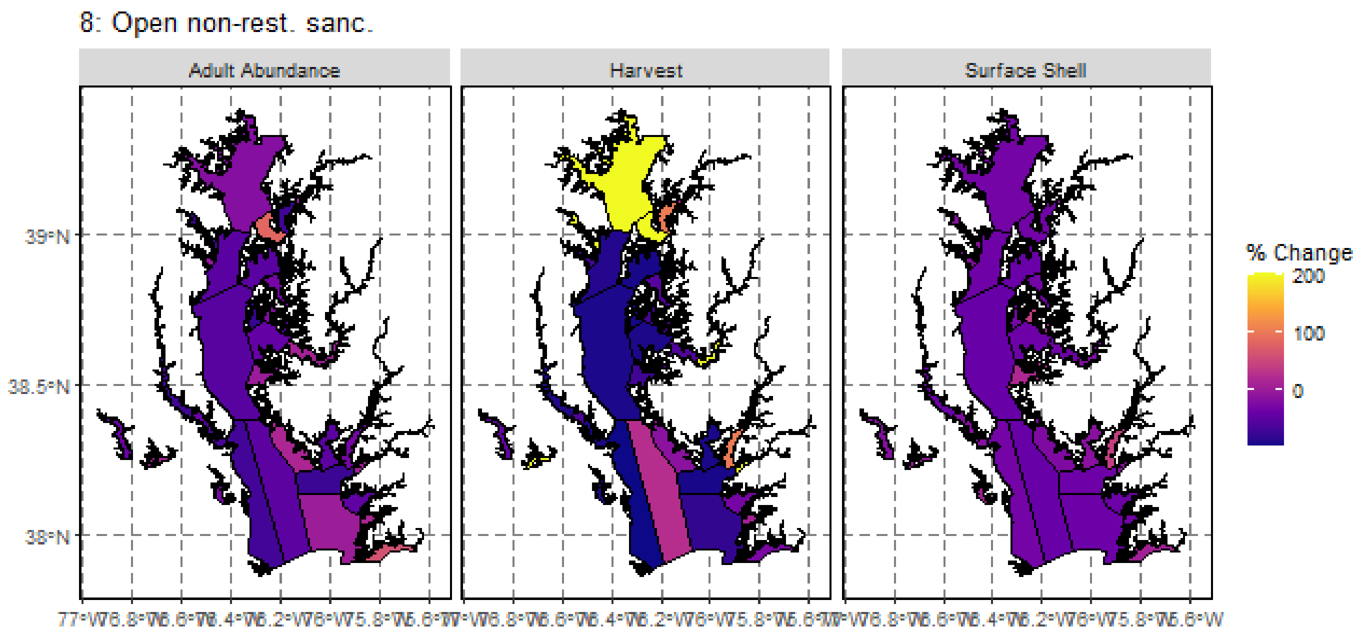

Fig. A224. Median percent change in adult abundance, harvest, and surface shell from 2019 to last year of simulations for Option 8.

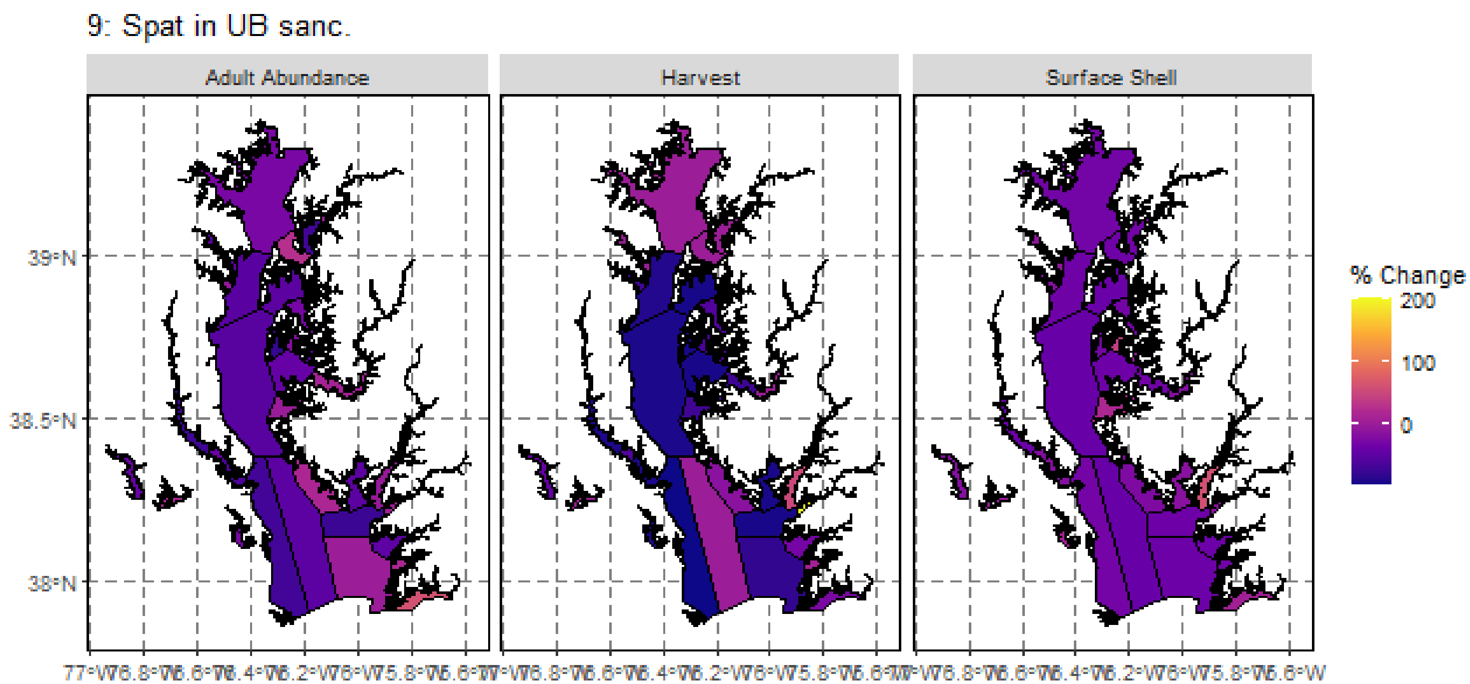

Fig. A225. Median percent change in adult abundance, harvest, and surface shell from 2019 to last year of simulations for Option 9.

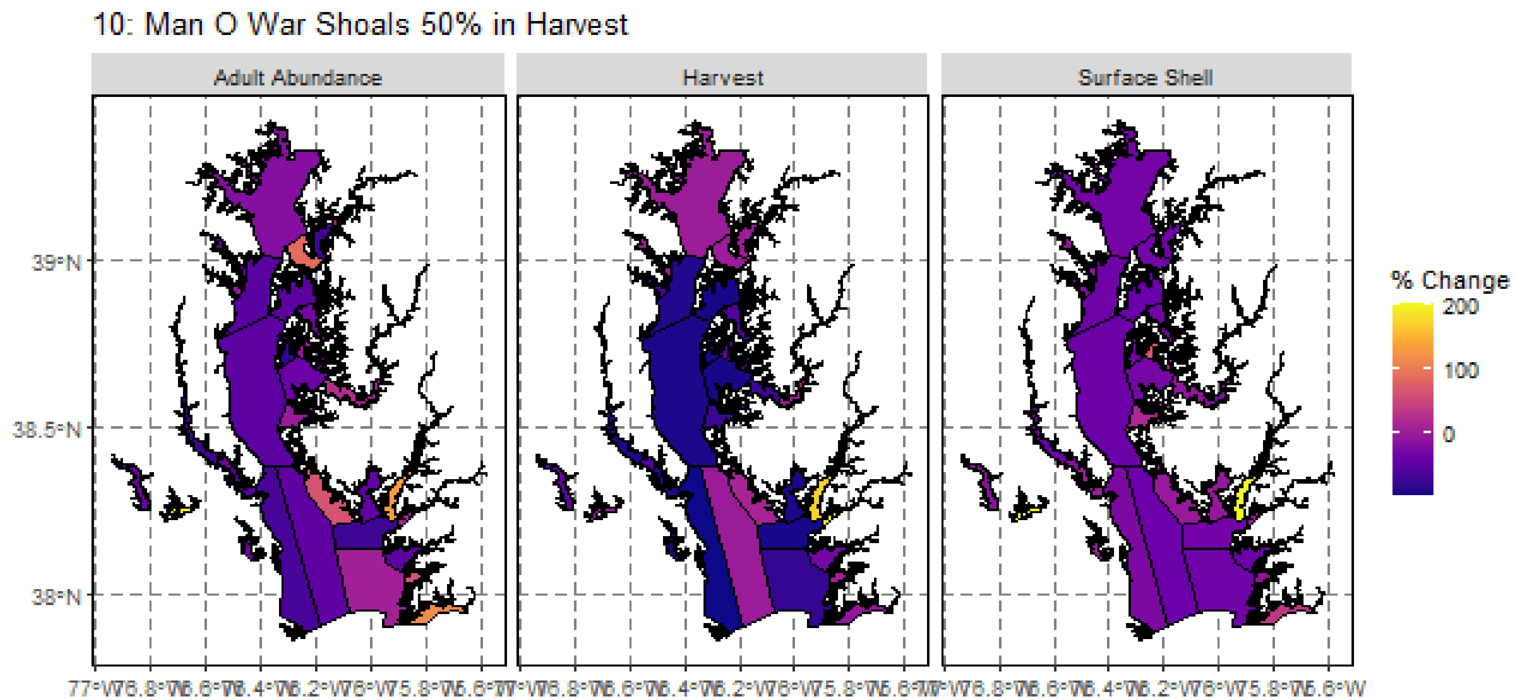

Fig. A226. Median percent change in adult abundance, harvest, and surface shell from 2019 to last year of simulations for Option 10.

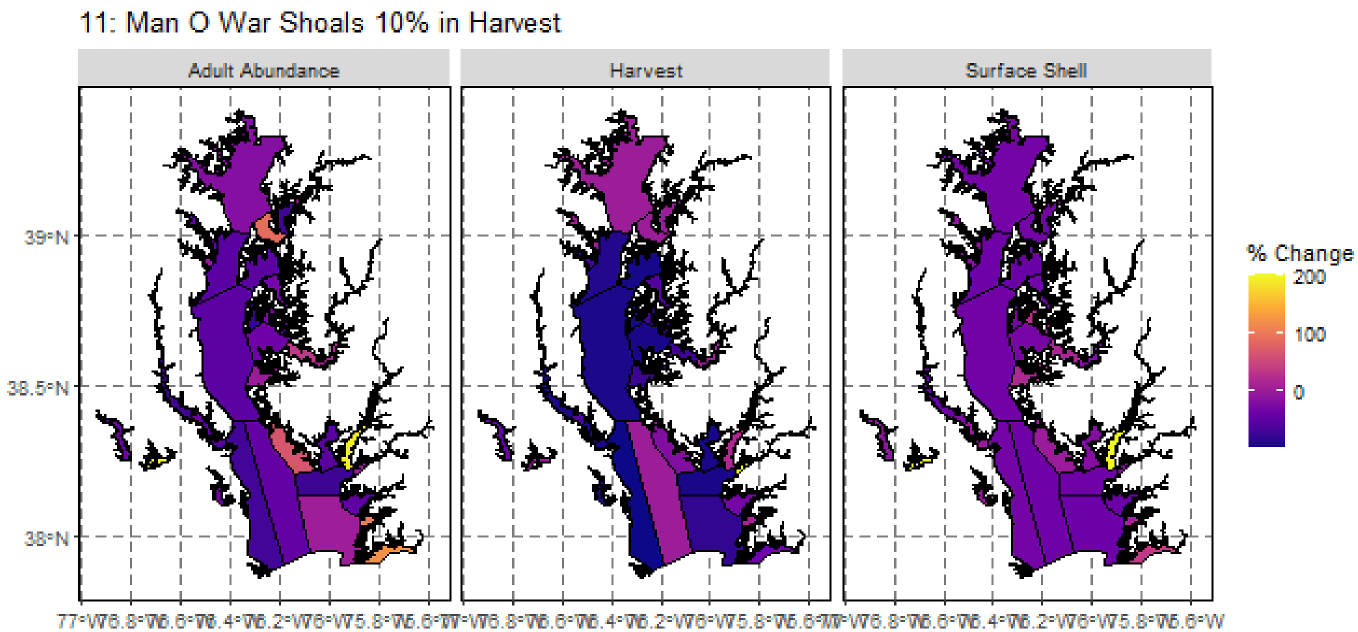

Fig. A227. Median percent change in adult abundance, harvest, and surface shell from 2019 to last year of simulations for Option 11.

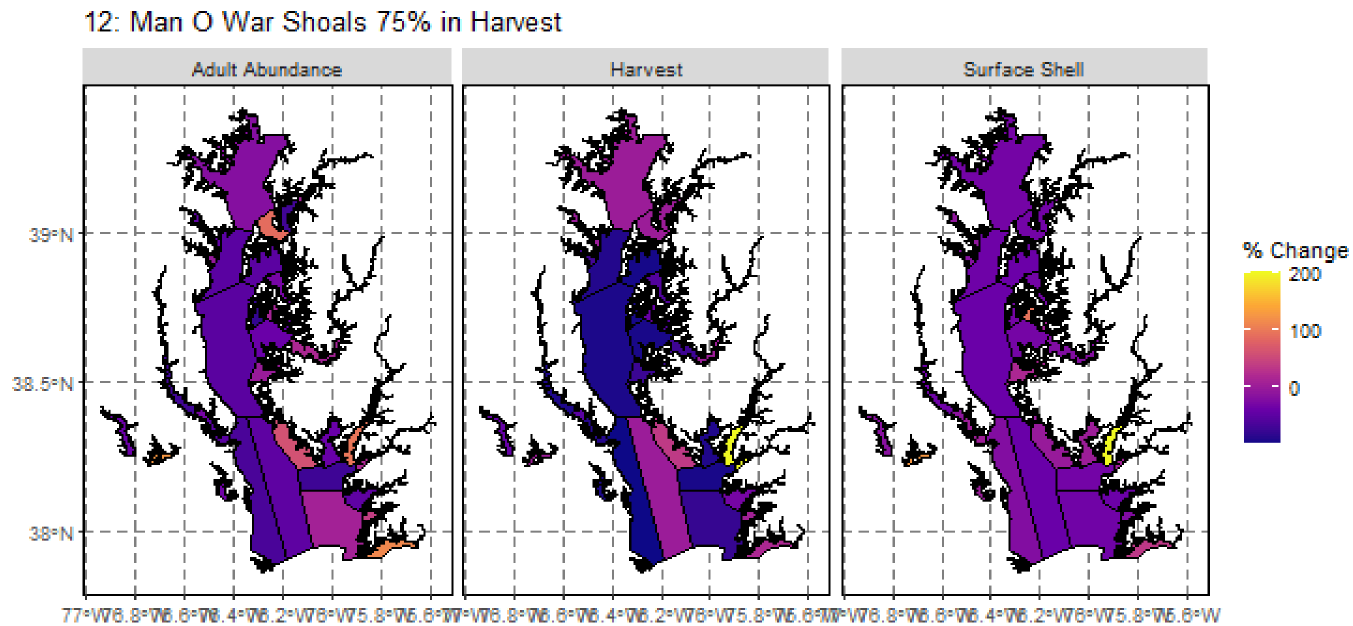

Fig. A228. Median percent change in adult abundance, harvest, and surface shell from 2019 to last year of simulations for Option 12.

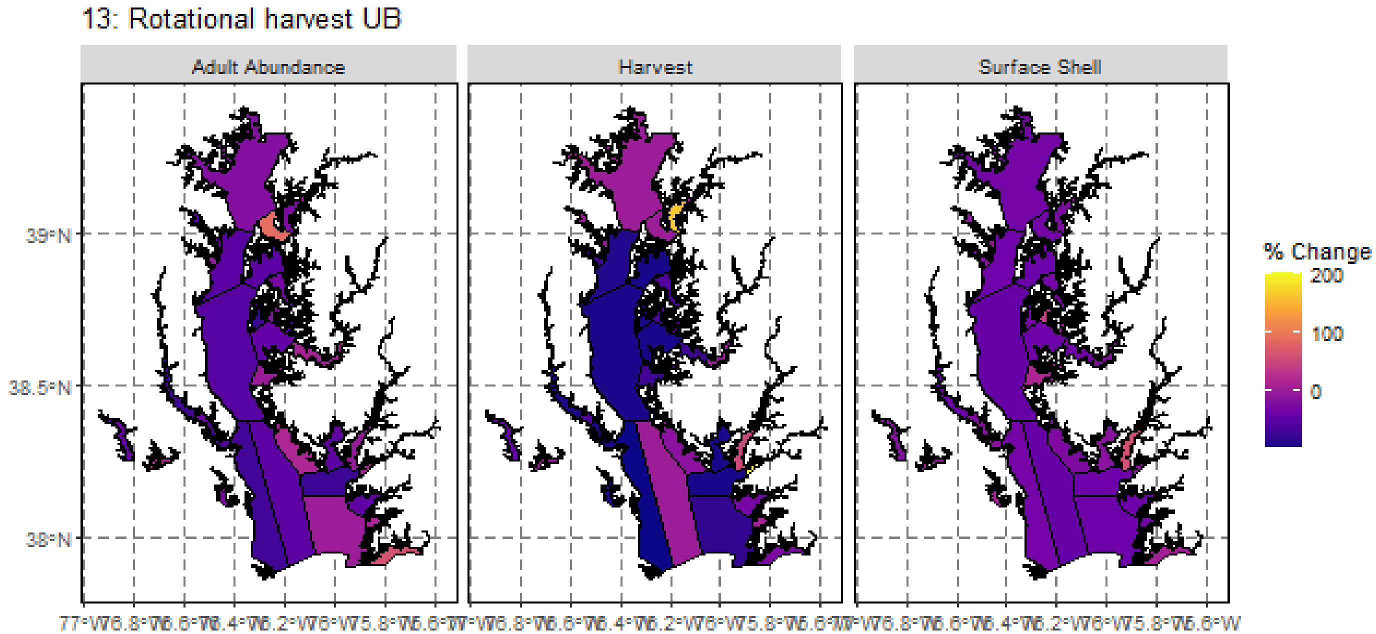

Fig. A229. Median percent change in adult abundance, harvest, and surface shell from 2019 to last year of simulations for Option 13.

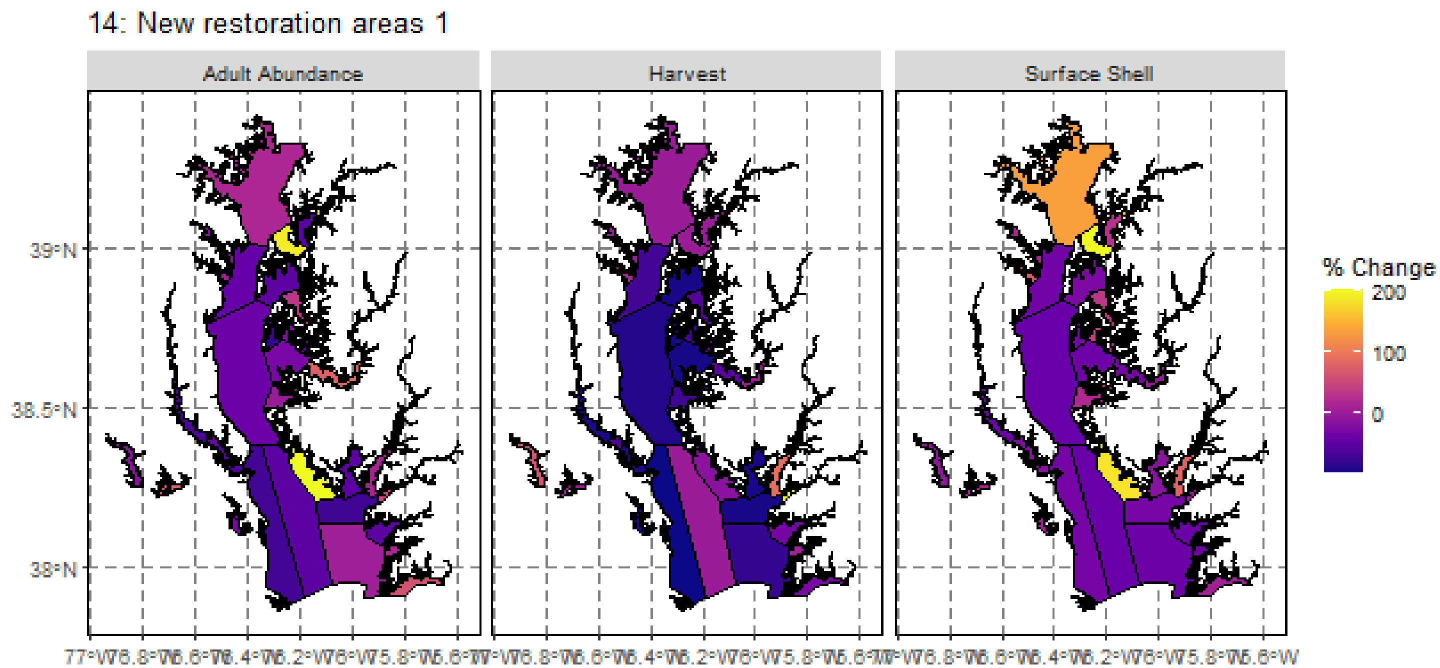

Fig. A230. Median percent change in adult abundance, harvest, and surface shell from 2019 to last year of simulations for Option 14.

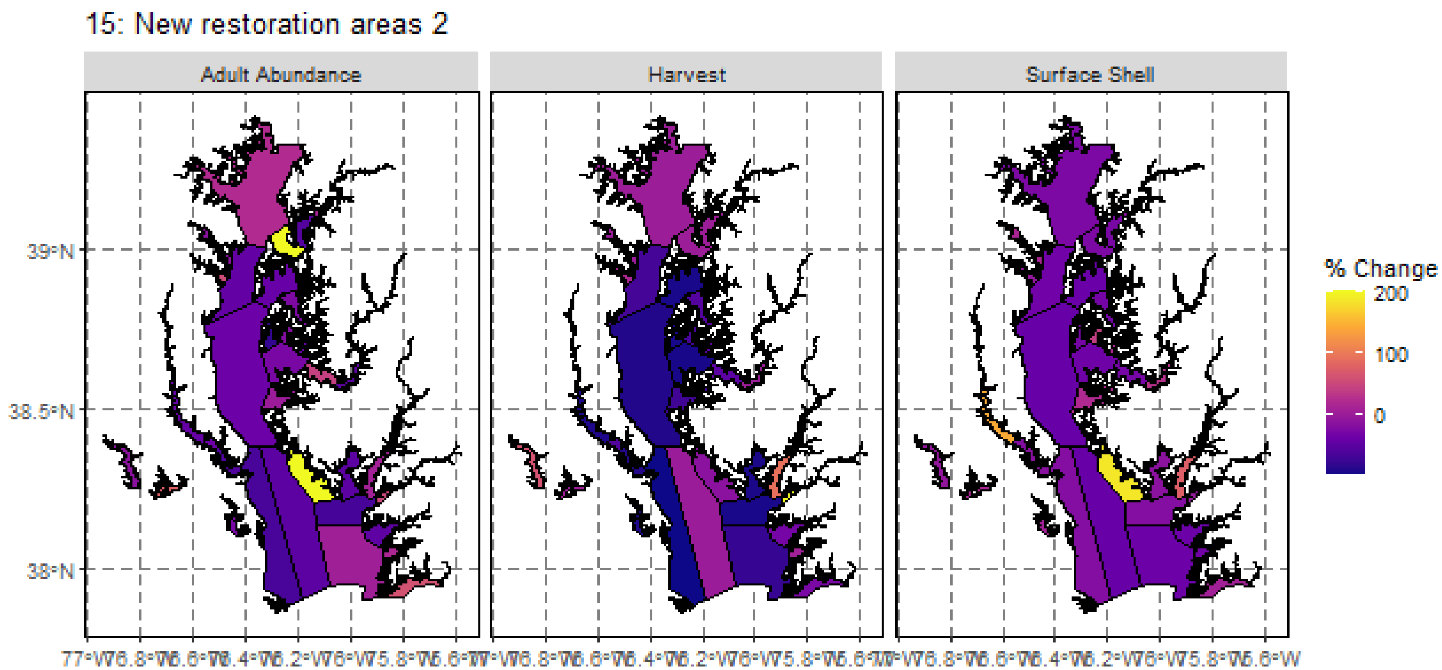

Fig. A231. Median percent change in adult abundance, harvest, and surface shell from 2019 to last year of simulations for Option 15.

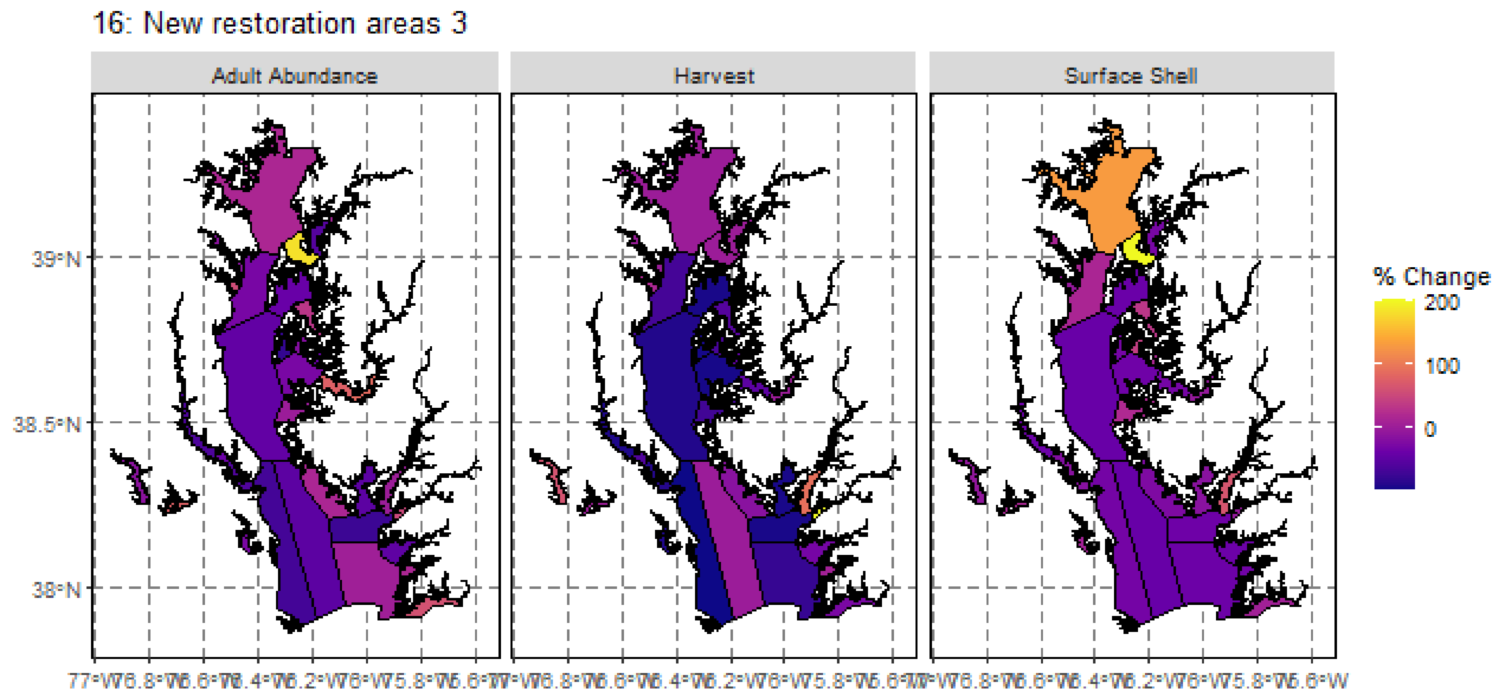

Fig. A232. Median percent change in adult abundance, harvest, and surface shell from 2019 to last year of simulations for Option 16.

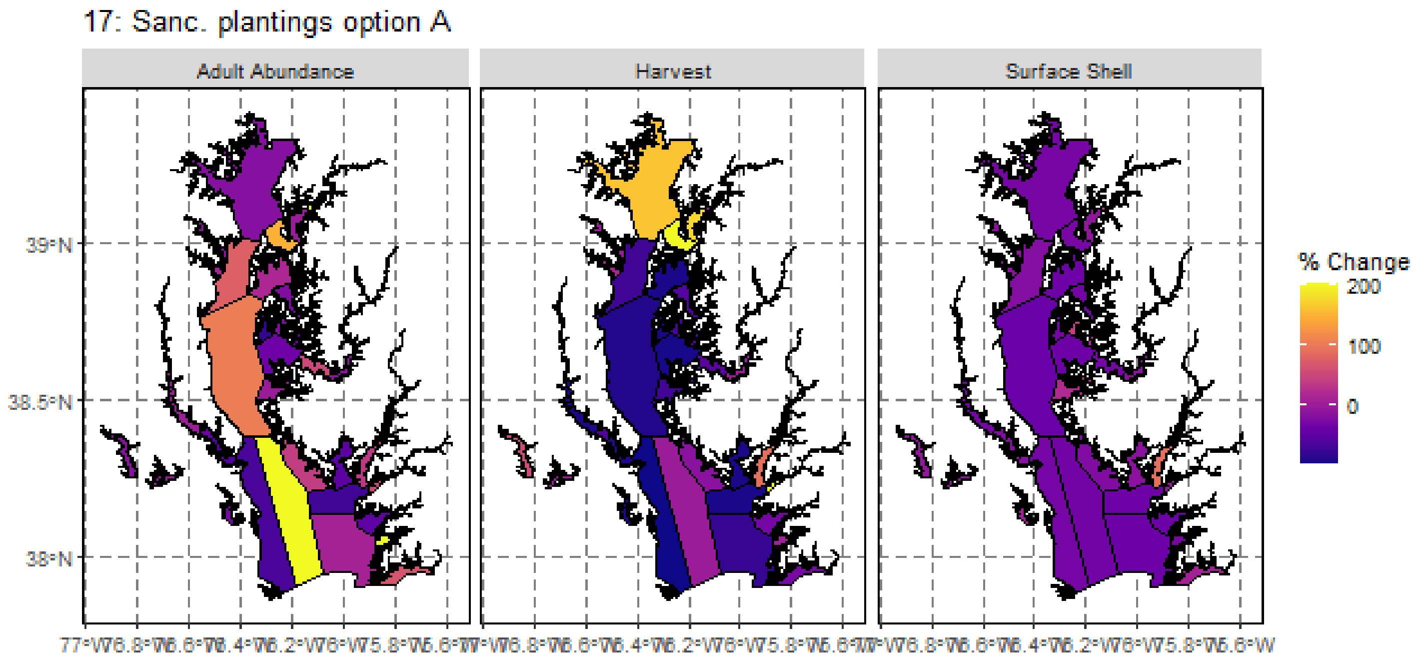

Fig. A233. Median percent change in adult abundance, harvest, and surface shell from 2019 to last year of simulations for Option 17.

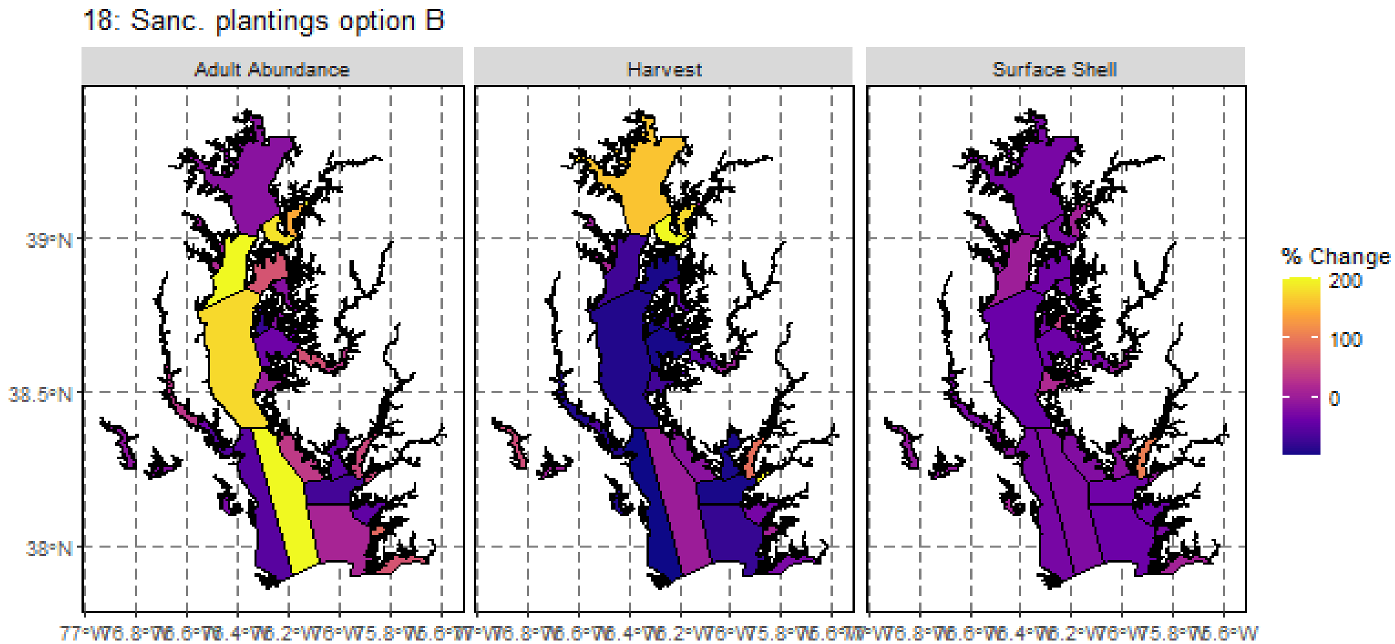

Fig. A234. Median percent change in adult abundance, harvest, and surface shell from 2019 to last year of simulations for Option 18.

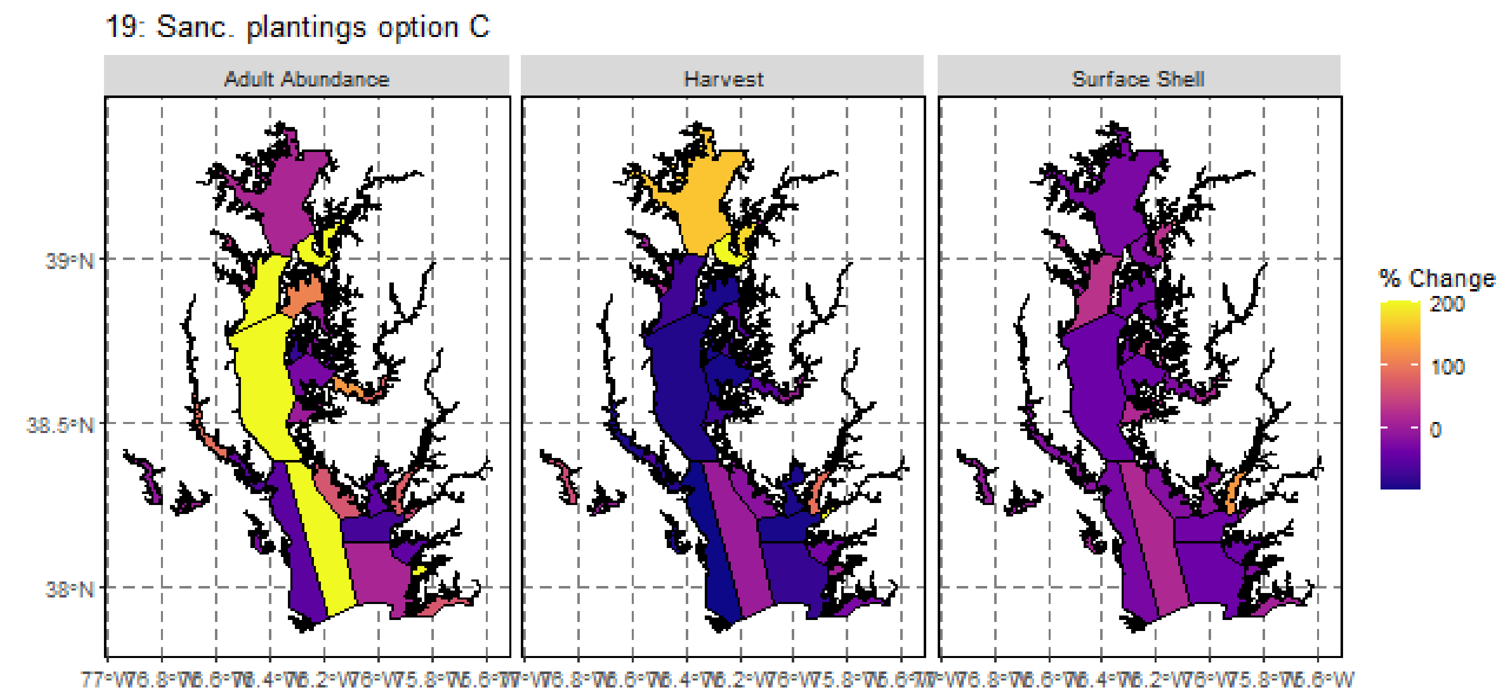

Fig. A235. Median percent change in adult abundance, harvest, and surface shell from 2019 to last year of simulations for Option 19.

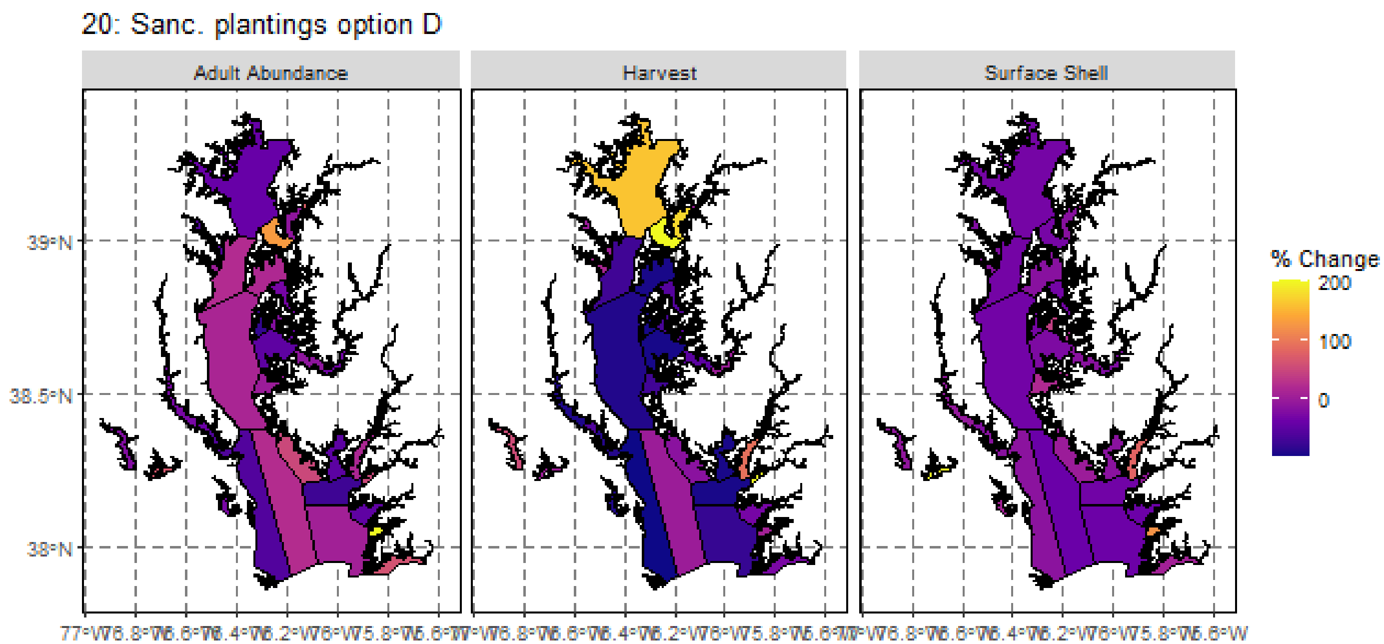

Fig. A236. Median percent change in adult abundance, harvest, and surface shell from 2019 to last year of simulations for Option 20.

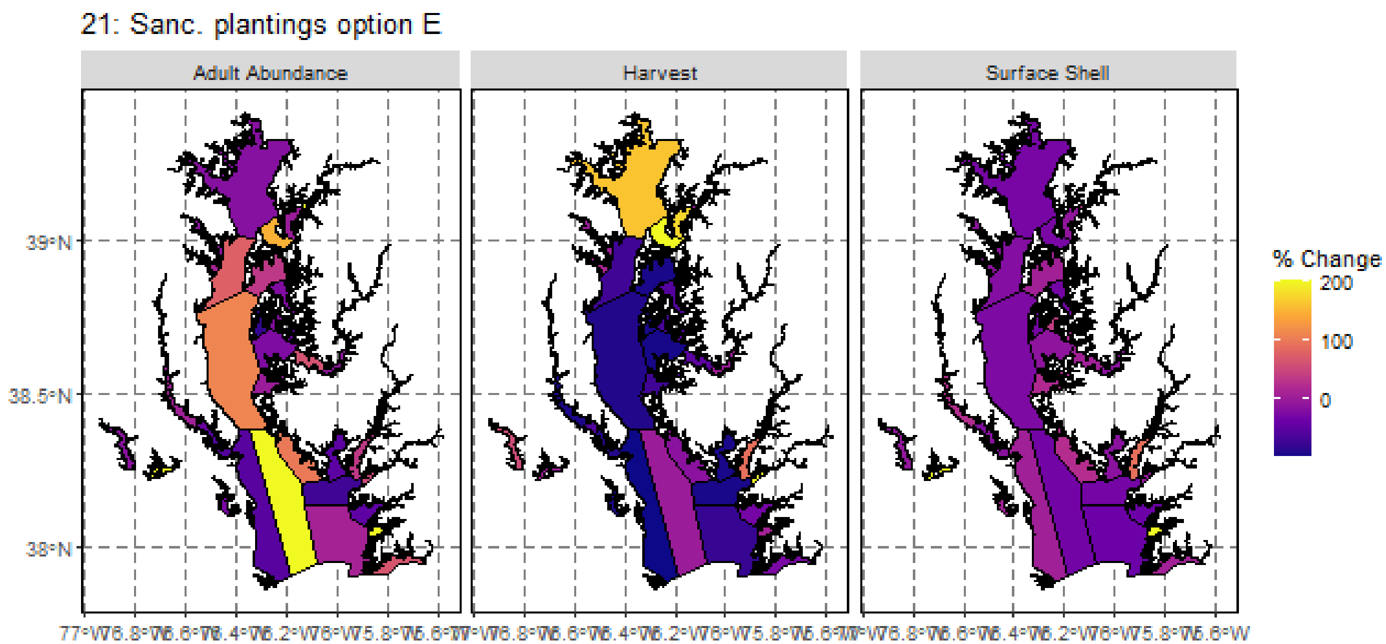

Fig. A237. Median percent change in adult abundance, harvest, and surface shell from 2019 to last year of simulations for Option 21.

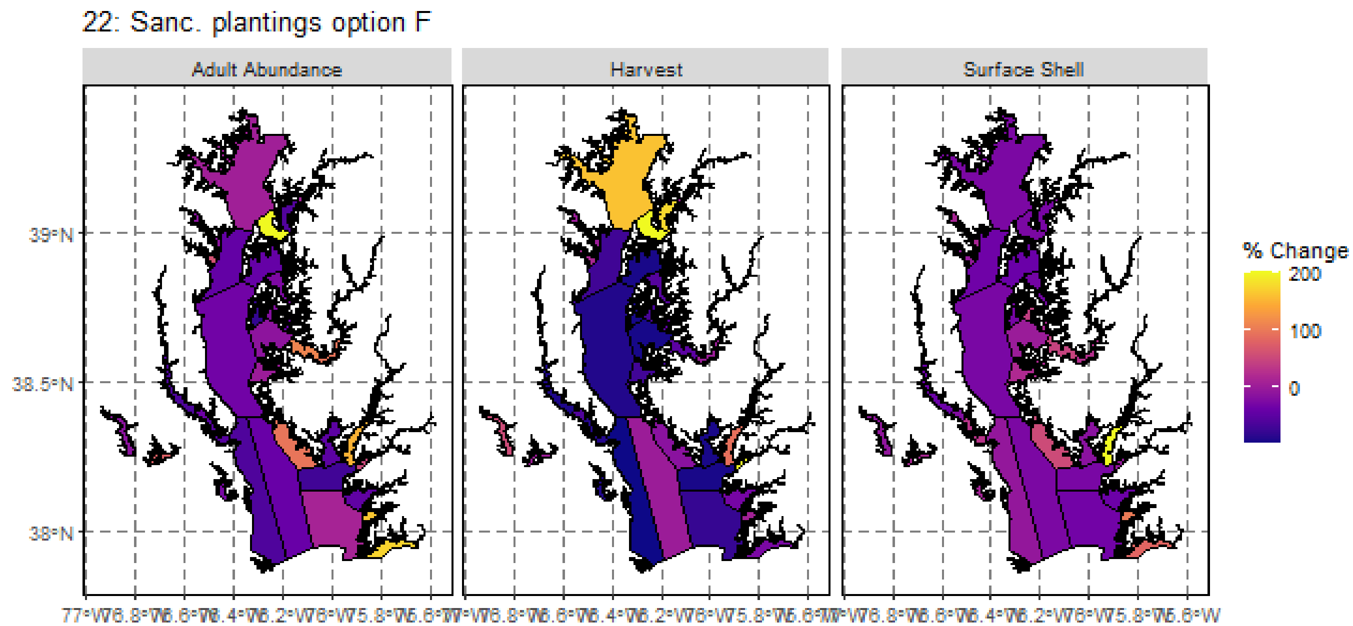

Fig. A238. Median percent change in adult abundance, harvest, and surface shell from 2019 to last year of simulations for Option 22.

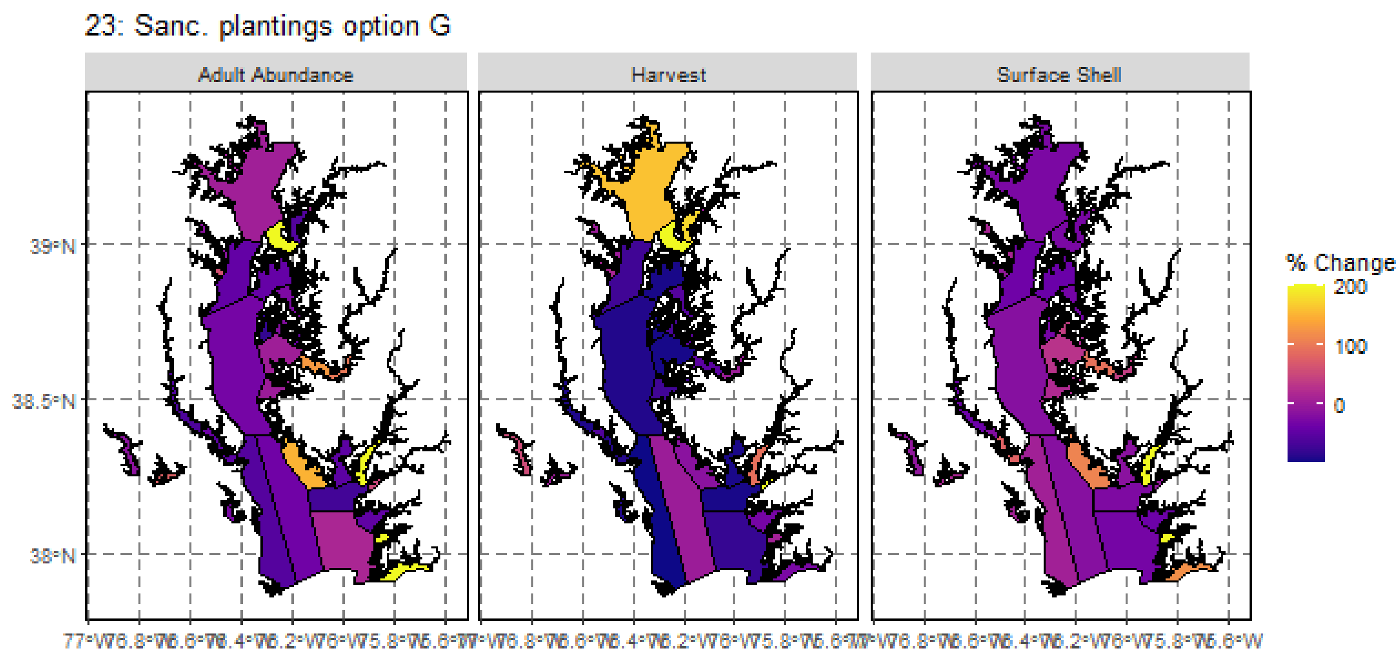

Fig. A239. Median percent change in adult abundance, harvest, and surface shell from 2019 to last year of simulations for Option 23.

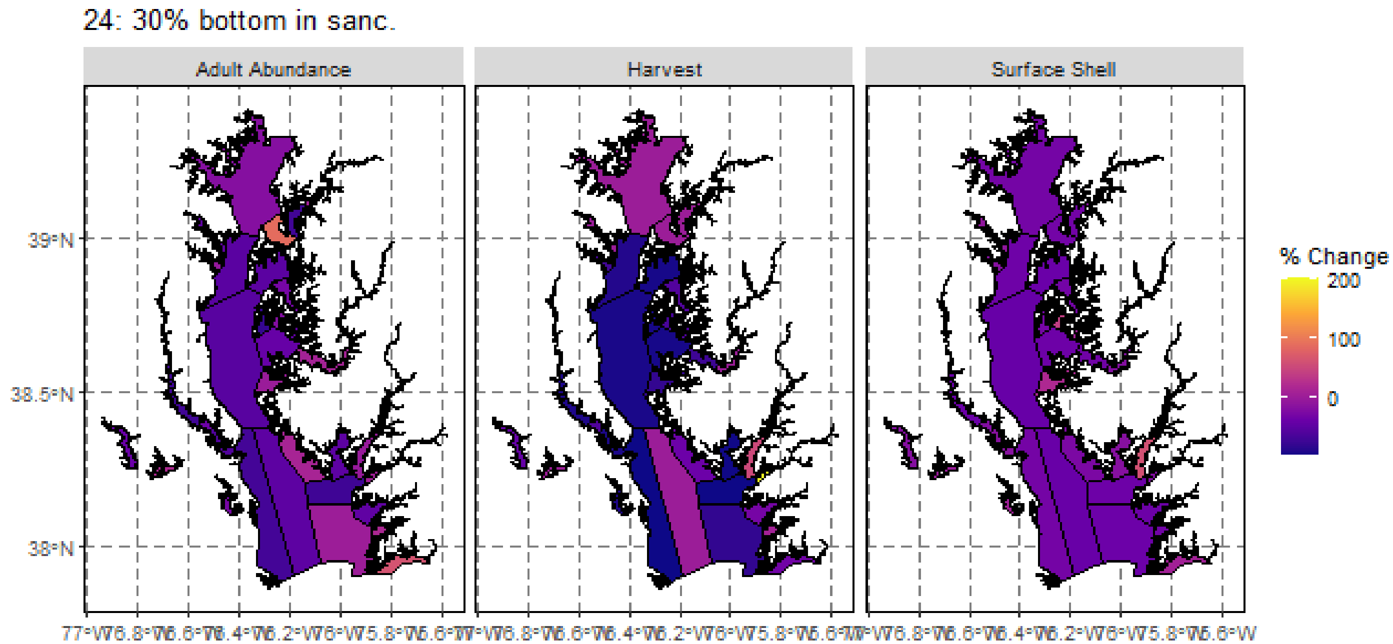

Fig. A240. Median percent change in adult abundance, harvest, and surface shell from 2019 to last year of simulations for Option 24.

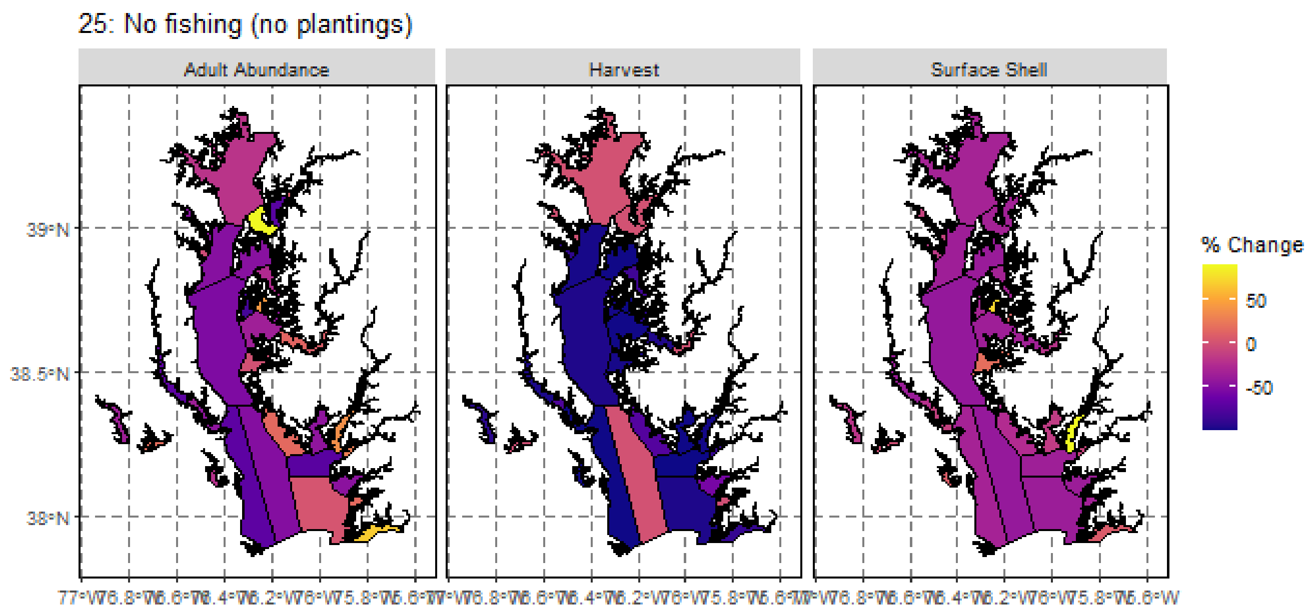

Fig. A241. Median percent change in adult abundance, harvest, and surface shell from 2019 to last year of simulations for Option 25.

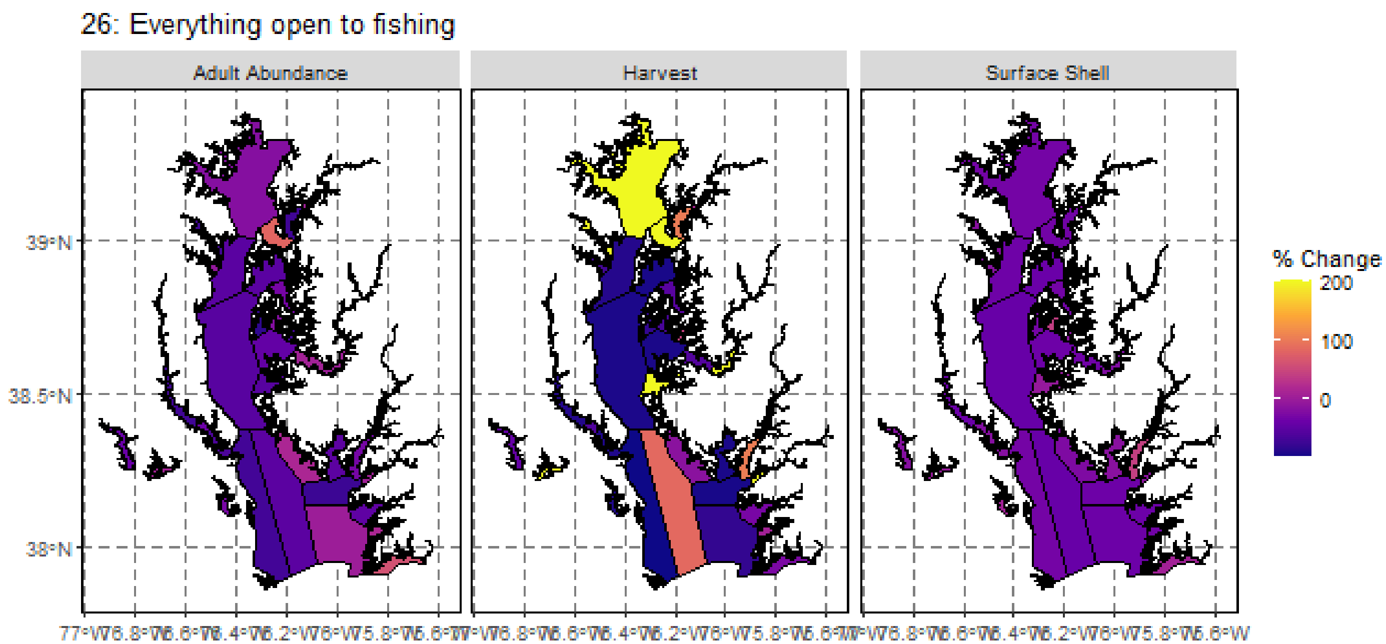

Fig. A242. Median percent change in adult abundance, harvest, and surface shell from 2019 to last year of simulations for Option 26.

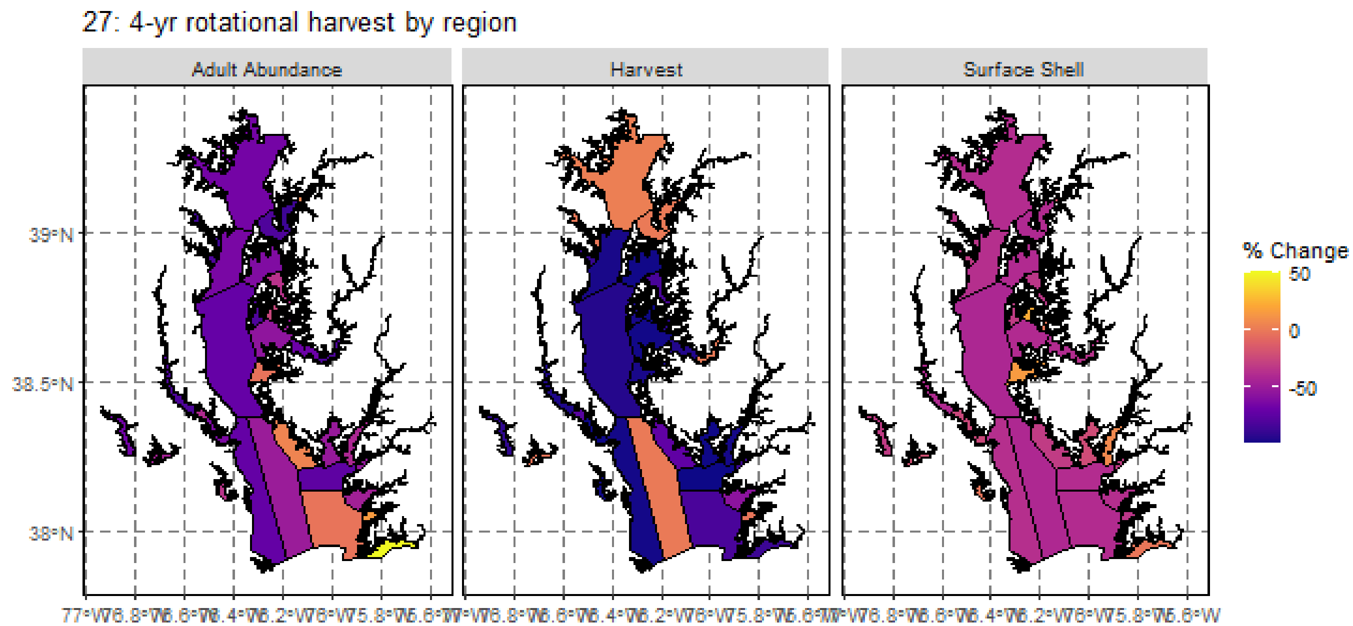

Fig. A243. Median percent change in adult abundance, harvest, and surface shell from 2019 to last year of simulations for Option 27.

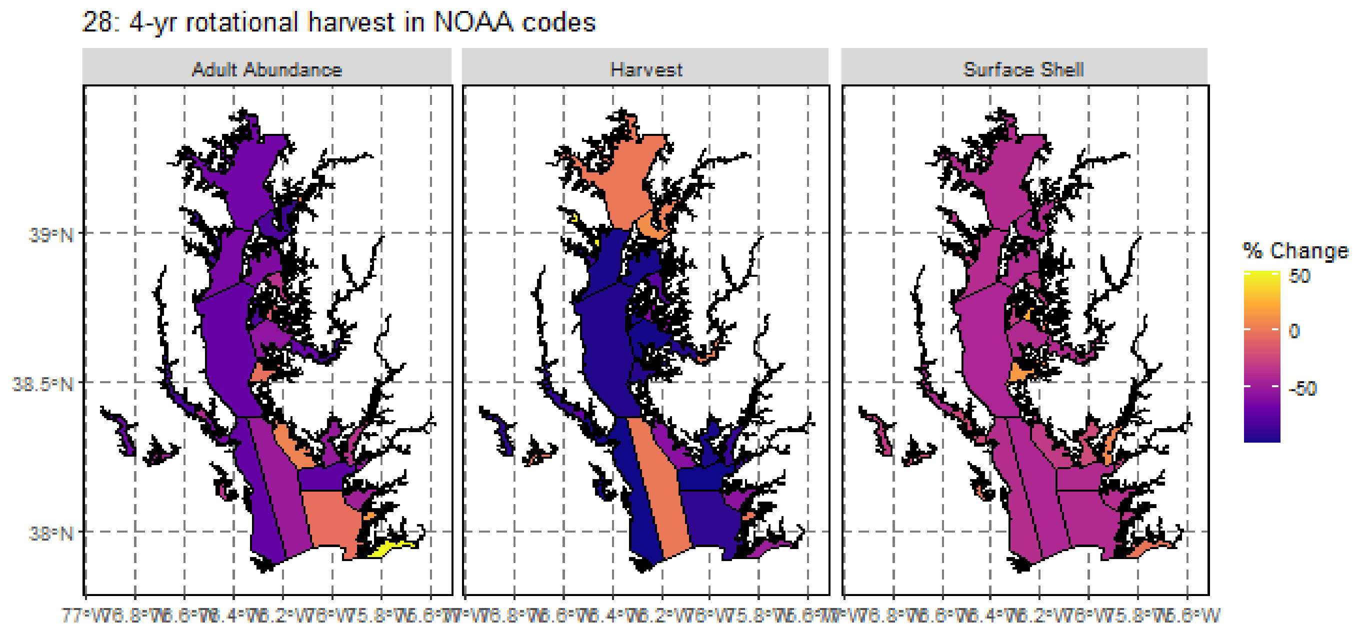

Fig. A244. Median percent change in adult abundance, harvest, and surface shell from 2019 to last year of simulations for Option 28.

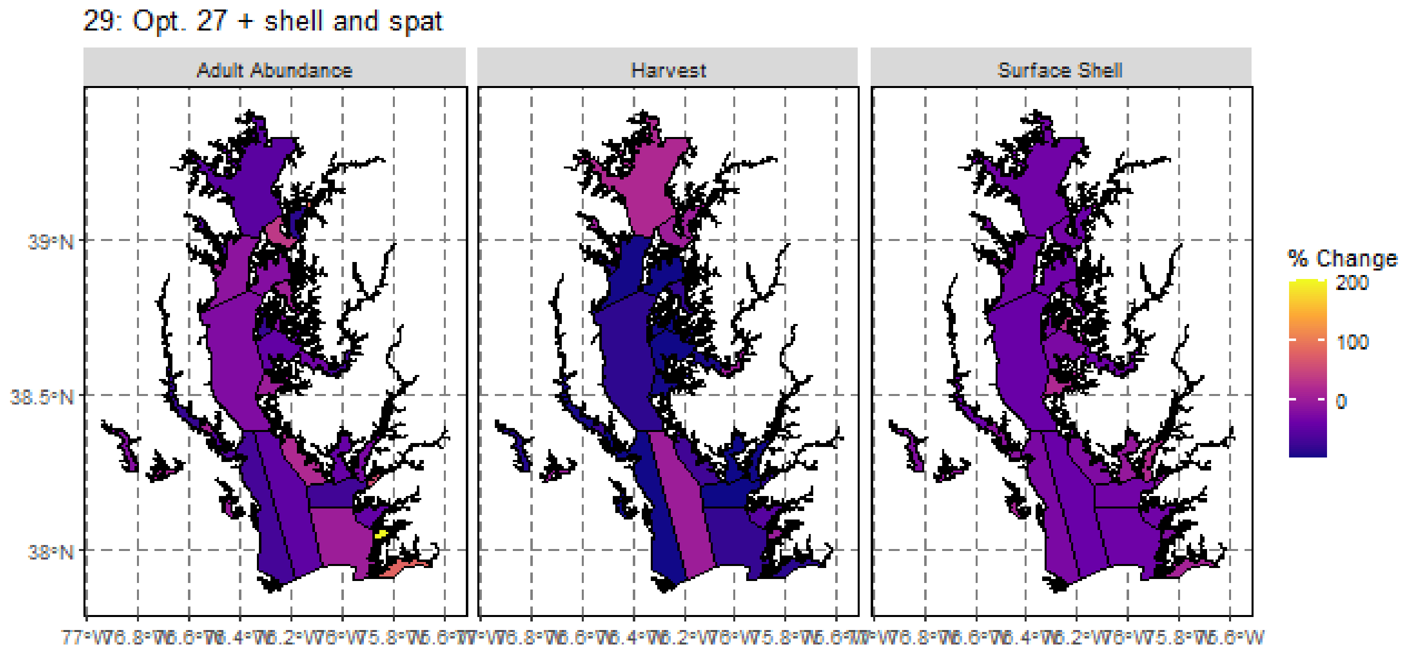

Fig. A245. Median percent change in adult abundance, harvest, and surface shell from 2019 to last year of simulations for Option 29.

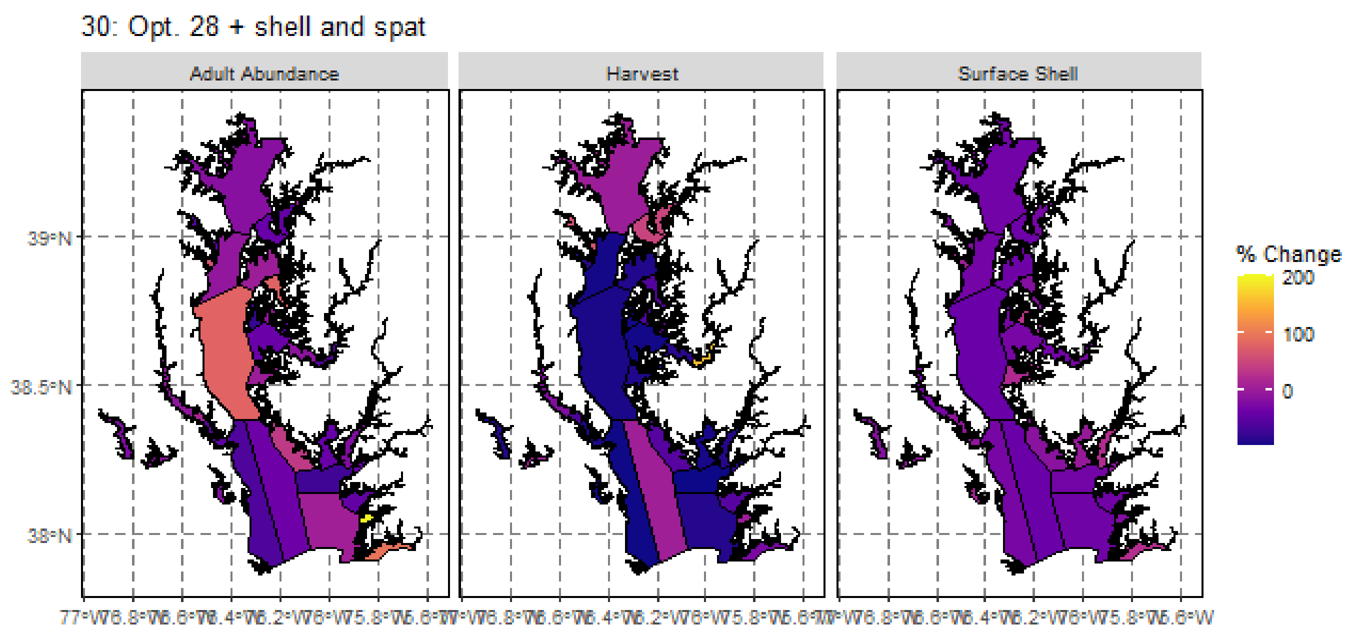

Fig. A246. Median percent change in adult abundance, harvest, and surface shell from 2019 to last year of simulations for Option 30.

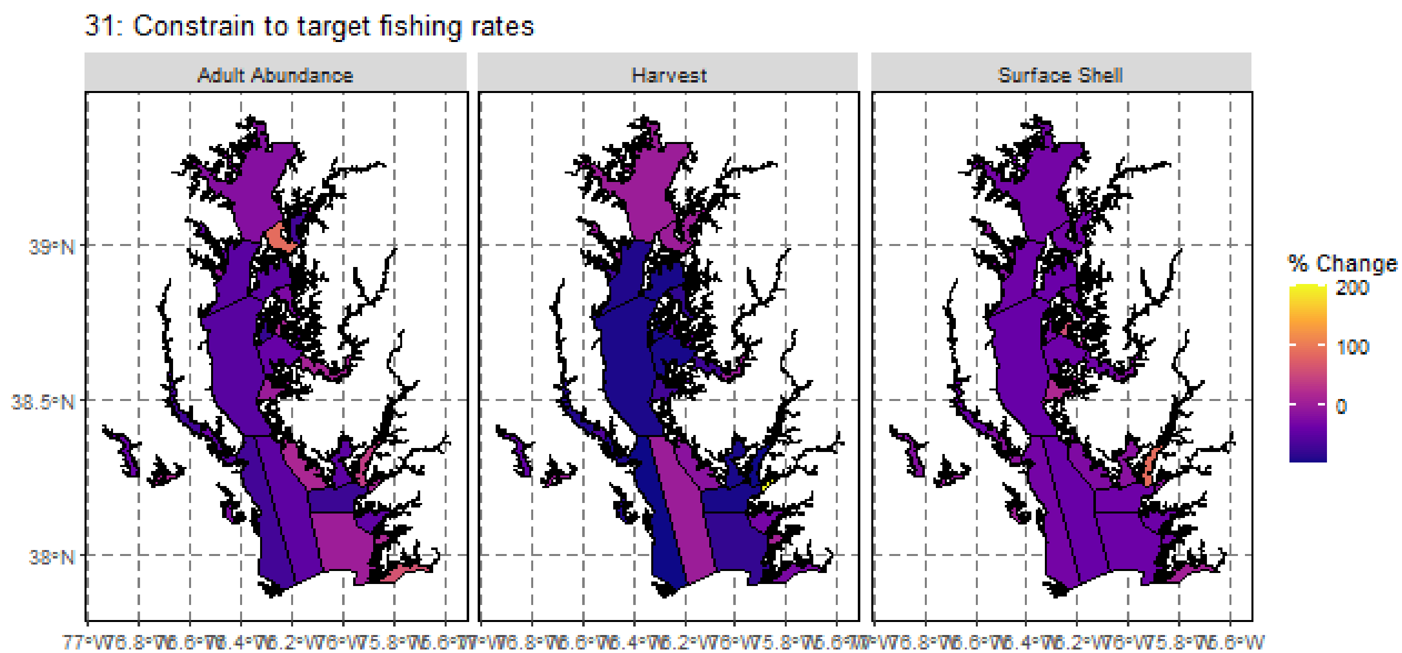

Fig. A247. Median percent change in adult abundance, harvest, and surface shell from 2019 to last year of simulations for Option 31.

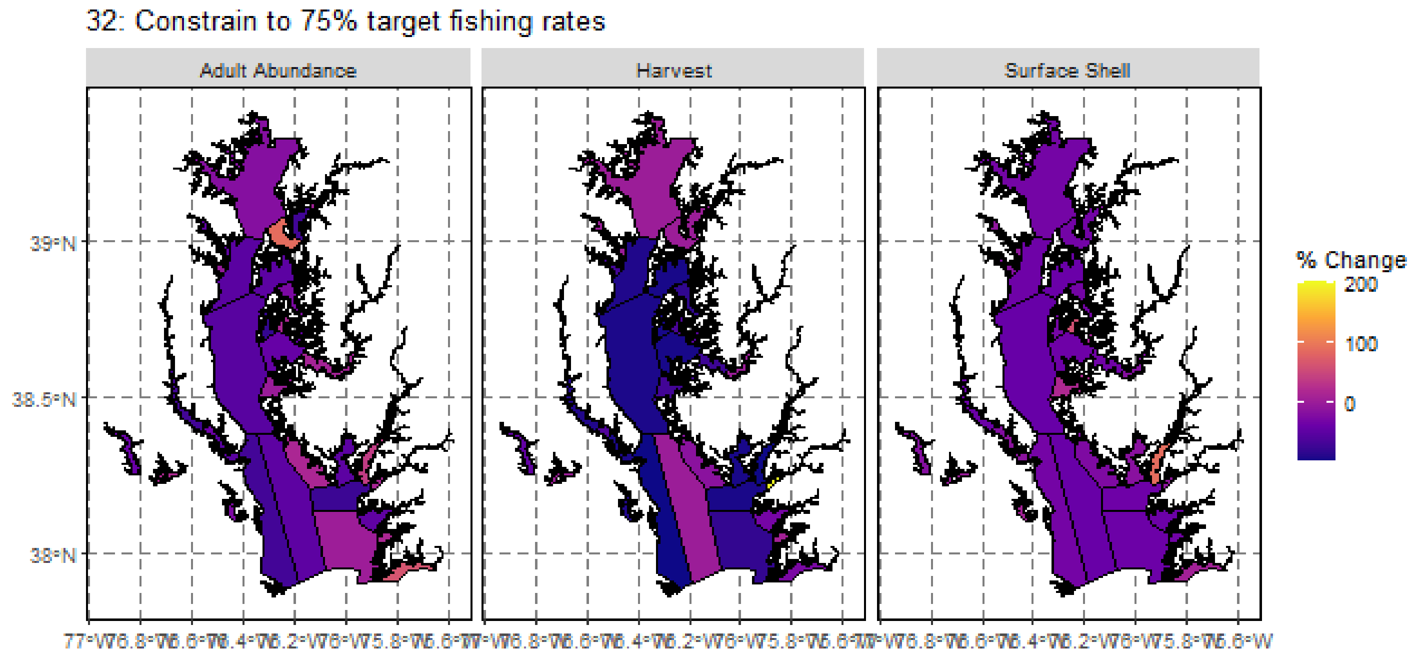

Fig. A248. Median percent change in adult abundance, harvest, and surface shell from 2019 to last year of simulations for Option 32.

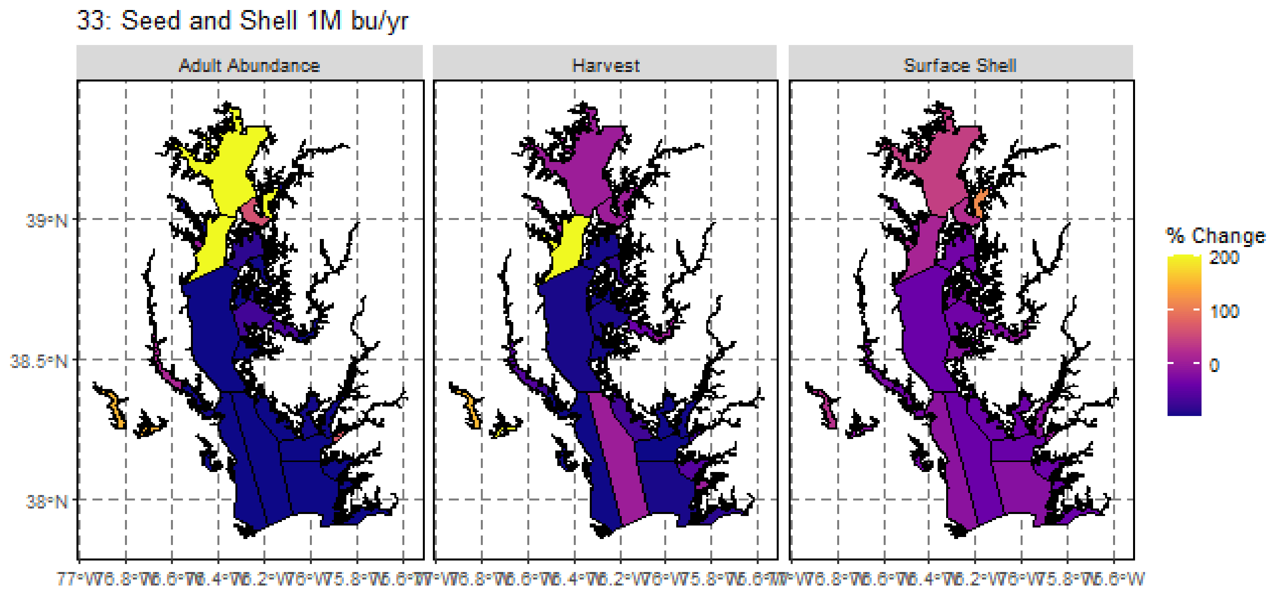

Fig. A249. Median percent change in adult abundance, harvest, and surface shell from 2019 to last year of simulations for Option 33.

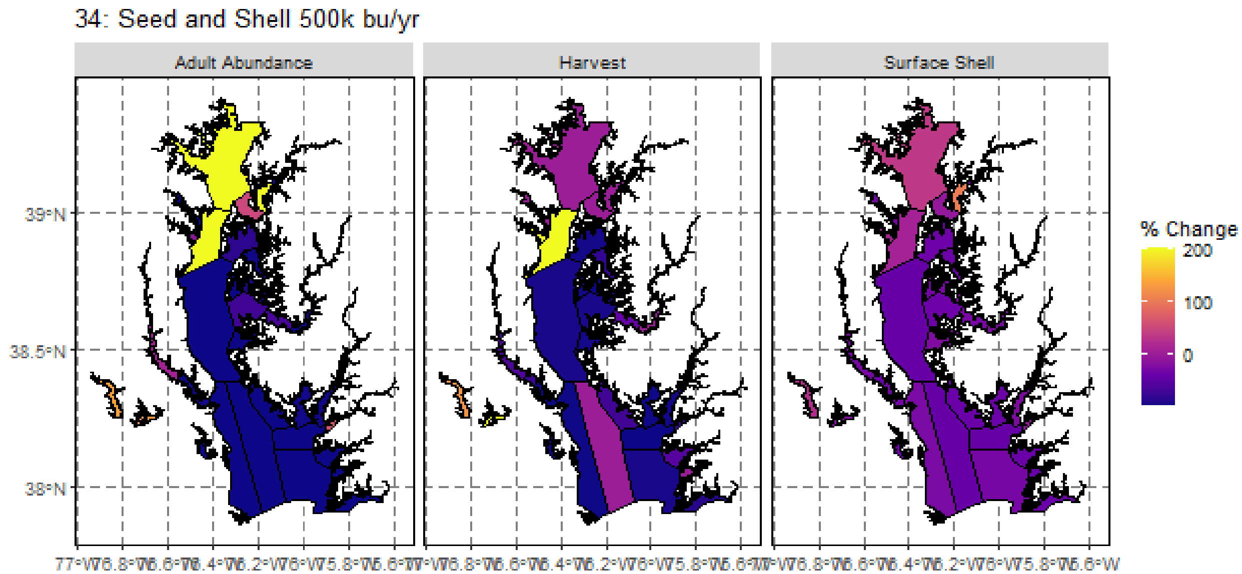

Fig. A250. Median percent change in adult abundance, harvest, and surface shell from 2019 to last year of simulations for Option 34.

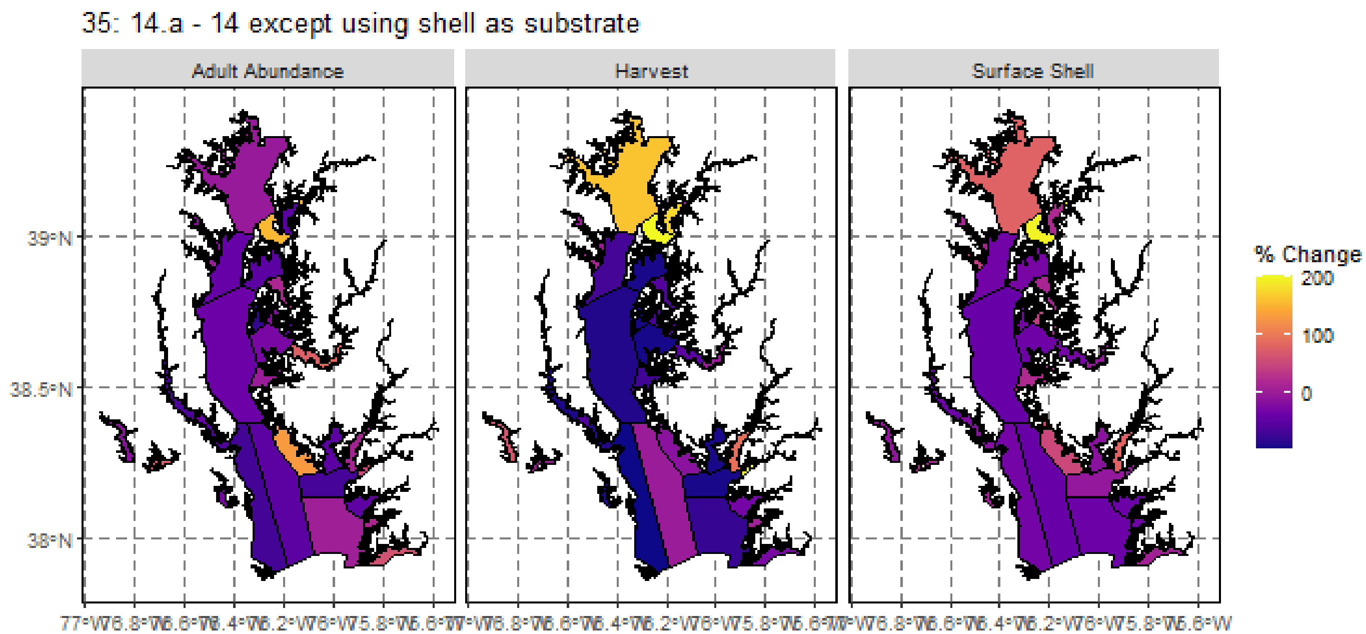

Fig. A251. Median percent change in adult abundance, harvest, and surface shell from 2019 to last year of simulations for Option 35.

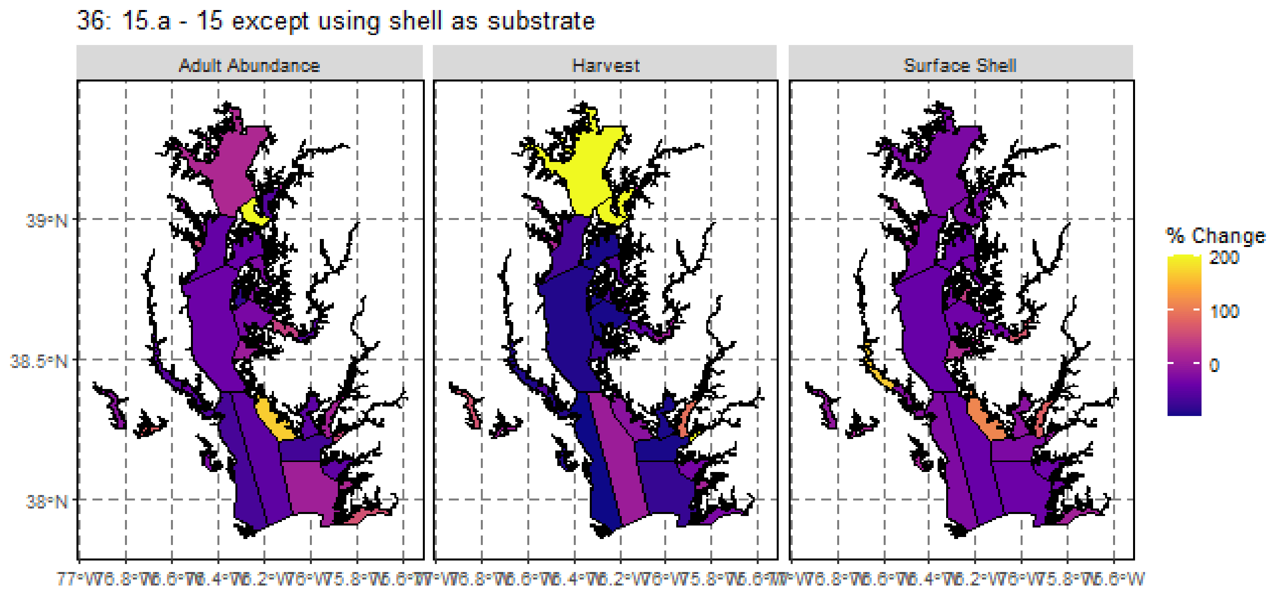

Fig. A252. Median percent change in adult abundance, harvest, and surface shell from 2019 to last year of simulations for Option 36.

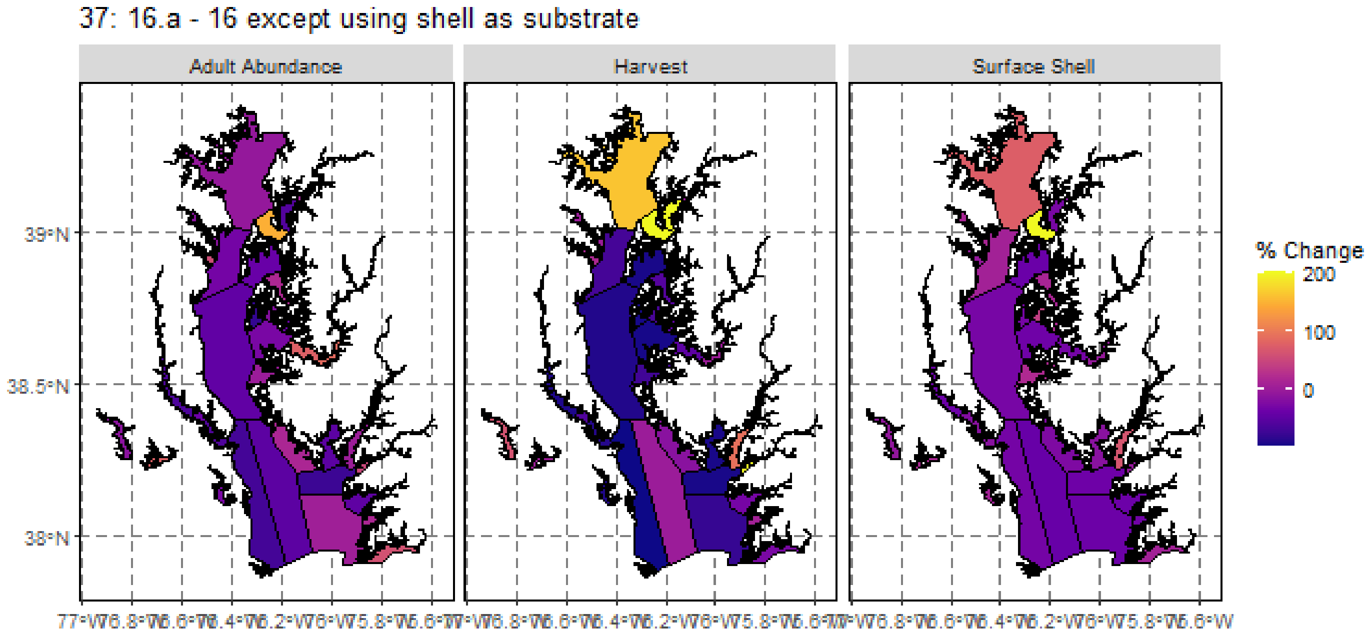

Fig. A253. Median percent change in adult abundance, harvest, and surface shell from 2019 to last year of simulations for Option 37.

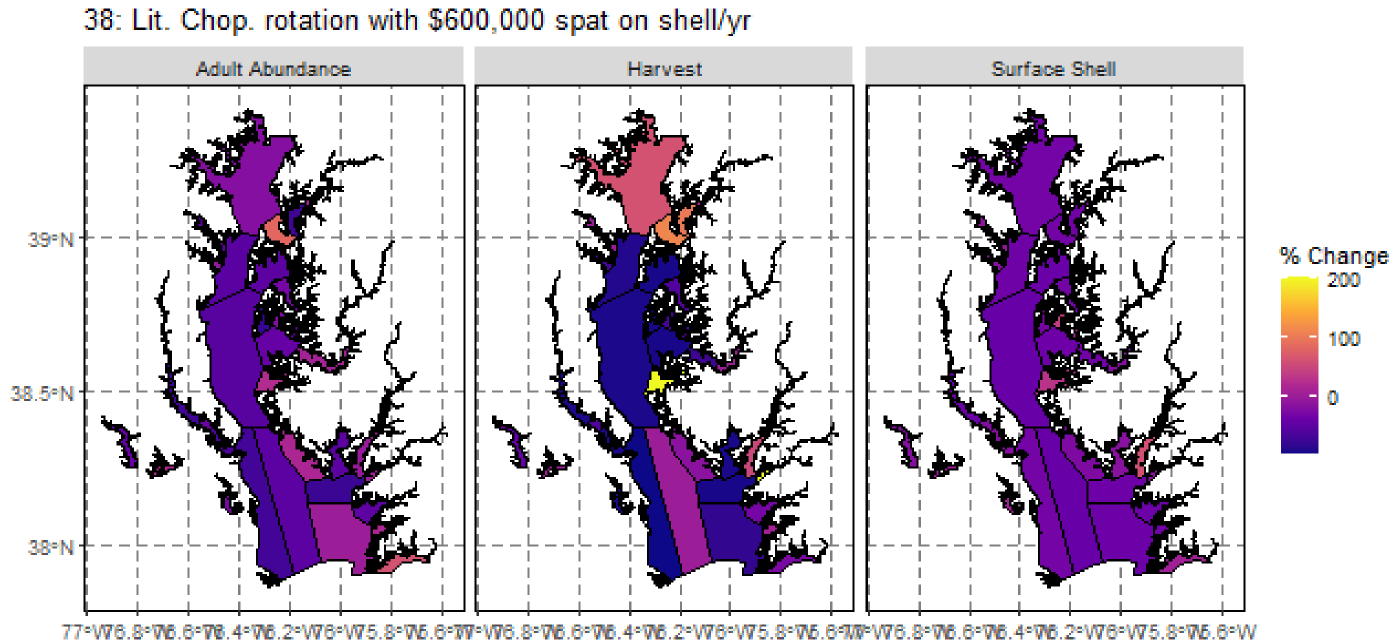

Fig. A254. Median percent change in adult abundance, harvest, and surface shell from 2019 to last year of simulations for Option 38.

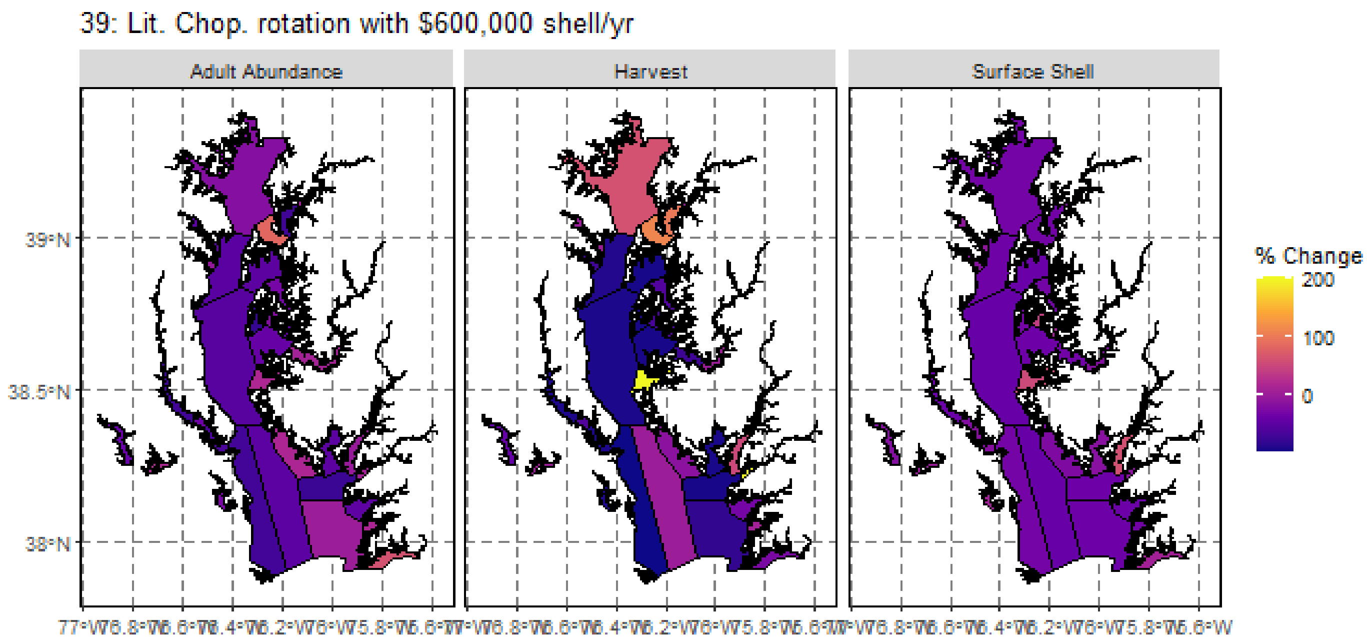

Fig. A255. Median percent change in adult abundance, harvest, and surface shell from 2019 to last year of simulations for Option 39.

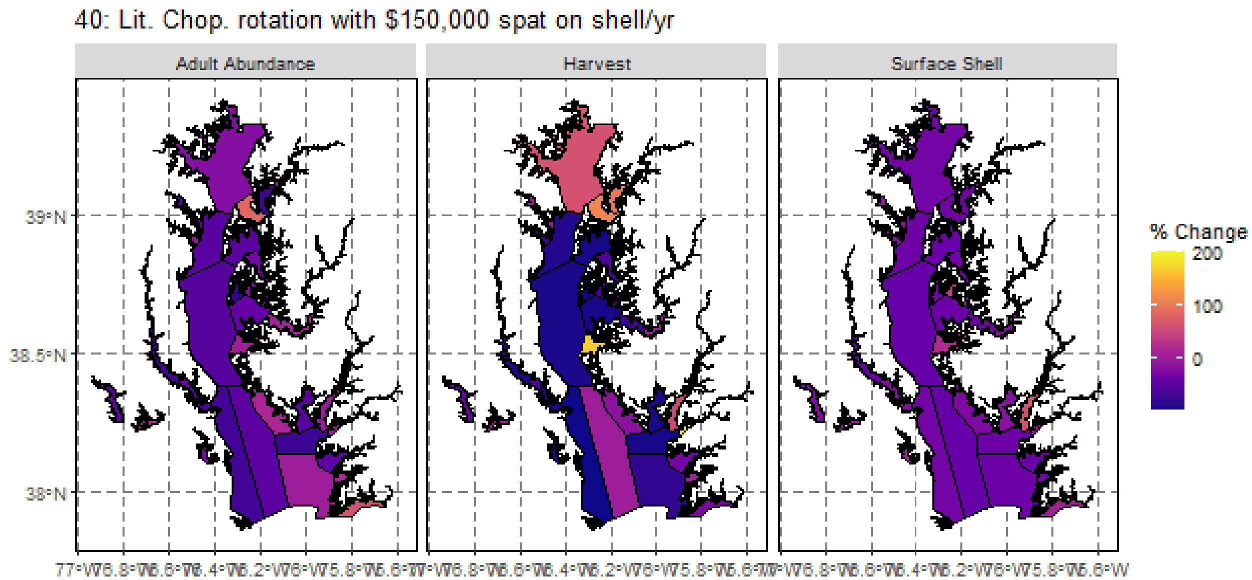

Fig. A256. Median percent change in adult abundance, harvest, and surface shell from 2019 to last year of simulations for Option 40.

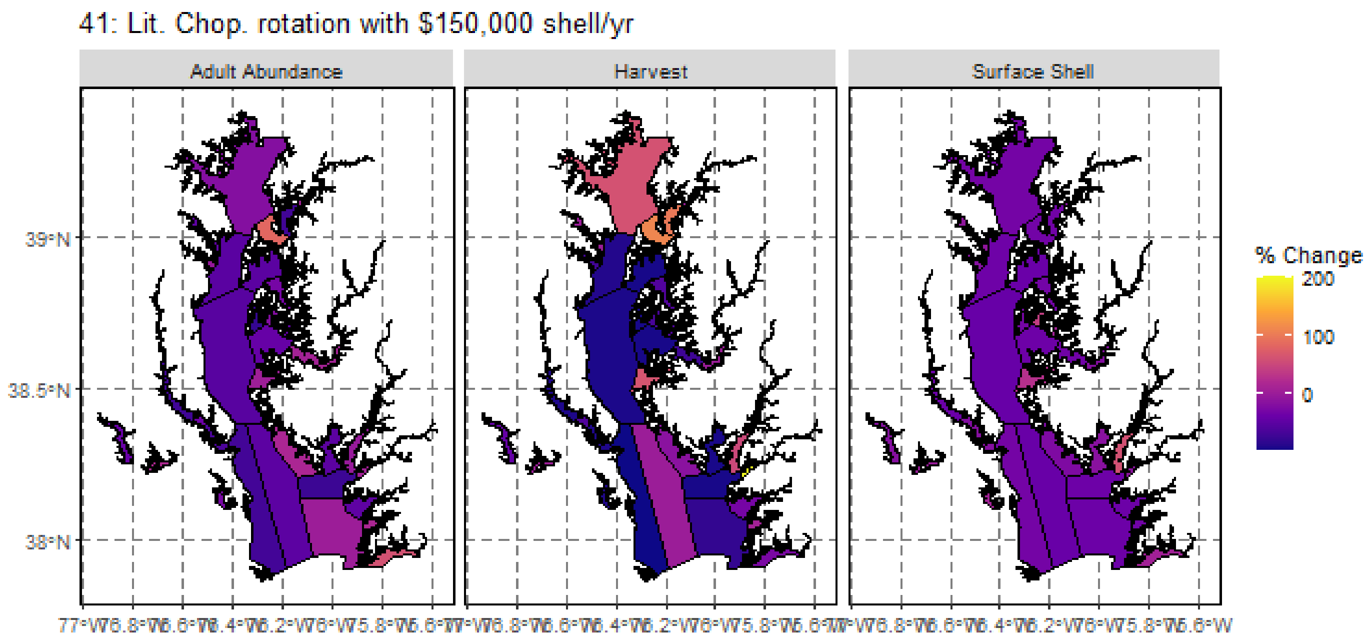

Fig. A257. Median percent change in adult abundance, harvest, and surface shell from 2019 to last year of simulations for Option 41.

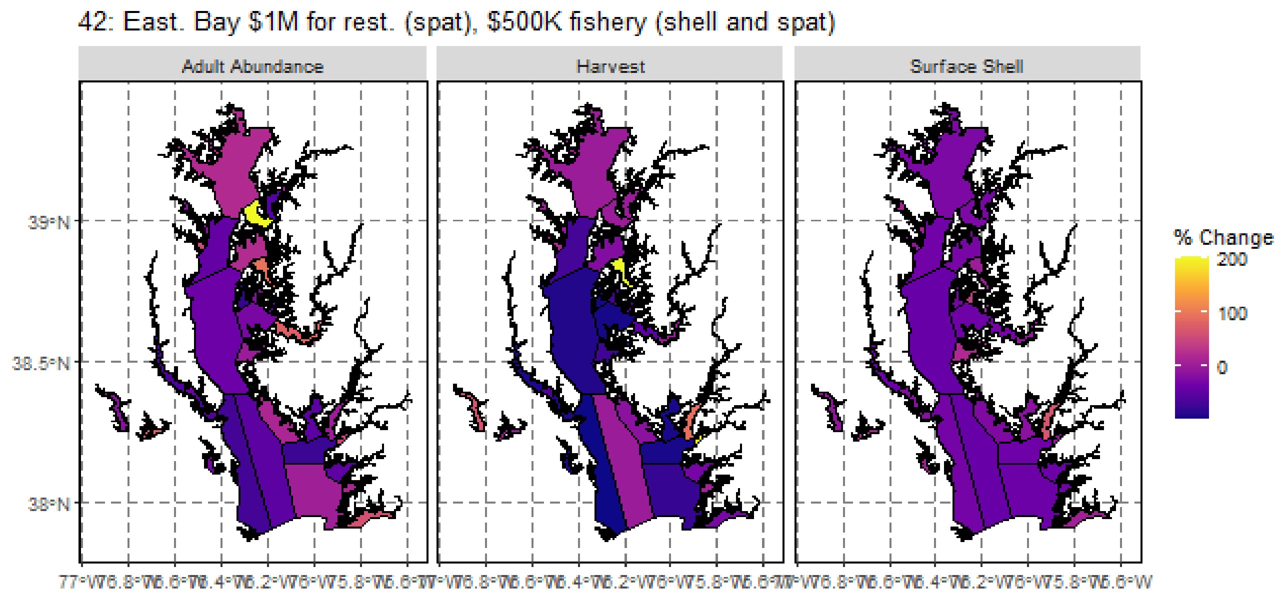

Fig. A258. Median percent change in adult abundance, harvest, and surface shell from 2019 to last year of simulations for Option 42.

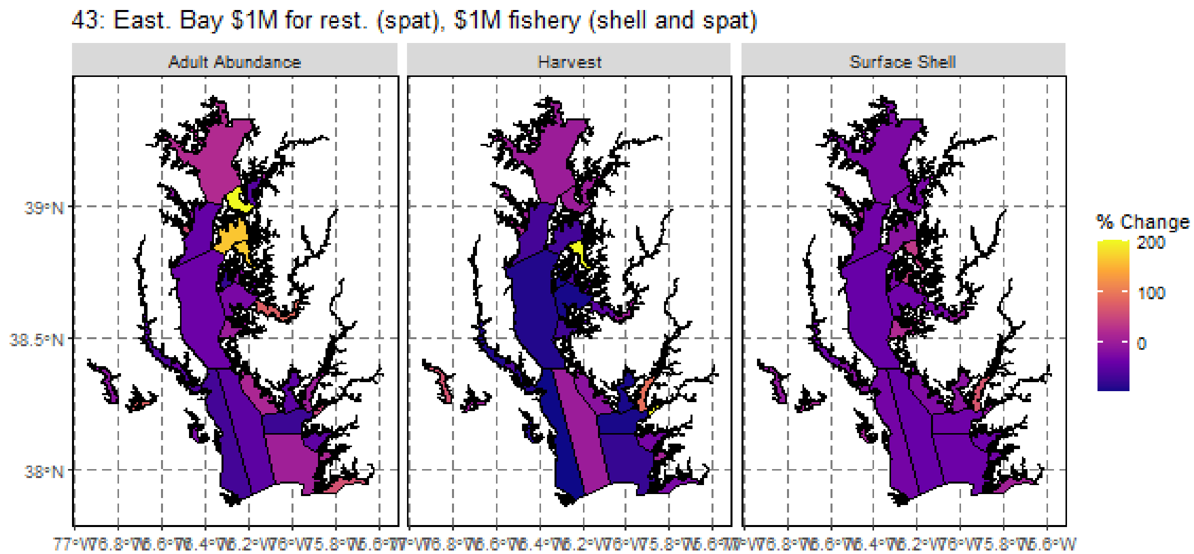

Fig. A259. Median percent change in adult abundance, harvest, and surface shell from 2019 to last year of simulations for Option 43.

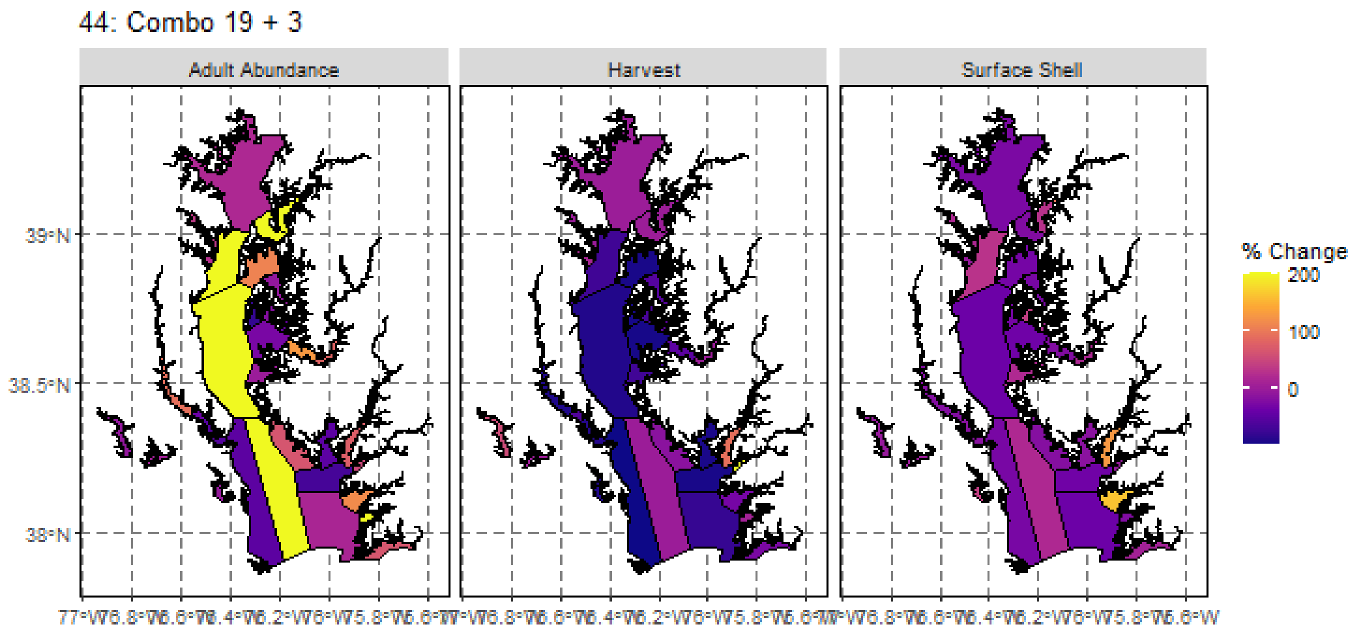

Fig. A260. Median percent change in adult abundance, harvest, and surface shell from 2019 to last year of simulations for Option 44.

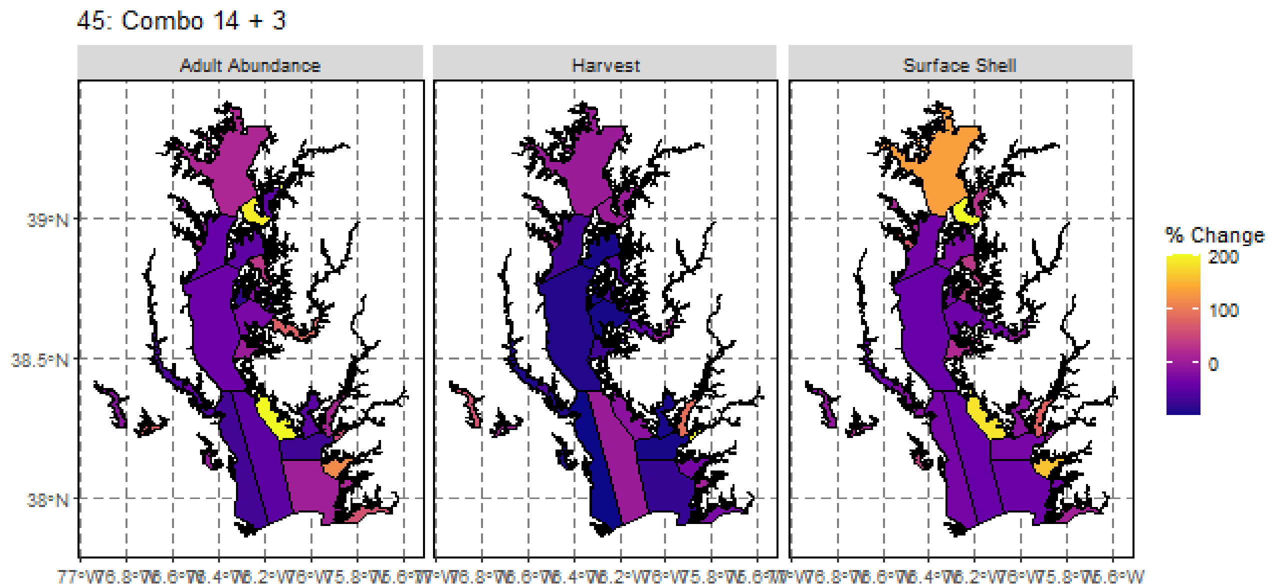

Fig. A261. Median percent change in adult abundance, harvest, and surface shell from 2019 to last year of simulations for Option 45.

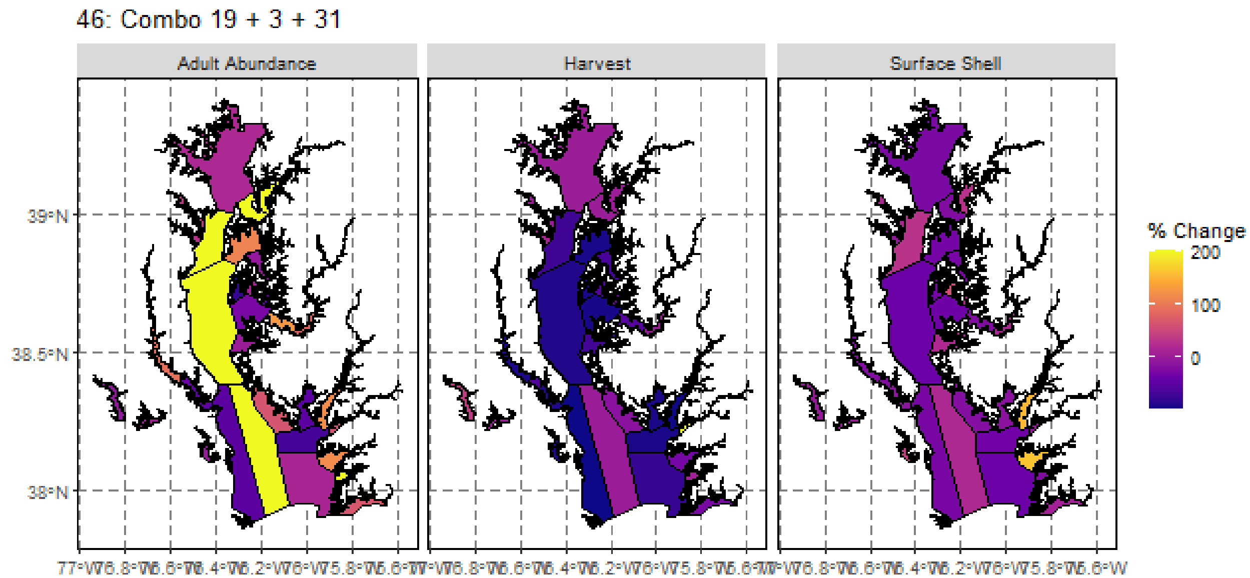

Fig. A262. Median percent change in adult abundance, harvest, and surface shell from 2019 to last year of simulations for Option 46.

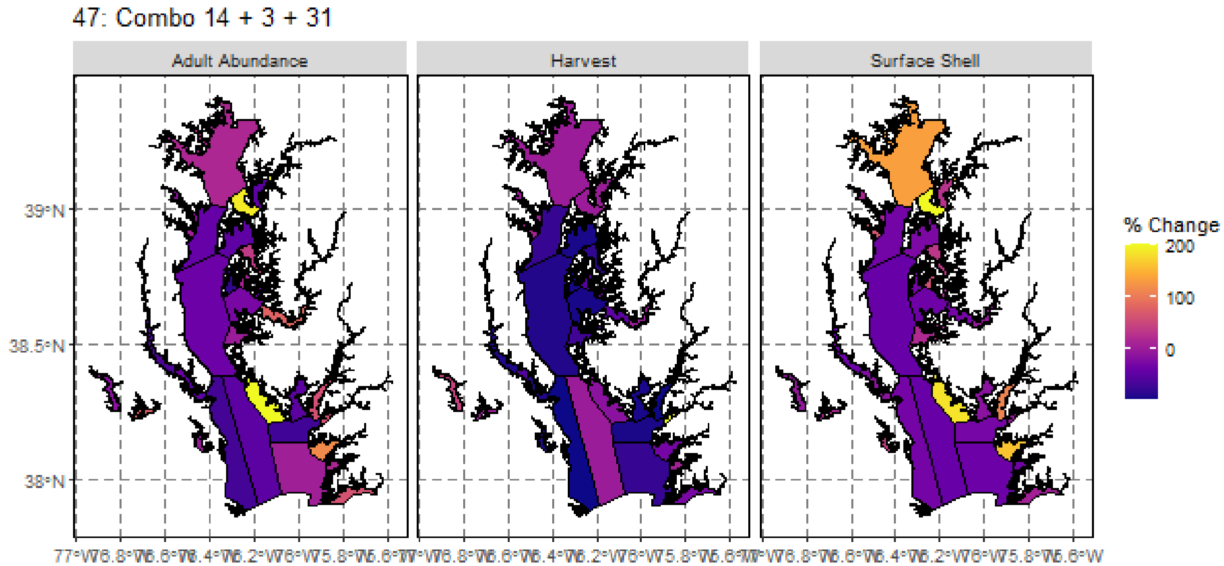

Fig. A263. Median percent change in adult abundance, harvest, and surface shell from 2019 to last year of simulations for Option 47.

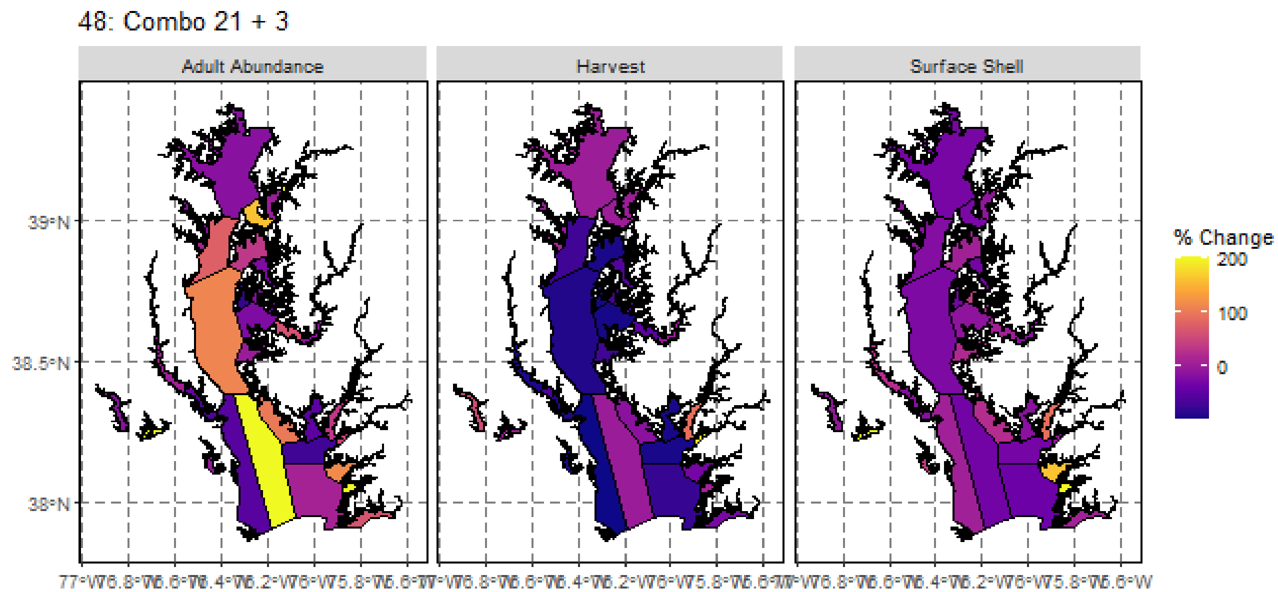

Fig. A264. Median percent change in adult abundance, harvest, and surface shell from 2019 to last year of simulations for Option 48.

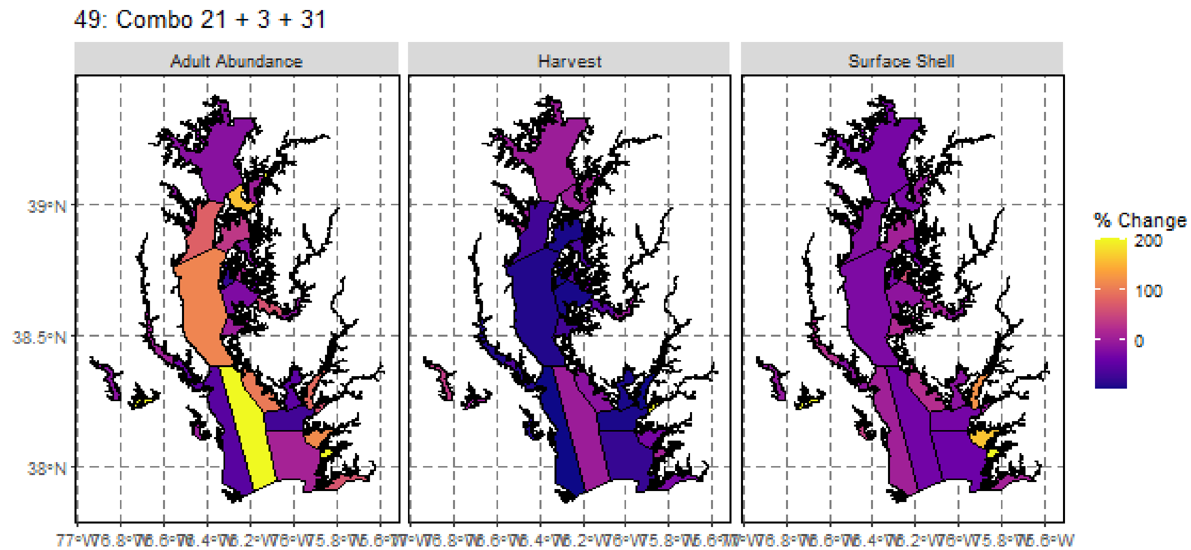

Fig. A265. Median percent change in adult abundance, harvest, and surface shell from 2019 to last year of simulations for Option 49.

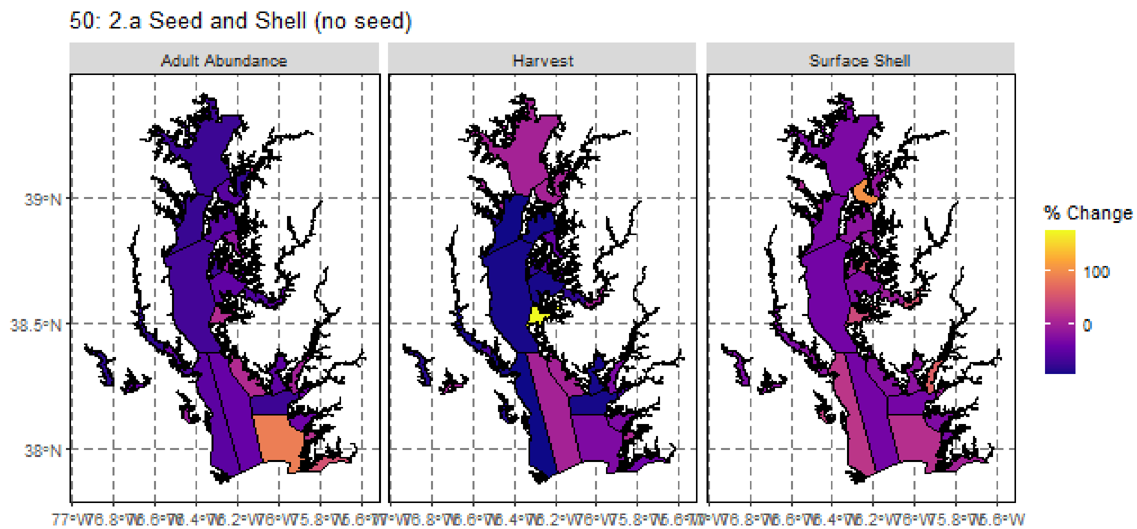

Fig. A266. Median percent change in adult abundance, harvest, and surface shell from 2019 to last year of simulations for Option 50.

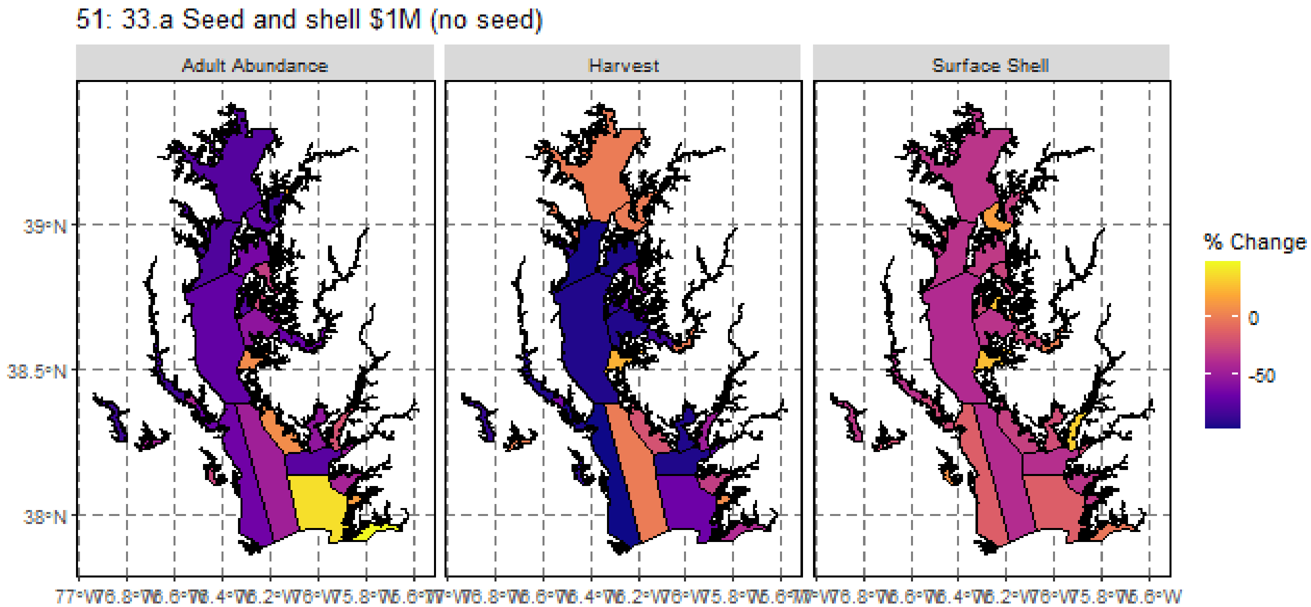

Fig. A267. Median percent change in adult abundance, harvest, and surface shell from 2019 to last year of simulations for Option 51.

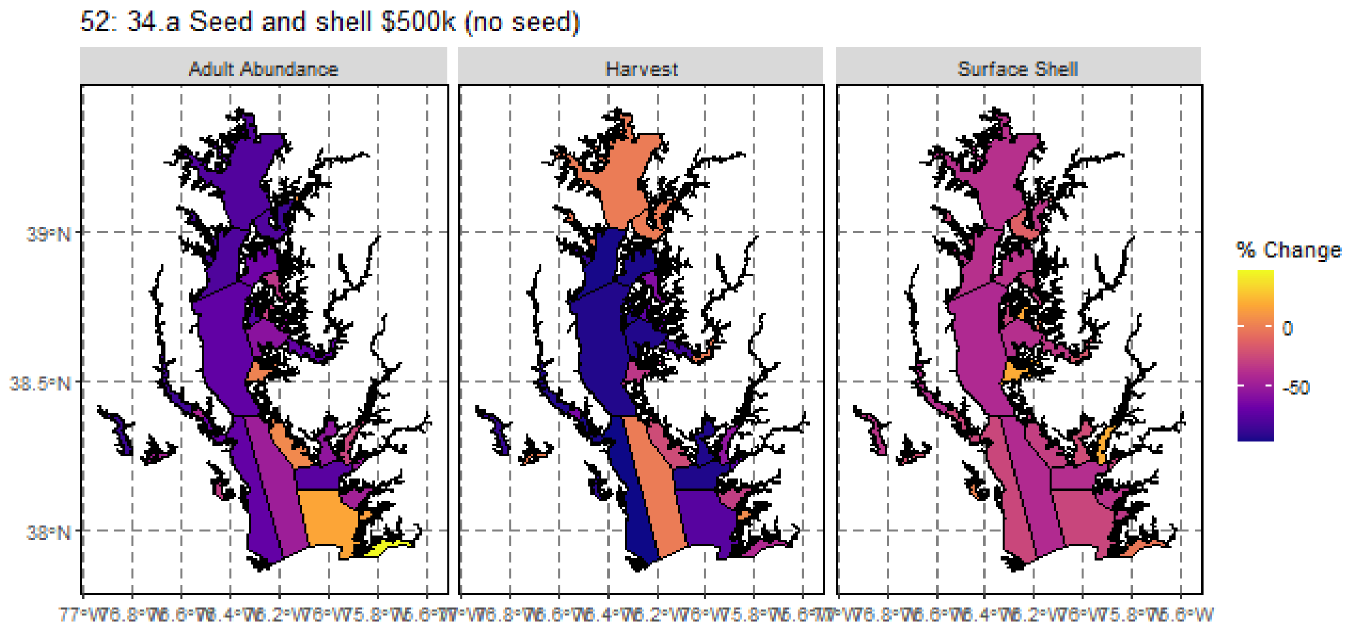

Fig. A268. Median percent change in adult abundance, harvest, and surface shell from 2019 to last year of simulations for Option 52.

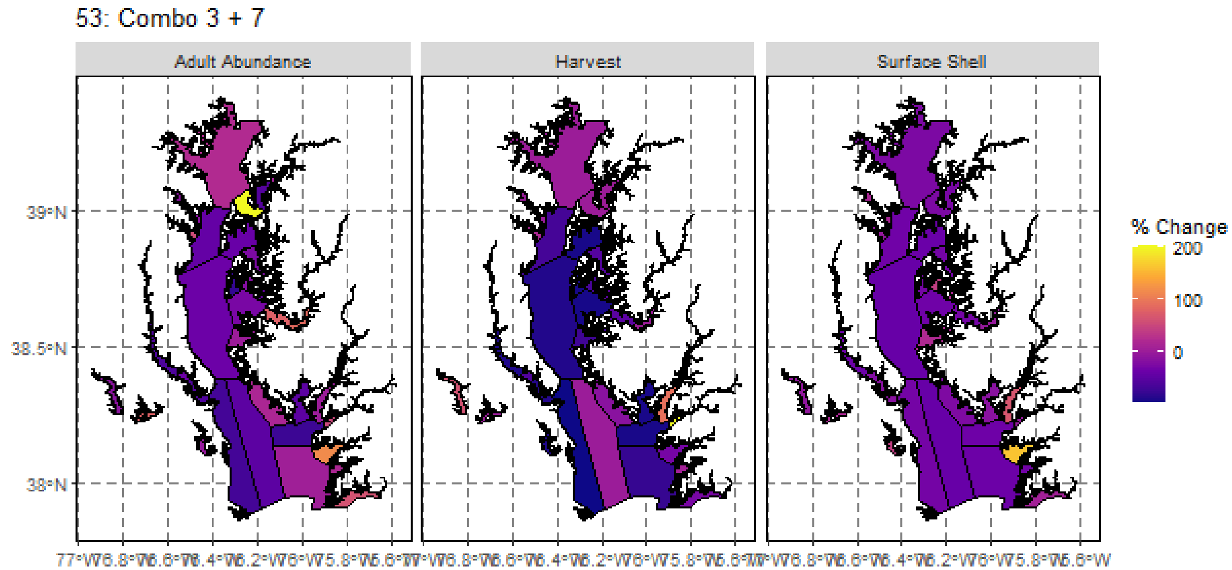

Fig. A269. Median percent change in adult abundance, harvest, and surface shell from 2019 to last year of simulations for Option 53.

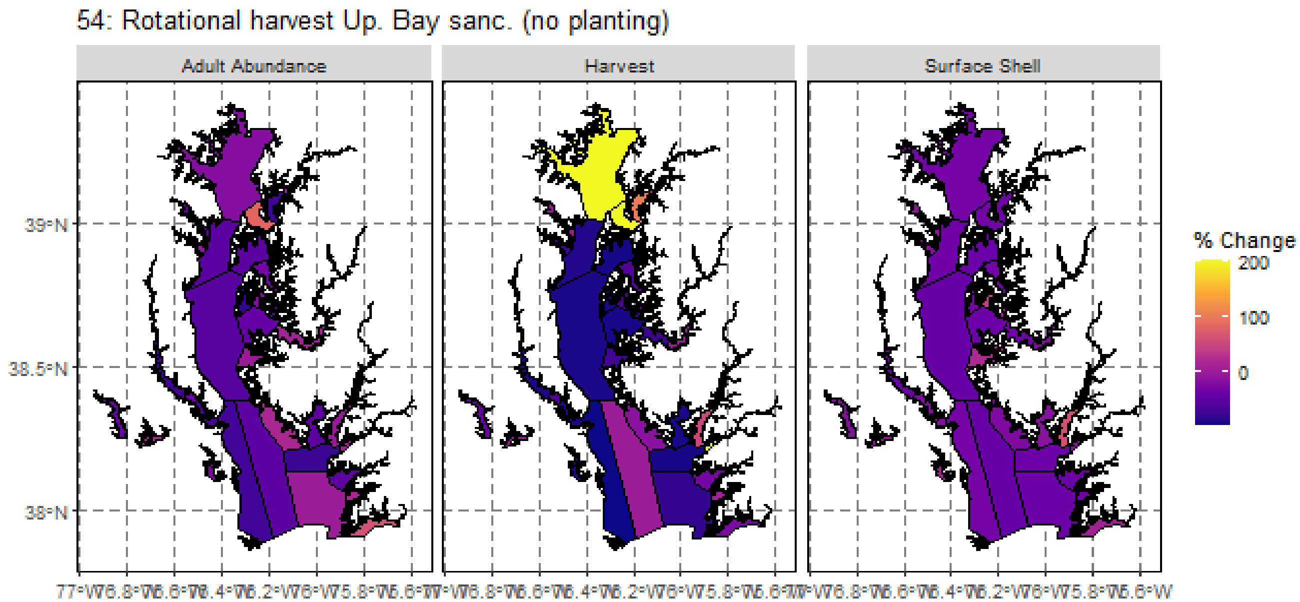

Fig. A270. Median percent change in adult abundance, harvest, and surface shell from 2019 to last year of simulations for Option 54.

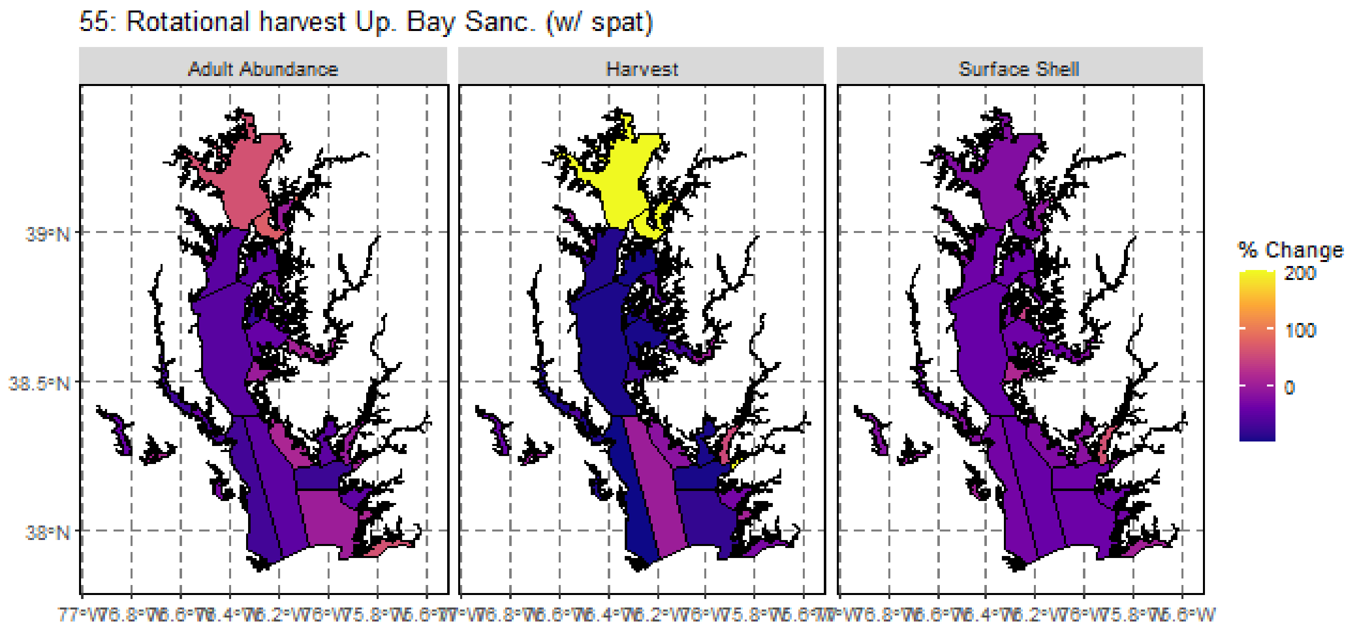

Fig. A271. Median percent change in adult abundance, harvest, and surface shell from 2019 to last year of simulations for Option 55.

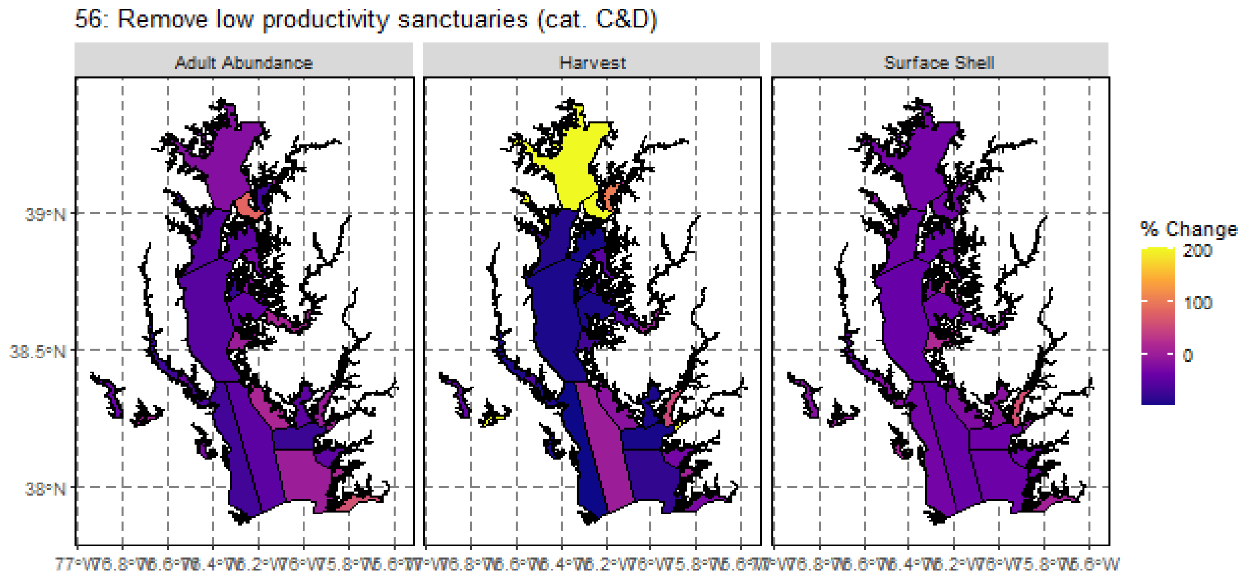

Fig. A272. Median percent change in adult abundance, harvest, and surface shell from 2019 to last year of simulations for Option 56.

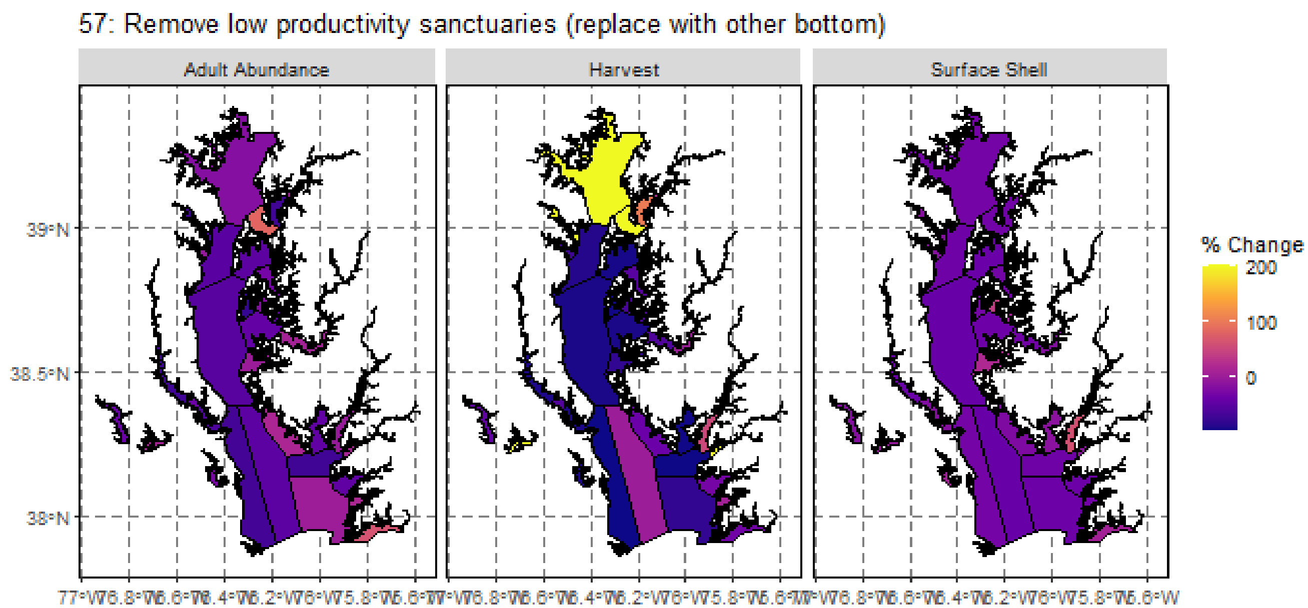

Fig. A273. Median percent change in adult abundance, harvest, and surface shell from 2019 to last year of simulations for Option 57.

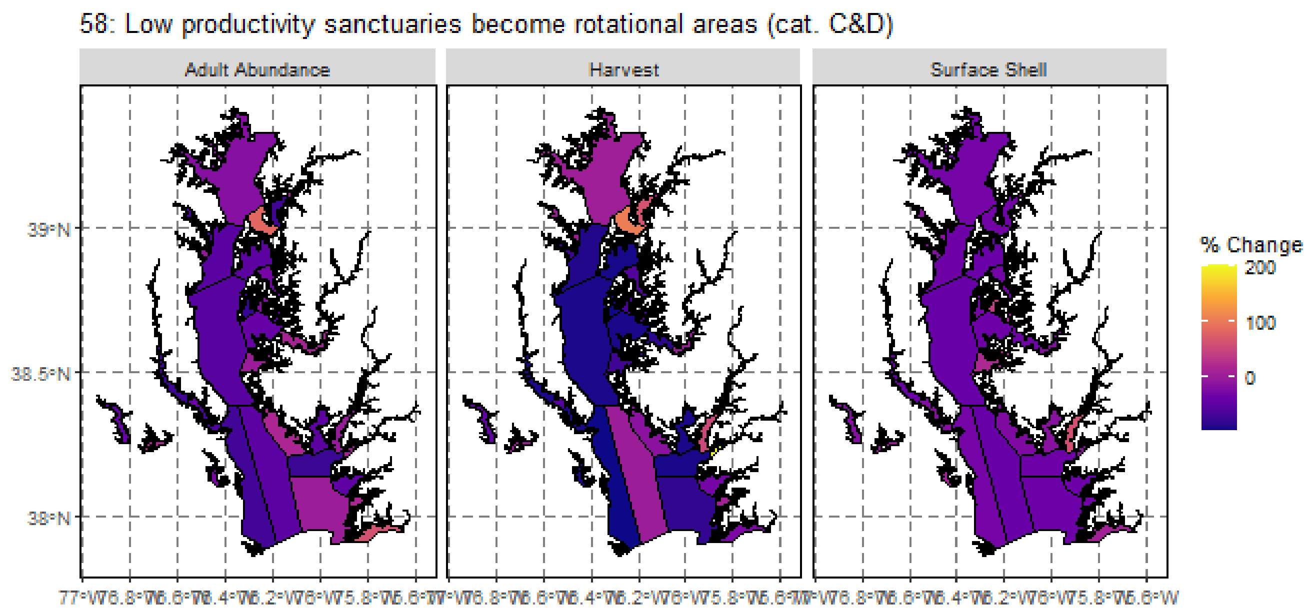

Fig. A274. Median percent change in adult abundance, harvest, and surface shell from 2019 to last year of simulations for Option 58.

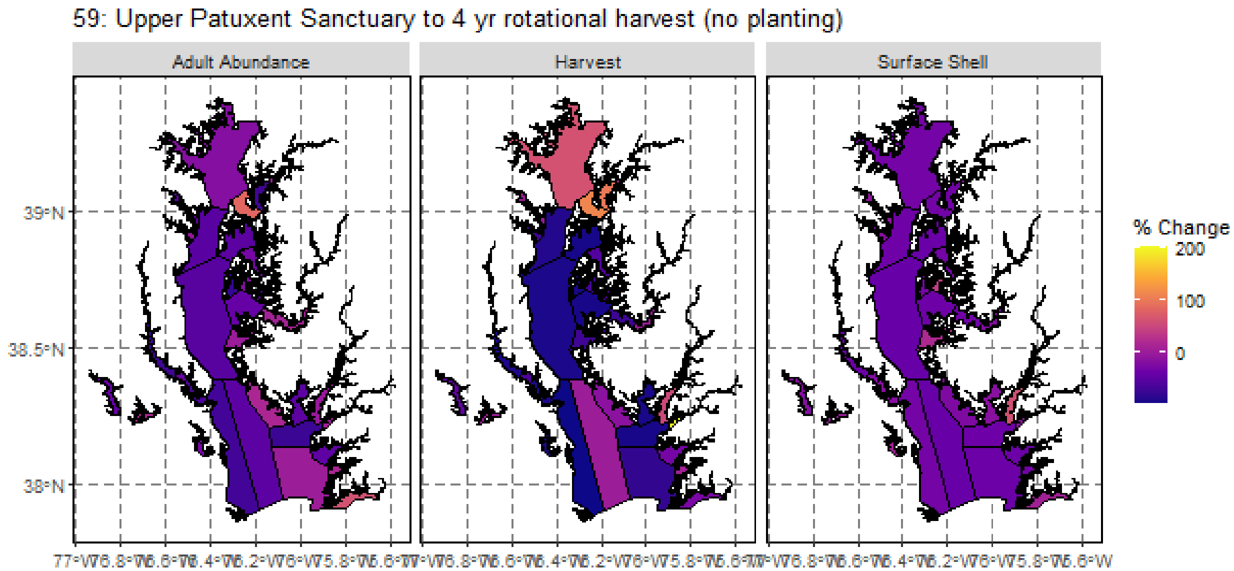

Fig. A275. Median percent change in adult abundance, harvest, and surface shell from 2019 to last year of simulations for Option 59.

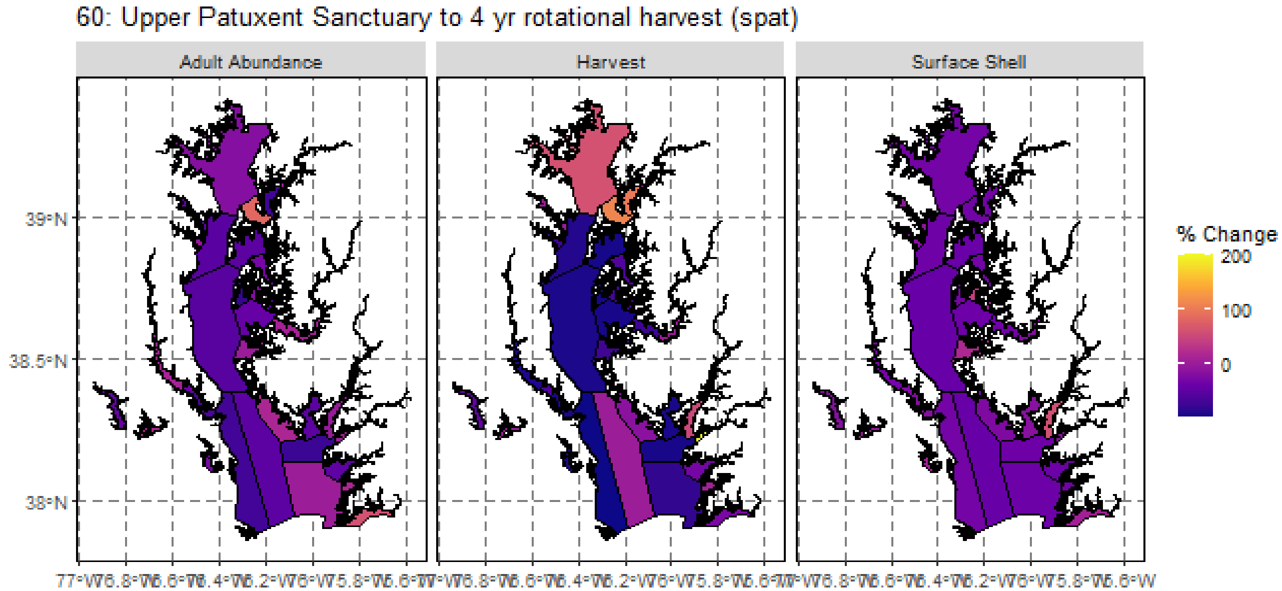

Fig. A276. Median percent change in adult abundance, harvest, and surface shell from 2019 to last year of simulations for Option 60.

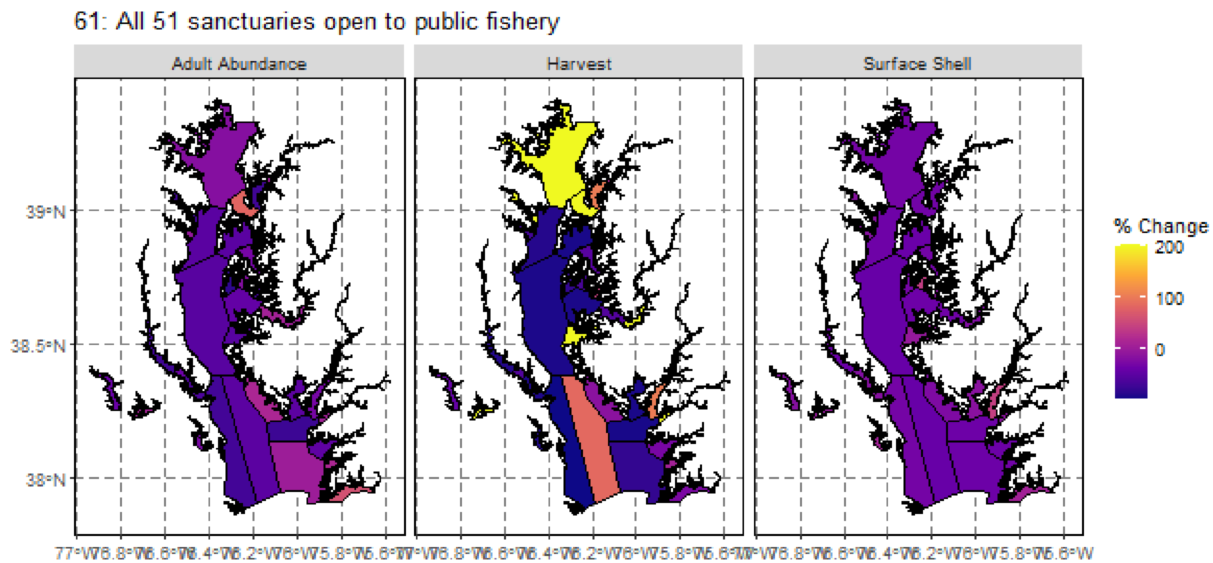

Fig. A277. Median percent change in adult abundance, harvest, and surface shell from 2019 to last year of simulations for Option 61.

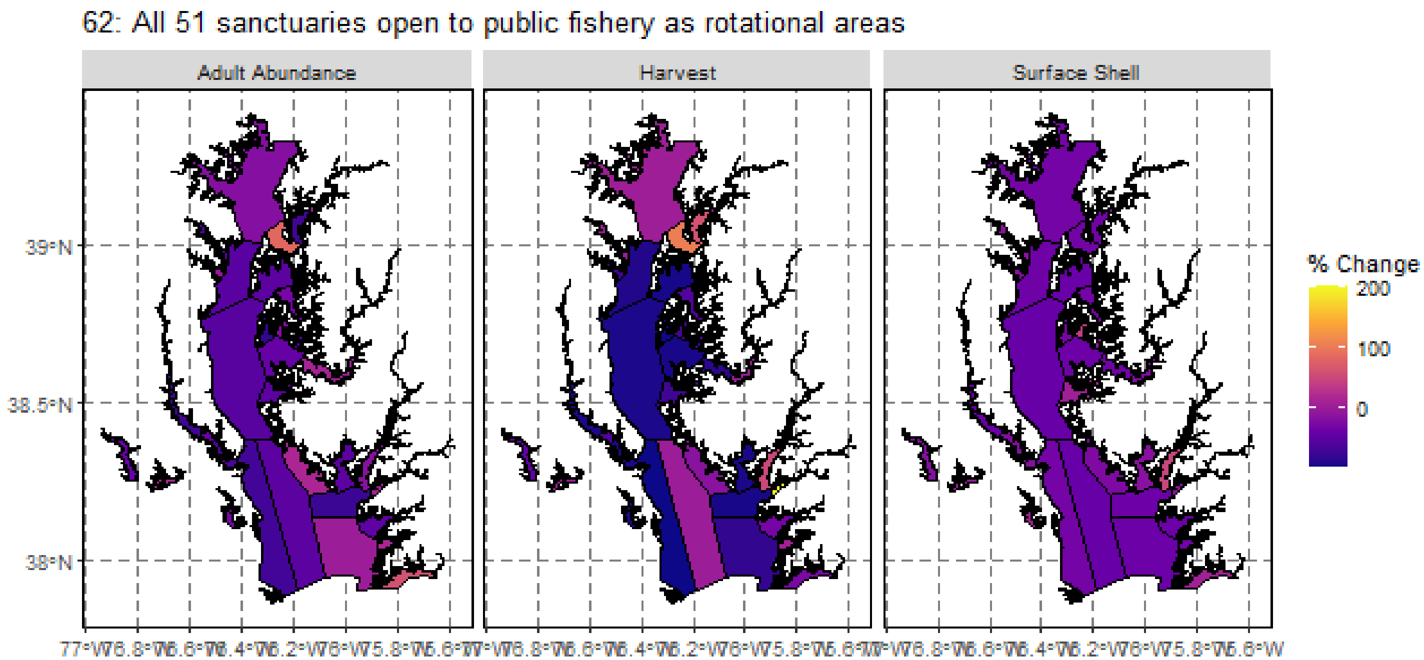

Fig. A278. Median percent change in adult abundance, harvest, and surface shell from 2019 to last year of simulations for Option 62.

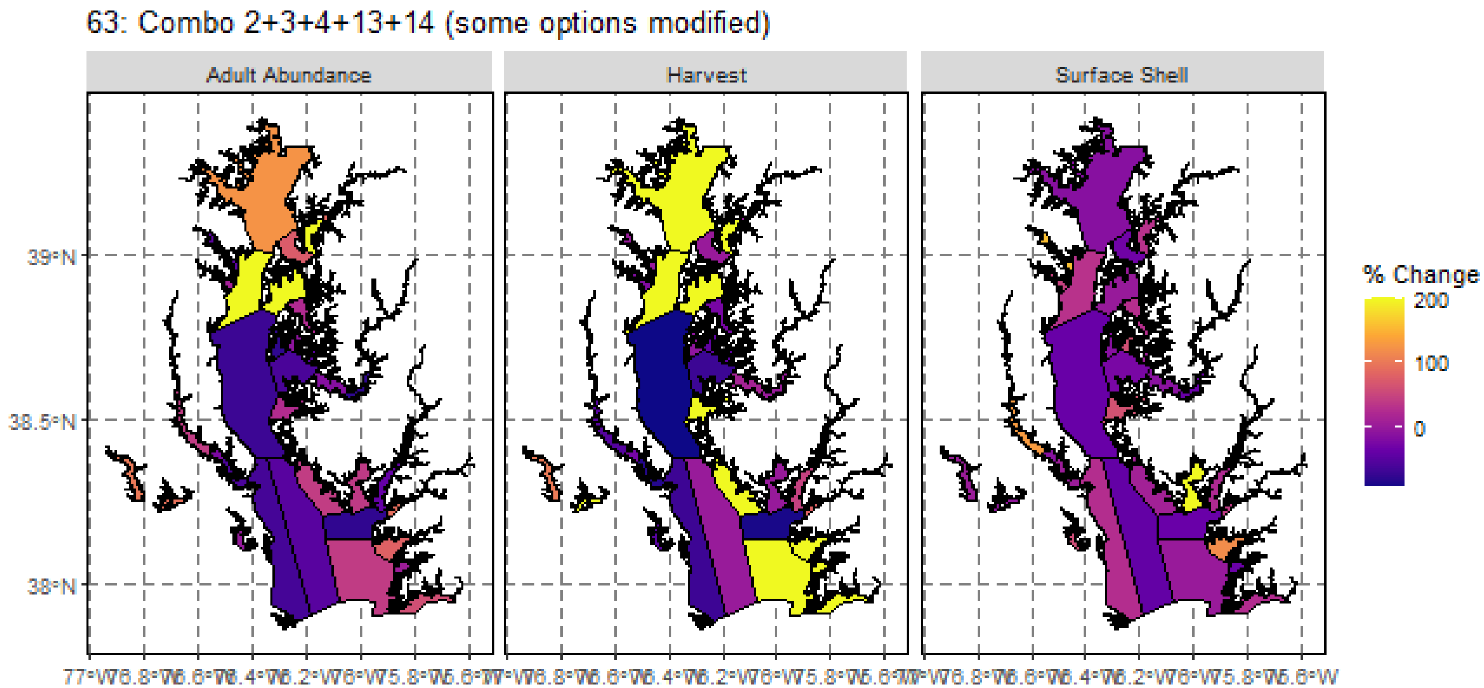

Fig. A279. Median percent change in adult abundance, harvest, and surface shell from 2019 to last year of simulations for Option 63.

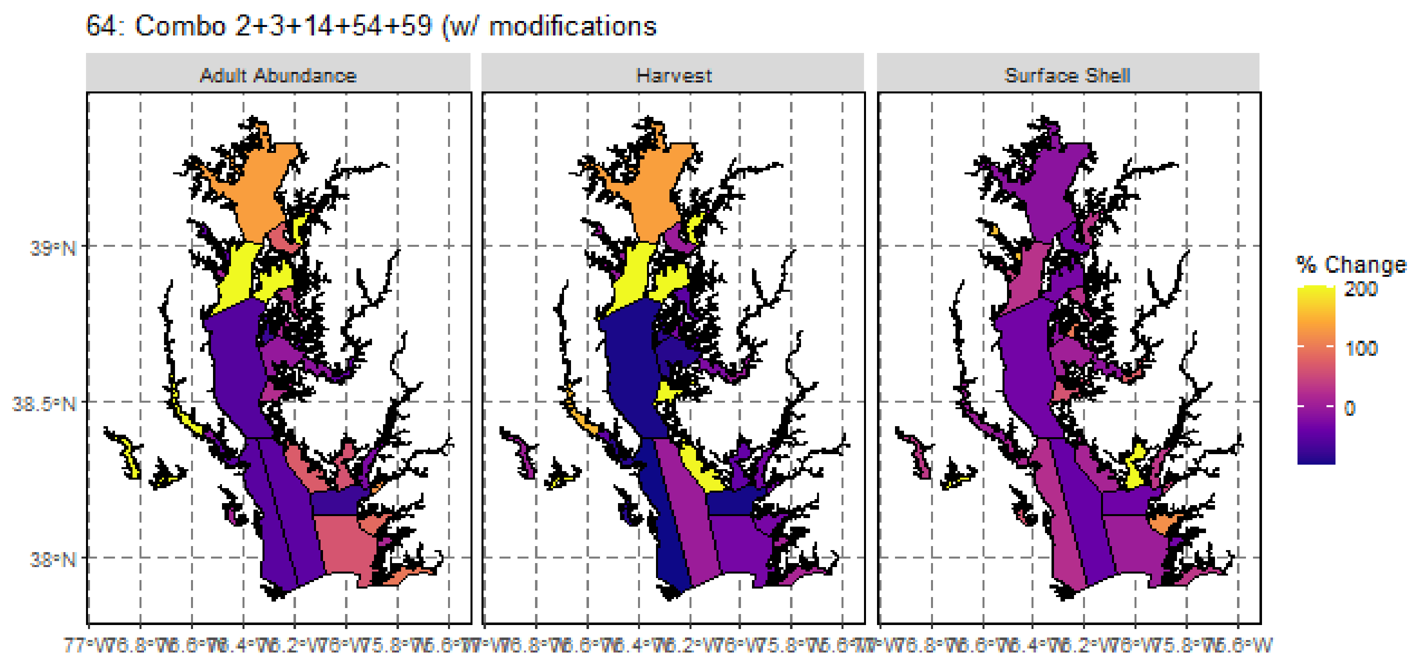

Fig. A280. Median percent change in adult abundance, harvest, and surface shell from 2019 to last year of simulations for Option 64.

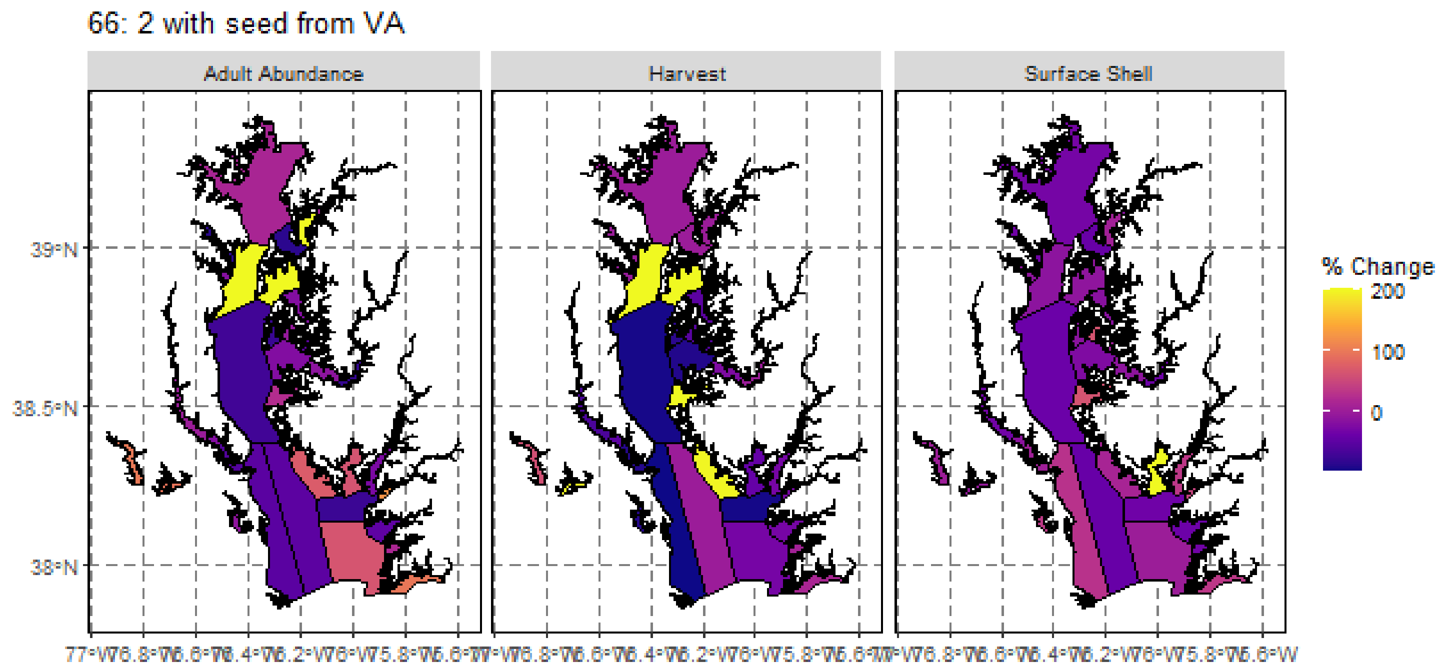

Fig. A281. Median percent change in adult abundance, harvest, and surface shell from 2019 to last year of simulations for Option 66.

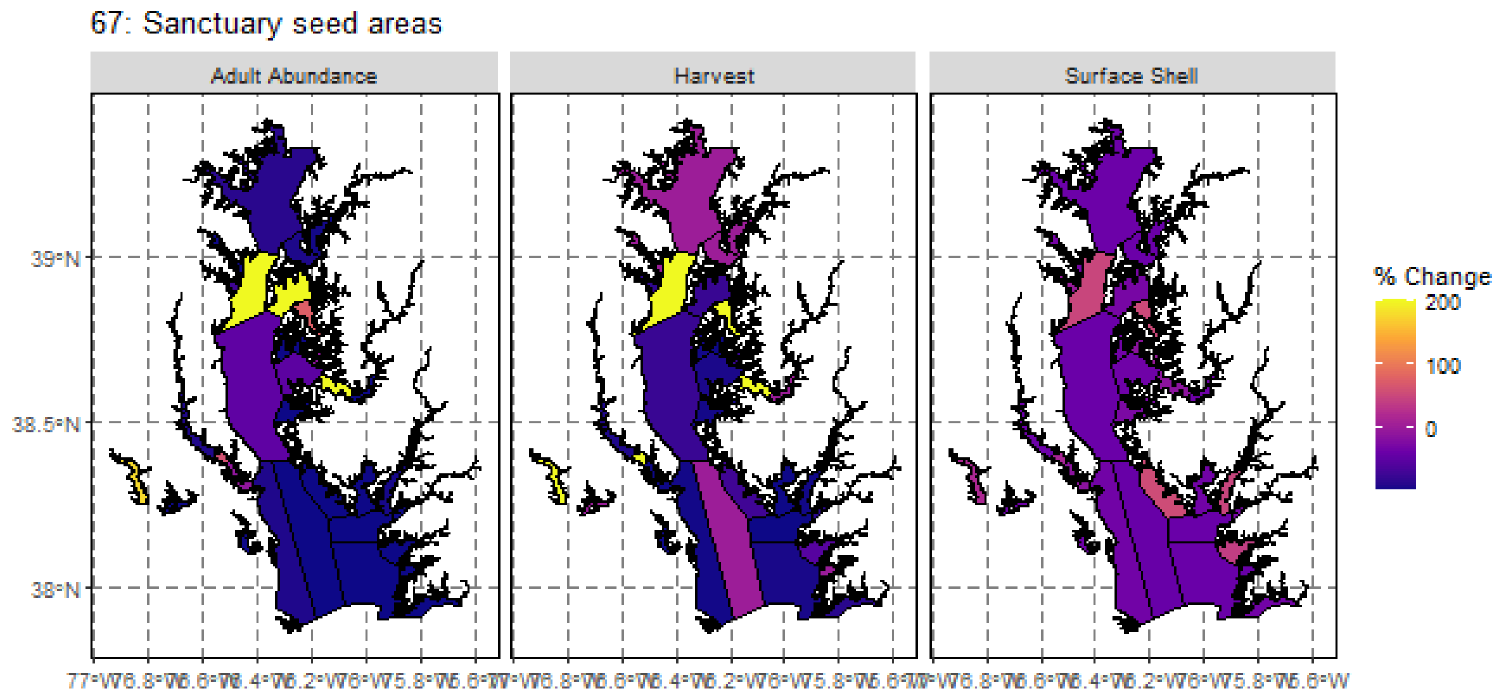

Fig. A282. Median percent change in adult abundance, harvest, and surface shell from 2019 to last year of simulations for Option 67.

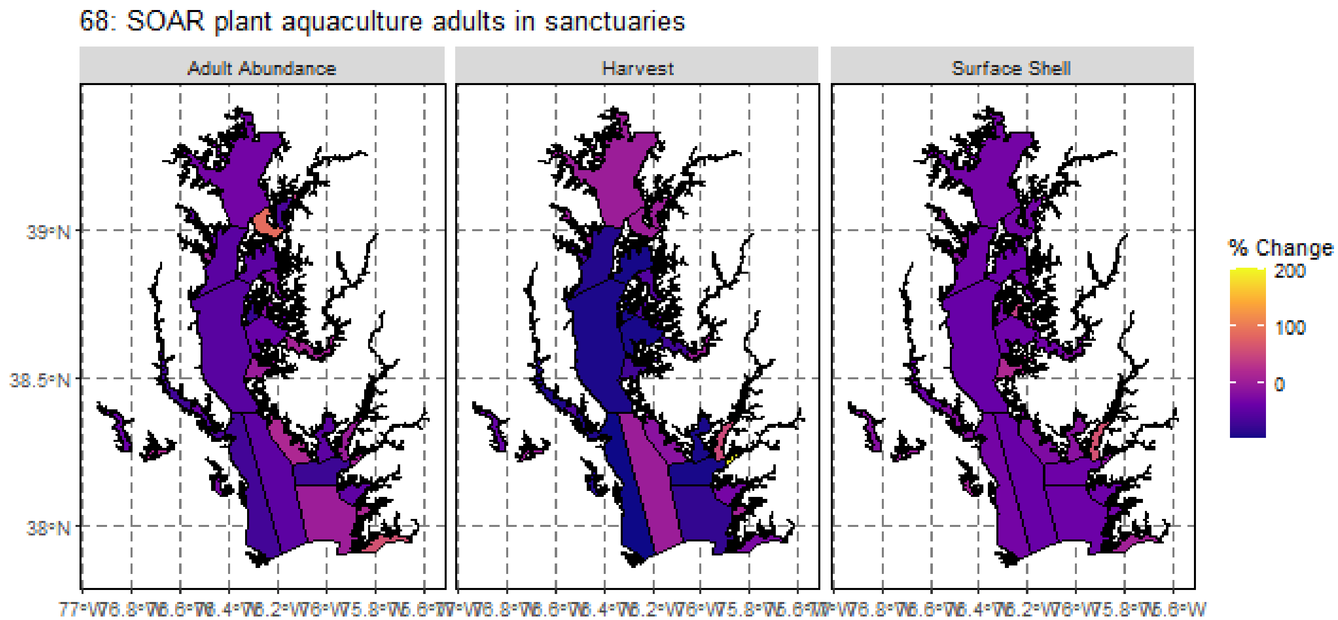

Fig. A283. Median percent change in adult abundance, harvest, and surface shell from 2019 to last year of simulations for Option 68.

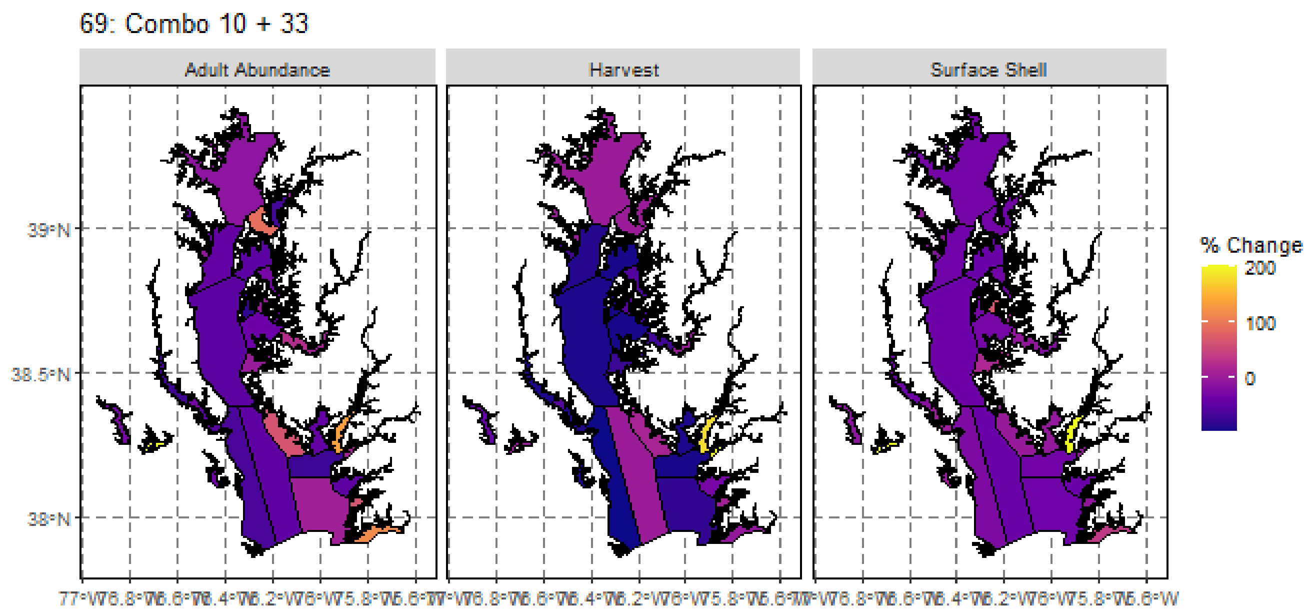

Fig. A284. Median percent change in adult abundance, harvest, and surface shell from 2019 to last year of simulations for Option 69.

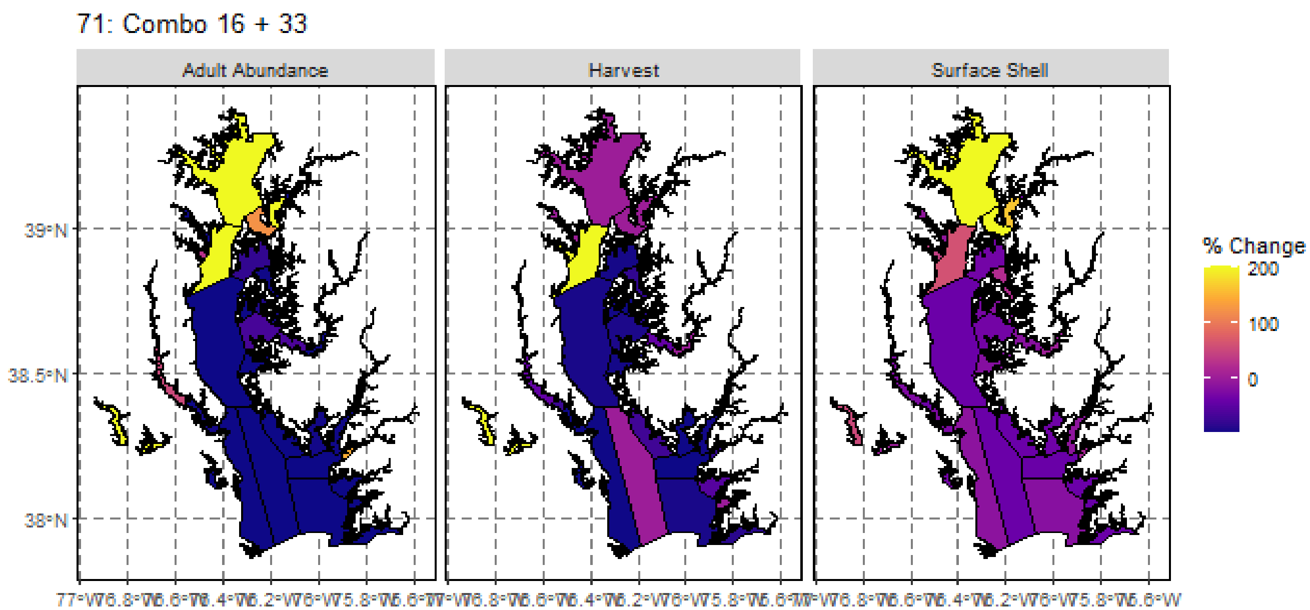

Fig. A285. Median percent change in adult abundance, harvest, and surface shell from 2019 to last year of simulations for Option 71.

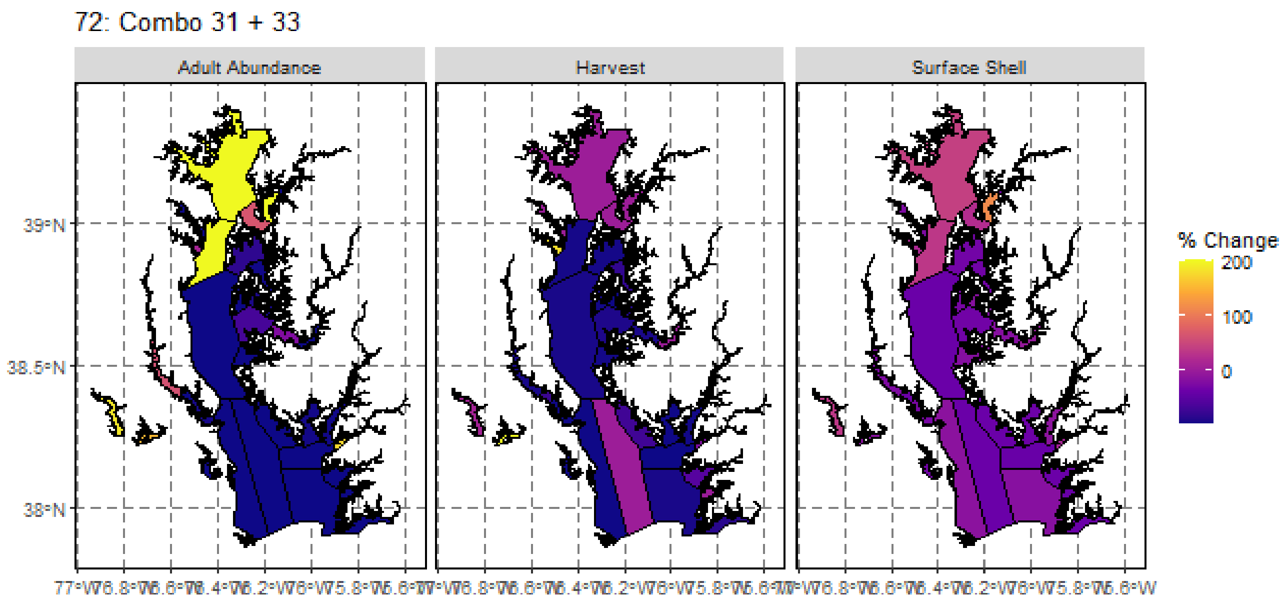

Fig. A286. Median percent change in adult abundance, harvest, and surface shell from 2019 to last year of simulations for Option 72.

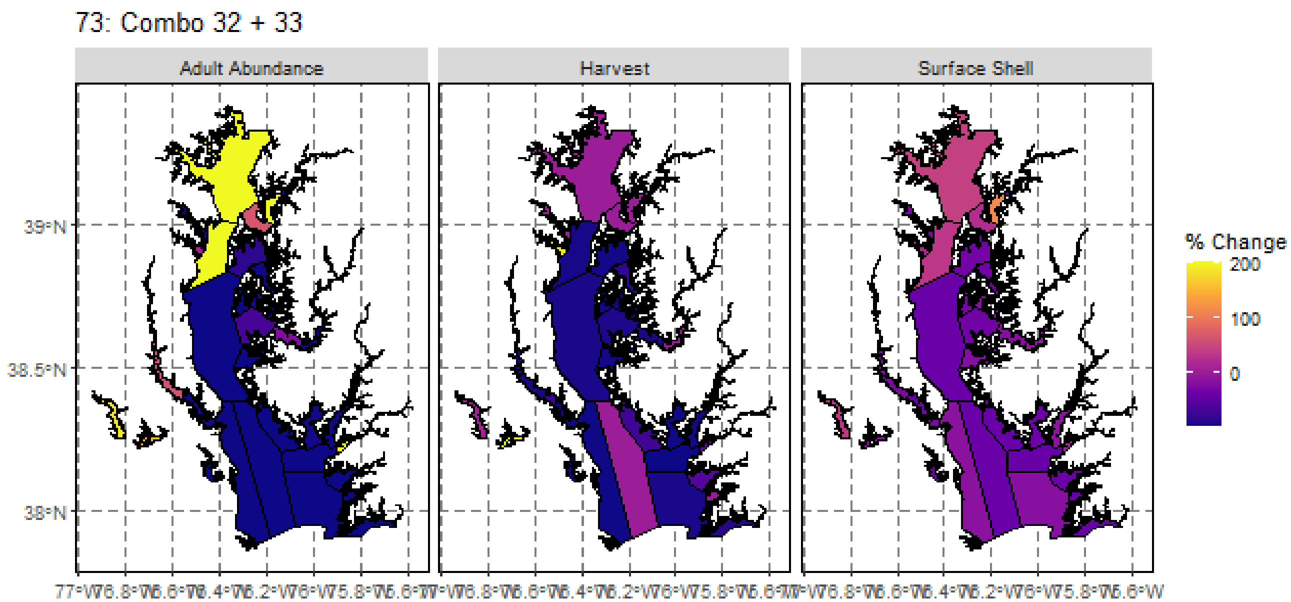

Fig. A287. Median percent change in adult abundance, harvest, and surface shell from 2019 to last year of simulations for Option 73.

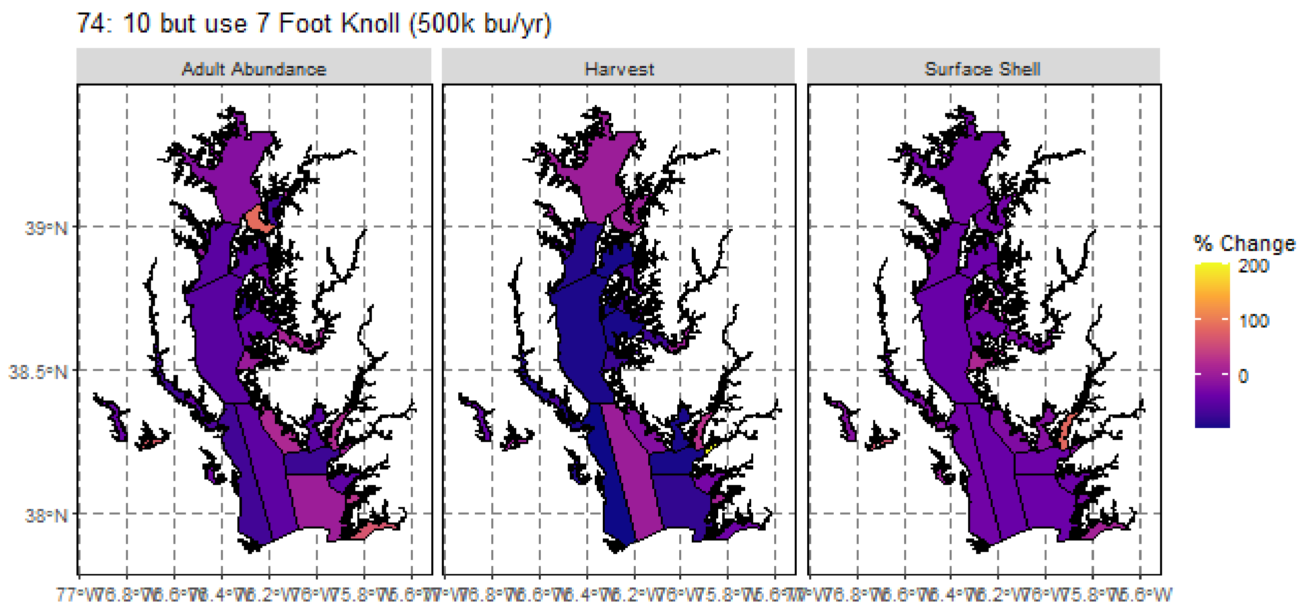

Fig. A288. Median percent change in adult abundance, harvest, and surface shell from 2019 to last year of simulations for Option 7

Appendix B. Locations where the LTRANS model has been used

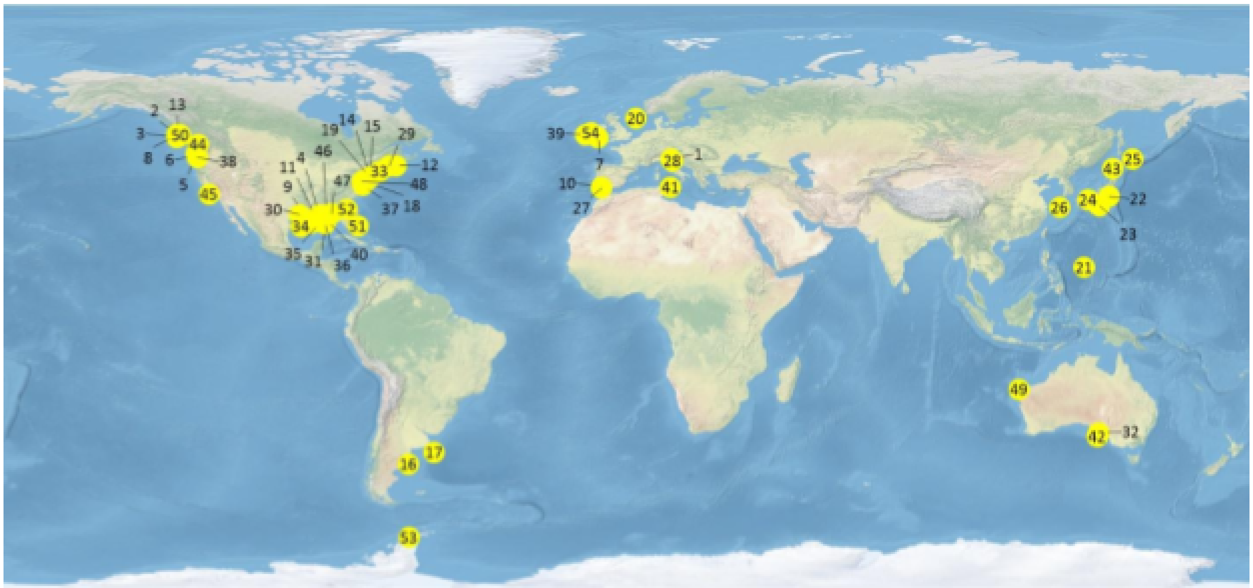

Fig. B1. Locations where the Lagrangian TRANSport (LTRANS) model has been used and published in peer-reviewed articles. Numbers correspond to the papers below. The total number of publications is 54, including the four authored by E. North (#18 and #35-37).

Peer-reviewed publications that have used LTRANS

1. Bandelj, V., Solidoro, C., Laurent, C., Querin, S., Kaleb, S., Gianni, F., & Falace, A. (2020). Cross-scale connectivity of macrobenthic communities in a patchy network of habitats: The Mesophotic Biogenic Habitats of the Northern Adriatic Sea. Estuarine, Coastal and Shelf Science, 245, 106978.
2. Bani, R., Fortin, M.-J., Daigle, R. M., & Guichard, F. (2019). Dispersal traits interact with dynamic connectivity to affect metapopulation growth and stability. Theoretical Ecology, 12(1), 111–127.
3. Bani, R., Marleau, J., Fortin, M., Daigle, R. M., & Guichard, F. (2021). Dynamic larval dispersal can mediate the response of marine metapopulations to multiple climate change impacts. Oikos, 130(6), 989–1000.
4. Barkan, R., McWilliams, J. C., Molemaker, M. J., Choi, J., Srinivasan, K., Shchepetkin, A. F., & Bracco, A. (2017). Submesoscale dynamics in the northern Gulf of Mexico. Part II: Temperature–salinity relations and cross-shelf transport processes. Journal of Physical Oceanography, 47(9), 2347–2360.
5. Bednaršek, N., Feely, R. A., Beck, M. W., Alin, S. R., Siedlecki, S. A., Calosi, P., Norton, E. L., Saenger, C., Štrus, J., & Greeley, D. (2020). Exoskeleton dissolution with mechanoreceptor damage in larval Dungeness crab related to severity of present-day ocean acidification vertical gradients. Science of The Total Environment, 716, 136610.
6. Berger, H. M., Siedlecki, S. A., Matassa, C. M., Alin, S. R., Kaplan, I. C., Hodgson, E. E., Pilcher, D. J., Norton, E. L., & Newton, J. A. (2021). Seasonality and life history complexity determine vulnerability of Dungeness crab to multiple climate stressors. AGU Advances, 2(4), e2021AV000456.
7. Berry, A., Dabrowski, T., & Lyons, K. (2012). The oil spill model OILTRANS and its application to the Celtic Sea. Marine Pollution Bulletin, 64(11), 2489–2501.

8. Blackford, C., Krkošek, M., & Fortin, M.-J. (2021). A data-limited modeling approach for conserving connectivity in marine protected area networks. Marine Biology, 168(6), 1–15.

9. Bracco, A., Choi, J., Joshi, K., Luo, H., & McWilliams, J. C. (2016). Submesoscale currents in the northern Gulf of Mexico: Deep phenomena and dispersion over the continental slope. Ocean Modelling, 101, 43–58.

10. Casaucao, A., González-Ortegón, E., Jiménez, M. P., Teles-Machado, A., Plecha, S., Peliz, A. J., & Laiz, I. (2021). Assessment of the spawning habitat, spatial distribution, and Lagrangian dispersion of the European anchovy (Engraulis encrasicolus) early stages in the Gulf of Cadiz during an apparent anomalous episode in 2016. Science of The Total Environment, 781, 146530.

11. Choi, J., Bracco, A., Barkan, R., Shchepetkin, A. F., McWilliams, J. C., & Molemaker, J. M. (2017). Submesoscale dynamics in the northern Gulf of Mexico. Part III: Lagrangian implications. Journal of Physical Oceanography, 47(9), 2361–2376.

12. Clark, S., Hubbard, K. A., McGillicuddy Jr, D. J., Ralston, D. K., & Shankar, S. (2021). Investigating Pseudo-nitzschia australis introduction to the Gulf of Maine with observations and models. Continental Shelf Research, 228, 104493.

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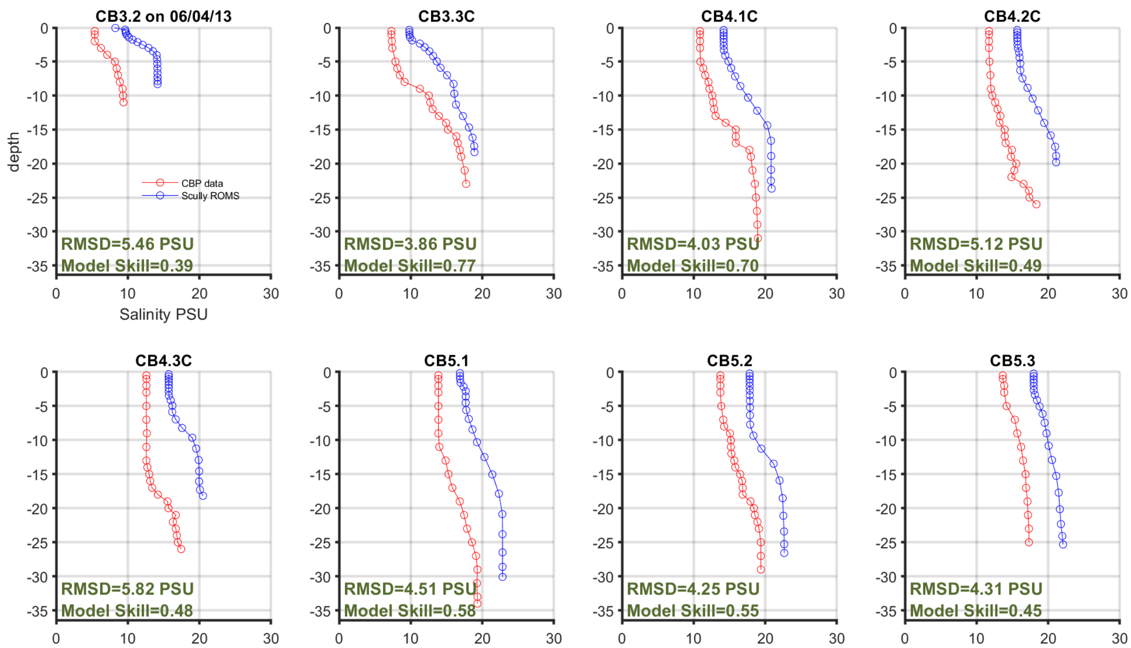
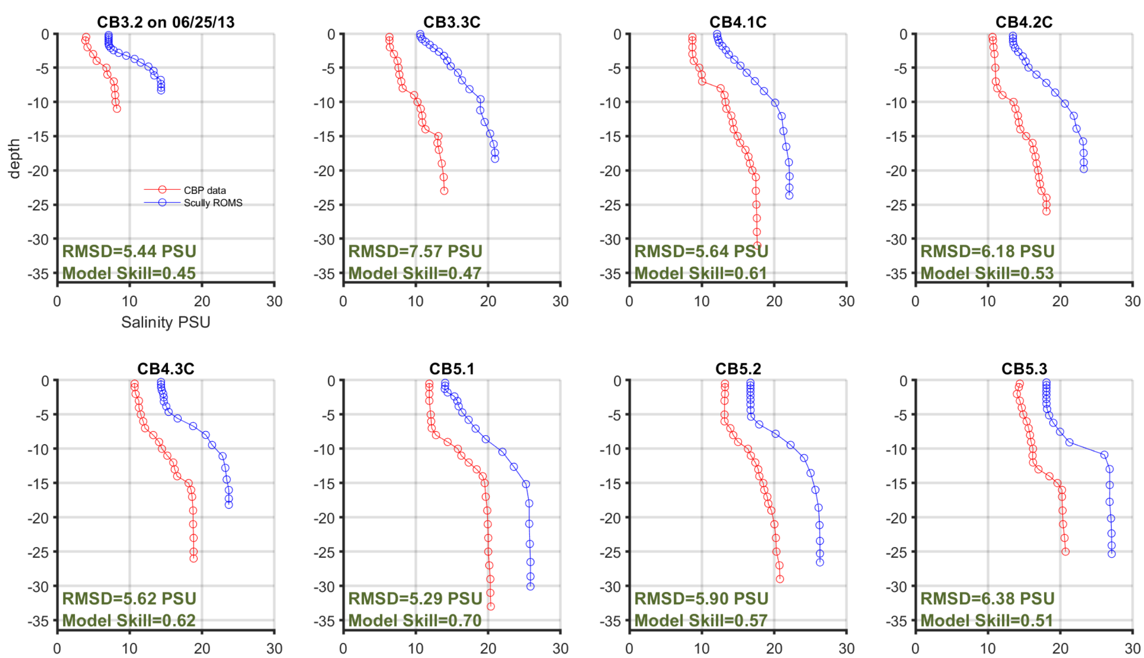
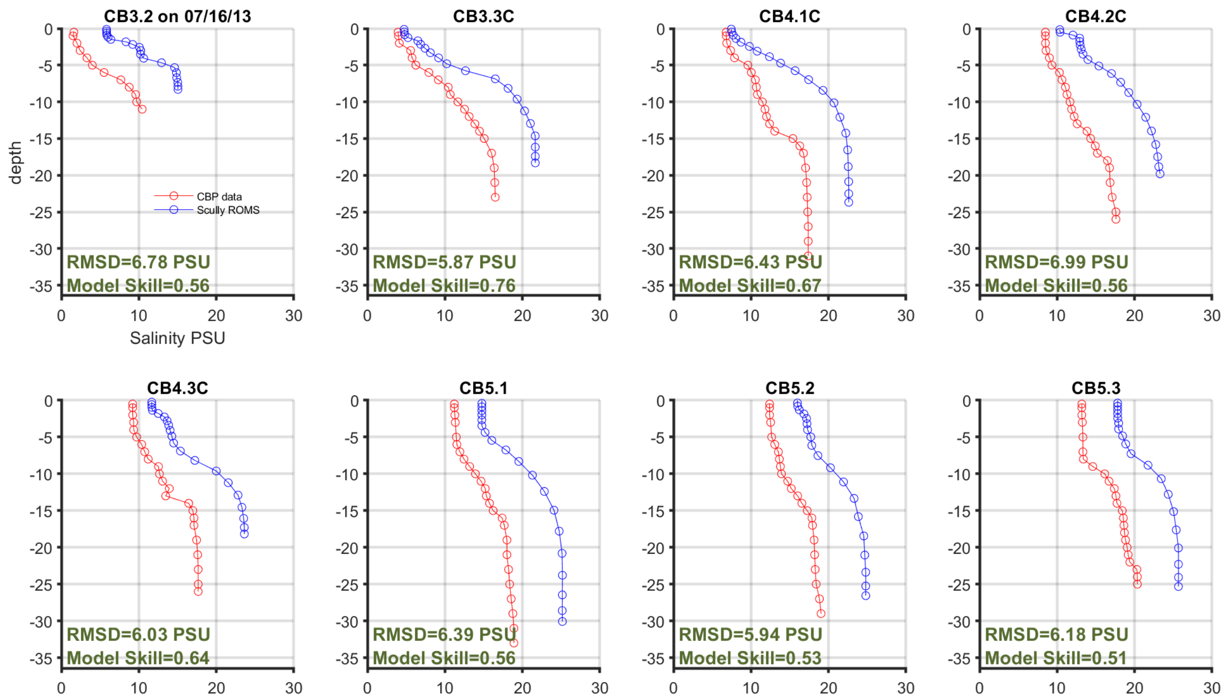
Appendix C. Vertical profiles of salinity in the hydrodynamic model and observations



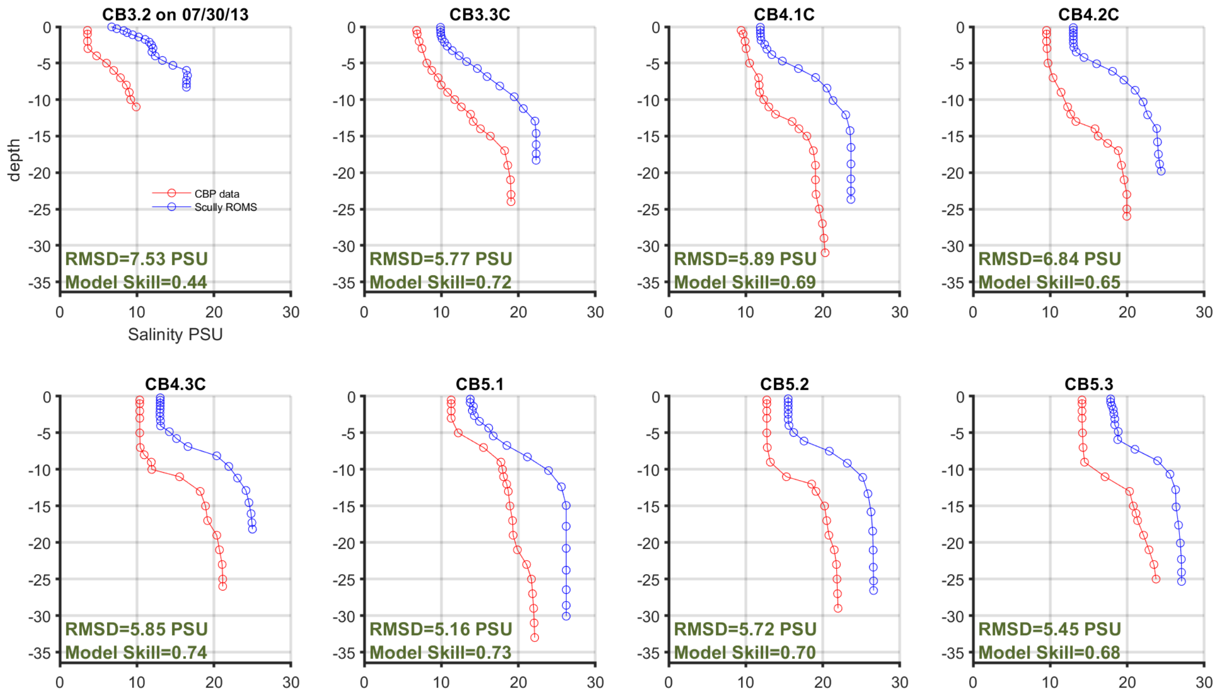
Appendix Figure 1. Observed (red) and simulated (blue) salinity profiles at CBP monitoring stations (station name on top of panels on June 4, 2013. RMSD and model skill values are included in the lower left of each panel. Station locations are in Fig. A.2.



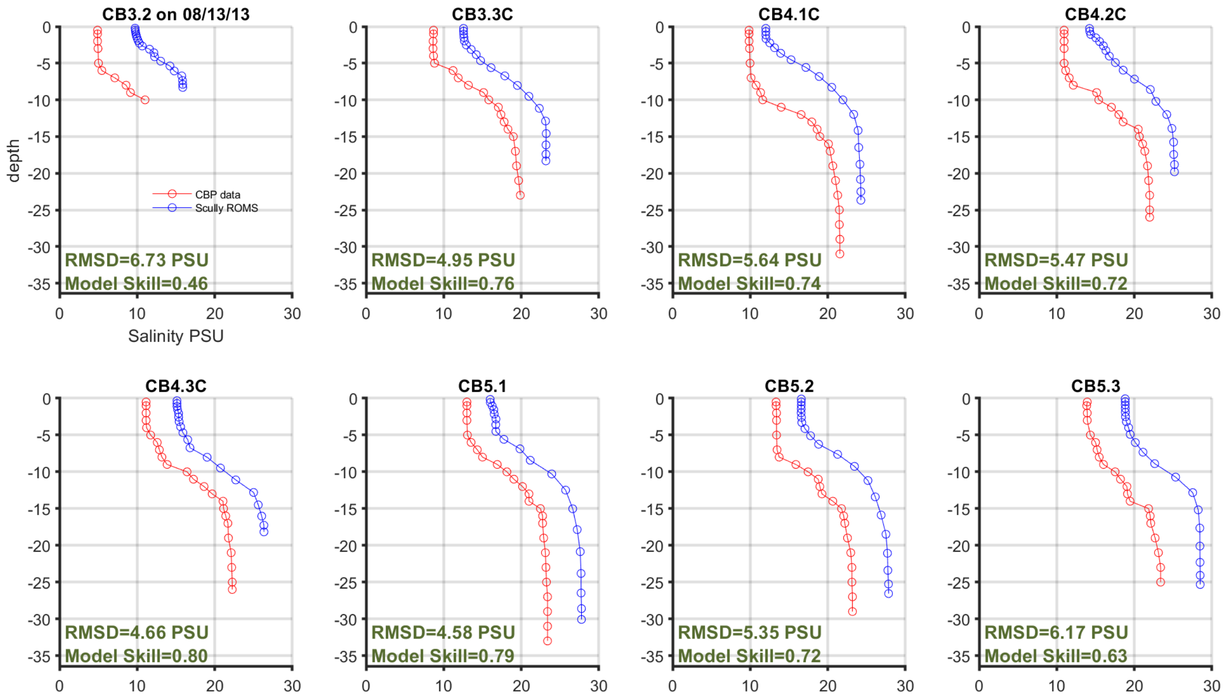
Appendix Figure 2. Observed (red) and simulated (blue) salinity profiles at CBP monitoring stations (station name on top of panels on June 25, 2013. RMSD and model skill values are included in the lower left of each panel. Station locations are in Fig. A.2.



Appendix Figure 3. Observed (red) and simulated (blue) salinity profiles at CBP monitoring stations (station name on top of panels on July 16, 2013. RMSD and model skill values are included in the lower left of each panel. Station locations are in Fig. A.2.



Appendix Figure 4. Observed (red) and simulated (blue) salinity profiles at CBP monitoring stations (station name on top of panels on July 30, 2013. RMSD and model skill values are included in the lower left of each panel. Station locations are in Fig. A.2.



Appendix Figure 5. Observed (red) and simulated (blue) salinity profiles at CBP monitoring stations (station name on top of panels on August 13, 2013. RMSD and model skill values are included in the lower left of each panel. Station locations are in Fig. A.2.

Appendix D. Development of Habitat Layers for the Oyster Advisory Commission Simulation Model

Kelly N. Greenhawk, December 2020

Introduction

The dataset described in this document was created for use by scientists at the University of Maryland Center for Environmental Science seeking to model and identify the impacts of various management actions on Maryland's oyster population. The final spatial dataset (filename "MdPotentialHabitat2020") is in the E.S.R.I. (Environmental Systems Research Institute) geodatabase format and is a spatial representation of the potential locations and extent of oyster habitat for the Maryland portion of the Chesapeake Bay. The file was used as input for modeling efforts related to the project referenced above, and in the generation of spatial products related to this project. The creation of this file was necessitated by of the lack of a recent comprehensive oyster bar survey in Maryland and an awareness that significant oyster habitat loss has occurred in recent years. This dataset is a compilation of selected data from Maryland's historic oyster bars, recent sonar surveys, oyster restoration efforts and the Maryland Bay Bottom Survey (MBBS).

The approach used to generate the files described here was agreed to by members of Maryland's Oyster Advisory Commission at the October 2020 monthly meeting. The agreed upon algorithm for approximation of habitat extent and quality within Maryland's oyster bars was to consider data from recent restoration activities first, then to use existing sonar characterization, and finally (for areas not covered by the previous) use data from the MBBS.

Created using E.S.R.I.'s ArcGIS software, the resulting file was derived from the following spatial data layers.

- E.S.R.I. shapefile which delineates historic, natural oyster bar boundaries charted by C.C. Yates (1906-1911), Gird, J. and F.W. Wheaton, 1976, and Merrit, D.W., 1977. (Data source: Maryland Department of Natural Resources)

- E.S.R.I. shapefile which delineates oyster restoration activities undertaken by the Maryland Department of Natural Resources, Oyster Recovery Project, Chesapeake Bay Foundation, NOAA and Army Corp of Engineers and other partners. (Data source: Maryland Department of Natural Resources)

- E.S.R.I. shapefiles of blueprints for restoration work planned. These layers represent restoration activities planned and already performed in the 5 Maryland tributaries called for by the 2014 Chesapeake Bay Watershed Agreement. Those tributaries are Harris Creek, the Little Choptank River, the Manokin River, the St. Mary's River and the Tred Avon River. (Data source: NOAA)

- E.S.R.I. geodatabase for bay wide benthic habitat classifications compiled from acoustic surveys and classified with an adaptation of the Coastal and Marine Ecological Classification Standard (CMECS) Substrate Component (SC). (Data source: NOAA)

- E.S.R.I. shapefile which delineates results from the Maryland Bay Bottom Survey, an acoustic and patent tong survey conducted by the Maryland Department of Natural Resources from 1978 to 1983. The results of the survey categorize Maryland's bay bottom into seven classifications: cultch, mud with cultch, sand with cultch, mud, sand, hard bottom and leased bottom. Areas classified as "cultch", "sand with cultch" and "mud with cultch" have been included in this data product. (Data source: Maryland Department of Natural Resources)

Supplemental attributes were assigned to each potential habitat polygon using the following datasets:

- E.S.R.I. shapefile for the Maryland and Virginia boundary (Data source: Original file from Maryland Department of Natural Resources; File was adjusted by modeling team to include only select Potomac River tributaries.)

- E.S.R.I. shapefile which delineates NOAA statistical regions. (Data source: Maryland Department of Natural Resources)
- E.S.R.I. shapefiles of Maryland oyster harvest gear areas such as hand tong, dredge, patent tong, power dredge and diving. (Data source: Maryland Department of Natural Resources)
- E.S.R.I. shapefile for Maryland's oyster sanctuaries (Data source: Maryland Department of Natural Resources)

- E.S.R.I. shapefile which delineates the Chesapeake Bay shoreline (Data source: NOAA)

Preparation of Data

The area of interest for the model was defined as the Maryland portion of the Chesapeake Bay except for in the Potomac River. In the Potomac, only the Wicomico River, St. Clement Bay, Breton Bay and the St. Mary's River were used.

All files were projected to UTM Zone 18 NAD 83.

Using the Maryland-Virginia boundary shapefile, a "clipper" file was created. This file was used repeatedly throughout this project to remove (Erase) features outside of the area of interest.

Fields for attributes to be computed were added to the master oyster bar file. See Table D3 for a list of the attributes contained in the final dataset.

<u>Preparation of historic bars</u>

The area of interest clipper file was used on Maryland's historic oyster bar layer. This operation resulted in a file containing 992 oyster bar boundaries.

To facilitate use of Maryland's harvest data, it was necessary to split the historic bars using the NOAA statistical regions, whereby bars that fell within 2 or more statistical areas were split. This operation resulted in 1,171 oyster bar features.

E.S.R.I.'s Multipart to Singlepart tool was then applied to ensure all bars were individual polygons and sliver polygons were removed. The resulting fie contained 1,087 oyster bars.

A unique identifier was assigned to each of the resulting 1,087 oyster bars. This id was created by concatenating the bar's 6-character barcode (assigned by MDNR) and the feature's object id. (e.g., BARMB0_319)

This file served as the master file into which all computations were written.

Preparation of restoration data

Spatial data for oyster restoration activities was obtained from MDNR. This data contained restoration information for activities performed by MDNR and all partner agencies from 1960 to 2019. The Maryland-Virginia clipper file was used to remove plantings outside of area of interest. Based on previous studies on the longevity of restoration plantings only data for activities from 2015 to 2019 were used.

Several features for partner activities in the resulting dataset were lacking corner coordinates and were represented by point features only. Since area calculations cannot be obtained for point data, the plantings represented by points were addressed by computing the average planting area of past deployments for that partner agency, rounding that value to the nearest acre, then buffering the points to create ellipses.

Restoration information from partners that contained no coordinate information was assigned the centroid values (latitude and longitude) for the targeted bar and buffered as described above.

A thorough comparison of features in NOAA's blueprint shapefiles to existing restoration data was necessary to ensure all activities in the 5 restoration tributaries were accounted for and to capture activities that are to take place in the near future.

The Intersect tool was used to extract restoration features inside the historic bars. The resulting file contained the barcode attribute for the bar corresponding to each planting feature. Areas were calculated for each planting.

Adjustments were made to volumetric values for each planting. For example, if 25,000 spat were placed on a bar but only 50 percent of the deployed material fell inside the historic bar, the volume for that planting was reduced by 50%.

Since many bars contained multiple plantings, a dissolve operation was performed (E.S.R.I.'s Dissolve tool) to aggregate the plantings inside each bar. The result was one acreage value and one volume for each bar, rather than several. This information was joined to the master oyster bar file and values for acreage of planted material, volume of planted material and percent of bar planted were updated for each bar.

Preparation of sonar data

Acoustic data categorized as "Acoustic" and "Restoration Blueprint" that fell outside the area of interest and polygons with areas less than 2 acres were removed from NOAA's sonar dataset. These small polygons were removed to minimize the number of polygons as input to the modeling software.

CMECS codes indicating oyster-related habitat were agreed upon and extracted. See Table D1 for a table of the sonar classifications that were used.

Acoustic data which intersected the historic oyster bars was extracted (Intersect tool) and a value for habitat quality was applied to each polygon in the file.

The Dissolve tool was used to fuse polygons with like quality values inside each bar together.

Polygons with quality equal to "1" were joined to each unique bar and the acreage of "quality 1 habitat" was saved to each bar.

Polygons with quality equal to "2", "3", "4" and "5" were joined to each unique bar and the acreages were saved to each bar.

Percentages of each habitat quality were calculated for each bar and QC was performed on each bar.

Preparation of Bay Bottom Survey data

Data from the Bay Bottom Survey for bottom types equal to "cultch", "sand with cultch" and "mud with cultch" were extracted from the master dataset. The resulting file contained 5,066 polygons.

The Intersect tool was used to extract Bay Bottom Survey data inside each oyster bar.

Quality values were applied to each BBS polygon as follows, with 3 being the best quality:

Quality 1 = “mud with cultch”

Quality 2 = “sand with cultch”

Quality 3 = “cultch”

The Dissolve tool was used to fuse polygons with like quality values inside each bar together.

Polygons with quality equal to “1” were joined to each unique bar and the acreage of quality “1” (“mud with cultch”) inside each bar was computed.

Polygons with quality equal to “2” were joined to each unique bar and the acreage of quality “2” (“sand with cultch”) inside each bar was computed.

Polygons with quality equal to “3” were joined to each unique bar and the acreage of quality “3” (“cultch”) inside each bar was computed.

It was necessary to perform the three joins above in separate steps to avoid errors related to cardinality.

The percentage of each habitat quality was calculated for each bar and QC was performed.

Preparation of sanctuary data

The Intersect tool was used to extract sanctuary data for each oyster bar.

As above, acreages were computed for the amount of sanctuary inside each bar.

The layer of sanctuary polygons was joined to the master bar layer using the unique polygon id in order to generate acreage and percent values for each bar.

Preparation of gear areas

A series of spatial layers for Maryland's oyster harvest gear areas was obtained from MDNR. These layers, developed in 2019, represent areas where fishermen may use specific harvest gears, such as hand tongs, patent tongs, power dredges, sail dredges, yawl boats and diving. The percentage of each bar under the influence of each of these gear types was computed using these layers. For each of the 6 gear types, the following steps were taken.

Sanctuaries were erased from the gear area layers. This step was necessary because when the regulations were digitized, they were interpreted literally, and many of Maryland's sanctuaries did not exist when some of the gear regulations were created.

The intersect tool was used to extract hand tong only areas for each bar. Each feature in the resulting file included an attribute for the polygon id for the bar inside which it fell.

The Dissolve tool was used to aggregate multiple hand tong features in a bar.

The hand tong only layer was joined (Join) to the master oyster bar layer based on the unique polygon id and acreages and percentages were updated.

These same steps were used to calculate the acreages for each of the other gear types. (patent tongs, power dredges, sail dredges, yawl boats and diving)

Preparation of oyster bar boundaries for LTRANS

Vertices for the 1,087 bars were generated and those points along with relevant attributes were exported to an ASCII file for use in LTRANS. See Table D4 for a sample of this file.

Table D1. Habitat-related CMECS codes used in computations.

CMECS_Unit_Code	CMECS_COE_Code	Substrate_Origin	Substrate_Class	Substrate_Subclass	Notes
S2.5.2.3	S1.2.2.2	Biogenic	Biogenic_Shell	Biogenic_Shell_Rubble	Natural 2 dimensional oyster shell (little relief) on bottom that is more shell than sand
S2.5.2.3	S1.2.2.5	Biogenic	Biogenic_Shell	Biogenic_Shell_Rubble	Natural 2 dimensional oyster shell (little relief) on bottom that is more shell than mud
S2.5.1.1		Biogenic	Biogenic_Shell	Biogenic_Shell_Reef	Natural 3 dimensional oyster shell (some relief)
S2.5.1.1(AI08)		Biogenic	Biogenic_Shell	Biogenic_Shell_Reef	Natural 3 dimensional oyster shell (some relief) planted with hatchery spat on shell
S3.6.1		Anthropogenic	Anthropogenic_Shell	Anthropogenic_Shell_Reef	(Provisional-Not in CMECS yet) Man made 3 dimensional non-native shell reef (some relief)
S3.6.1(AI08)	S2.5.2.3	Anthropogenic	Anthropogenic_Shell	Anthropogenic_Shell_Reef	Man made 3 dimensional non-native shell reef (some relief) planted with hatchery spat on shell
S3.1.1		Anthropogenic	Anthropogenic_Rock	Anthropogenic_Rock_Reef	Man made 3 dimensional rock reef (some relief)
S3.1.1(AI08)	S2.5.2.3	Anthropogenic	Anthropogenic_Rock	Anthropogenic_Rock_Reef	Man made 3 dimensional rock reef (some relief) planted with hatchery spat on shell
S2.5.2.3		Biogenic	Biogenic_Shell	Biogenic_Shell_Rubble	Natural 2 dimensional oyster shell (little relief)
S2.5.2.3(AI08)		Biogenic	Biogenic_Shell	Biogenic_Shell_Rubble	Natural 2 dimensional oyster shell (little relief) planted with hatchery spat on shell
S3.6.2		Anthropogenic	Anthropogenic_Shell	Anthropogenic_Shell_Rubble	(Provisional-Not in CMECS yet) Man made 2 dimensional transported shell rubble (little relief)
S3.6.2(AI08)	S2.5.2.3	Anthropogenic	Anthropogenic_Shell	Anthropogenic_Shell_Rubble	Man made 2 dimensional transported shell rubble (little relief) planted with hatchery spat on shell

Table D2. Habitat quality values assigned to CMECS codes in Table D1.

Habitat Quality Value	Description of Habitat Classes
0	Mud, sand, or unclassified
1	Shell fragments
2	no relief (2D) - manmade or biogenic - shell with sand or mud
3	no relief (2D) - manmade or biogenic - shell
4	relief (3D) - manmade or biogenic - shell
5	relief (3D) - manmade - stone (anything with relief and nonshell material)

Table D3. Attributes in the final dataset.

Feature acres (acreage of bar)
NOAA code
Acres of quality 1 bottom detected in recent sonar surveys
Percent of bar containing quality 1 bottom
Acres of quality 2 bottom detected in recent sonar surveys
Percent of bar containing quality 2 bottom
Acres of quality 3 bottom detected in recent sonar surveys
Percent of bar containing quality 3 bottom
Acres of quality 4 bottom detected in recent sonar surveys
Percent of bar containing quality 4 bottom
Acres of quality 5 bottom detected in recent sonar surveys
Percent of bar containing quality 5 bottom
Acres of quality 1 bottom from MBBS data
Percent of bar containing quality 1 bottom from MBBS
Acres of quality 2 bottom from MBBS data
Percent of bar containing quality 2 bottom from MBBS
Acres of quality 3 bottom from MBBS data
Percent of bar containing quality 3 bottom from MBBS
Acres of bar within a sanctuary
Percent of bar within a sanctuary
Acres of bar within a hand-tong only area
Percent of bar within a hand-tong only area
Acres of bar within a patent tong area
Percent of bar within a patent tong area
Acres of bar within a power dredge area
Percent of bar within a power dredge area
Acres of bar within an area where yawl boats are permitted
Percent of bar within an area where yawl boats are permitted
Acres of bar within a dredge area
Percent of bar within a dredge area
Acres of bar within a dive area
Percent of bar within an area where diving is permitted
Acres of bar planted
Percent of bar planted
Volume of material planted (number of spat or spat on shell)

Table D4. Sample listing of ASCII file for use in LTRANS.

PgonId	Acres	Inside_X	Inside_Y	Point_X	Point_Y
BARBA0_1	1220.219971	-75.839801	38.056784	-75.820183	38.064283
BARBA0_1	1220.219971	-75.839801	38.056784	-75.813222	38.052272
BARBA0_1	1220.219971	-75.839801	38.056784	-75.815225	38.050856
BARBA0_1	1220.219971	-75.839801	38.056784	-75.815452	38.050948
BARBA0_1	1220.219971	-75.839801	38.056784	-75.825325	38.054936
BARBA0_1	1220.219971	-75.839801	38.056784	-75.842383	38.051511
BARBA0_1	1220.219971	-75.839801	38.056784	-75.862739	38.047481
BARBA0_1	1220.219971	-75.839801	38.056784	-75.863803	38.054589
BARBA0_1	1220.219971	-75.839801	38.056784	-75.852106	38.062517
BARBA0_1	1220.219971	-75.839801	38.056784	-75.820183	38.064283
BARBA1_2	391.463013	-75.850402	38.045081	-75.843798	38.037654
BARBA1_2	391.463013	-75.850402	38.045081	-75.857557	38.042204
BARBA1_2	391.463013	-75.850402	38.045081	-75.862739	38.047481
BARBA1_2	391.463013	-75.850402	38.045081	-75.842383	38.051511
BARBA1_2	391.463013	-75.850402	38.045081	-75.843798	38.037654
BARCC0_3	114.194000	-75.806325	38.059945	-75.806377	38.062034
BARCC0_3	114.194000	-75.806325	38.059945	-75.800335	38.059957
BARCC0_3	114.194000	-75.806325	38.059945	-75.798804	38.062503
BARCC0_3	114.194000	-75.806325	38.059945	-75.798248	38.057306

Section 4. Acknowledgements

The department would like to acknowledge many individuals that assisted in the Oyster Advisory Commission consensus project.

The department would like to acknowledge the commissioners themselves. Commissioners met after normal business hours on a volunteer basis. Between meetings, commissioners took the time to review presentation material, attend supplemental meetings, and work toward developing the package of recommendations. This process would not have been successful without their time and devotion to this process.

The department would like to acknowledge the facilitators (Dr. Memo Diriker, Quinn Fowler, and Dr. Brian Polkinghorn) and the UMCES modeling team (Dr. Michael Wilberg, Dr. Elizabeth North, and Dr. Jeff Cornwell).

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Multiple staff with the department assisted with this process including Paul Genovese and Kevin Ensor for IT support, Dr. Marvin "Trey" Mace for modeling support to UMCES; also Secretary Jeannie Haddaway-Riccio, Assistant Secretary Bill Anderson, and Chris Judy and Jodi Baxter of the Shellfish Division who supported the project as a whole.

Appendix: List of Management Options Examined

During the Oyster Advisory Commission (OAC) consensus process (February 2020 to November 2021), over 100 different management options for Maryland's oyster resource were examined. Two types of options were developed and examined by OAC:

- Management options that were modeled to predict the relative performance of oyster abundance, oyster harvest, and nitrogen removal and surface shell over 25 years.
- Management options that could not be modeled.

Each management option was rated by each commissioner as either being acceptable, having minor reservations, having major reservations, or not acceptable. Percent agreement was calculated for each option as being the sum of acceptable and minor reservation ratings divided by the total number for ratings for that option. It is important to note that non-voting members were able to rate each option, however, their ratings did not factor into the percent agreement. Also, not all commissioners rated every option. Individual commissioner ratings of each option can be found at: https://dnr.maryland.gov/fisheries/pages/mgmt-committees/oac-index.aspx

This appendix lists all the management options, both modeled and non-modeled, examined by OAC and the percent agreement to conduct the action in the future.

Modeled Options

Option 1: Status Quo (SQ)					
Description: The status quo option is set up to resemble the oyster management in Maryland during 2010-2020. All planting activity (i.e., shell, hatchery spat, wild seed, and alternate substrate) in this option is based on planting data from 2010-2020. The gear allowed on each bar, including bars that allow no gear (i.e., sanctuaries), is based on regulations during the 2019-2020 fishing season. The pattern of how fishing responds to oyster abundance is based on 2019. For the status quo there are no bars open to rotational harvest and there is no shell dredging on any bars.					
	% Agreement	# Acceptable	# Minor Reservations	# Major Reservations	# Not Acceptable
Voting Members	38%	3	3	3	7
Non-Voting Members	N/A	0	1	0	1

Option 2: Seed and Shell 2M bu/yr					
Description: The second option is designed to resemble the seed and shell program as it was conducted during 1991-2006. The amount of seed planted each year and the locations of plantings are based on historical data from 1991-2006. The gear allowed on each bar, including bars that allow no gear (i.e., sanctuaries), is the same as the status quo. There are no bars open to rotational harvest and there is no shell dredging on any bars.					
	% Agreement	# Acceptable	# Minor Reservations	# Major Reservations	# Not Acceptable
Voting Members	47%	7	1	1	8
Non-Voting Members	N/A	0	1	0	1

Option 3: Complete Restoration					
Description: This option is the same as the status quo except that restoration of the St. Mary's and Manokin Rivers is completed as described in the restoration blueprints.					
	% Agreement	# Acceptable	# Minor Reservations	# Major Reservations	# Not Acceptable
Voting Members	47%	6	2	7	2
Non-Voting Members	N/A	2	0	0	0

Option 4: SQ with 2018 Regs					
Description: This option is the same as the status quo except for the use of fishing regulations prior to the 2018-2019 season when bushel limits were modified and harvesting oysters was prohibited on Wednesdays.					
	% Agreement	# Acceptable	# Minor Reservations	# Major Reservations	# Not Acceptable
Voting Members	48%	8	2	2	9
Non-Voting Members	N/A	0	0	2	0

Option 5: SQ regs, no planting					
Description: This option is the same as the status quo except that all plantings (shell, spat on shell, wild seed, and artificial substrate) are stopped. This was done to examine the effect of planting activities similar to those planting activities done during 2010-2020 on oyster populations in Maryland.					
	% Agreement	# Acceptable	# Minor Reservations	# Major Reservations	# Not Acceptable
Voting Members	0%	0	0	0	21
Non-Voting Members	N/A	0	0	0	2

Option 6: Power dredging UB (Upper Bay)					
Description: This option is the same as the status quo except that power dredging is allowed on all oyster bars north of the Bay Bridge except those bars that are in sanctuaries.					
	% Agreement	# Acceptable	# Minor Reservations	# Major Reservations	# Not Acceptable
Voting Members	43%	7	2	3	9
Non-Voting Members	N/A	0	0	1	1

Option 7: Low harvest bars -> sanctuaries					
Description: This option is the same as the status quo except that all oyster bars with < 200 bushels of reported harvest during 1999-2020 were placed into sanctuaries.					
	% Agreement	# Acceptable	# Minor Reservations	# Major Reservations	# Not Acceptable
Voting Members	0%	0	0	5	16
Non-Voting Members	N/A	0	0	2	0

Option 8: Open non-restoration sanctuaries					
Description: This option is the same as the status quo except that all oyster bars except for those bars in sanctuaries in large scale restoration tributaries (i.e., Harris Creek, Tred Avon, Little Choptank, Manokin, St. Mary's) are opened to hand tonging.					
	% Agreement	# Acceptable	# Minor Reservations	# Major Reservations	# Not Acceptable
Voting Members	43%	6	3	1	11
Non-Voting Members	N/A	0	1	0	1

Option 9: Spat in UB sanctuaries					
Description: This option is the same as the status quo except that all oyster bars above the Bay Bridge receive a one time planting of hatchery spat. The planting is done on three bars each year spending $500,000 total until all bars are planted once.					
	% Agreement	# Acceptable	# Minor Reservations	# Major Reservations	# Not Acceptable
Voting Members	22%	0	4	5	9
Non-Voting Members	N/A	0	0	0	2

Option 10: Man O War Shoals 50% in Harvest					
Description: This option is the same as the status quo except the plan for dredging Man O War shoals is implemented as described in the permit application. There are 3 scenarios in the permit application for dividing the dredged shell among restoration and fishery areas. This option places 50% of dredge shell in restoration areas and 50% in public fishery areas. Dredging takes place every 3 years and 2 million bushels of shell are dredged each year and then all placed on oyster bars the same year.					
	% Agreement	# Acceptable	# Minor Reservations	# Major Reservations	# Not Acceptable
Voting Members	44%	6	2	3	7
Non-Voting Members	N/A	0	1	1	0

Option 11: Man O War Shoals 10% in Harvest					
Description: This option is the same as the status quo except the plan for dredging Man O War shoals is implemented as described in the permit application. There are 3 scenarios in the permit application for dividing the dredged shell among restoration and fishery areas. This option places 90% of dredge shell in restoration areas and 10% in harvest areas. Dredging takes place every 3 years and 2 million bushels of shell are dredged each year and then all placed on oyster bars the same year.					
	% Agreement	# Acceptable	# Minor Reservations	# Major Reservations	# Not Acceptable
Voting Members	10%	1	1	4	15
Non-Voting Members	N/A	0	0	0	2

Option 12: Man O War Shoals 75% in Harvest					
Description: This option is the same as the status quo except the plan for dredging Man O War shoals is implemented as described in the permit application. There are 3 scenarios in the permit application for dividing the dredged shell among restoration and fishery areas. This option places 25% of dredged shell in restoration areas and 75% in harvest areas. Dredging takes place every 3 years and 2 million bushels of shell are dredged each year and then all placed on oyster bars the same year.					
	% Agreement	# Acceptable	# Minor Reservations	# Major Reservations	# Not Acceptable
Voting Members	44%	8	0	2	8
Non-Voting Members	N/A	0	2	0	0

Option 13: Rotational harvest UB					
Description: This option is the same as the status quo except there are 4 bars in the middle Chester River that are open to rotational harvest. Each bar is open to harvest every four years with only one bar open to harvest in a given year. Each bar is planted with 10 million hatchery spat the year after it is closed to harvesting.					
	% Agreement	# Acceptable	# Minor Reservations	# Major Reservations	# Not Acceptable
Voting Members	78%	9	5	4	0
Non-Voting Members	N/A	1	1	0	0

Option 14: New restoration areas 1					
Description: This option is the same as the status quo except there is major restoration work in 5 additional tributaries. For each tributary, 8% of historic bottom is used as a proxy for how much area to restore. Hatchery spat is planted at a target density of 988 individuals per square meter and alternate substrate is planted at a target of 12 inches. The restoration sites in this option include areas in the Nanticoke River, Eastern Bay, South River, Hooper Strait (Tangier Sound), and Chester River.					
	% Agreement	# Acceptable	# Minor Reservations	# Major Reservations	# Not Acceptable
Voting Members	47%	6	2	3	6
Non-Voting Members	N/A	1	0	1	0

Option 15: New restoration areas 2					
Description: This option is the same as the status quo except there is major restoration work in 5 additional tributaries. For each tributary, 8% of historic bottom is used as a proxy for how much area to restore. Hatchery spat is planted at a target density of 988 individuals per square meter and alternate substrate is planted at a target of 12 inches. The restoration sites in this option include areas in the Nanticoke River, Point Lookout, Upper Patuxent, Upper Choptank, and Hooper's Strait.					
	% Agreement	# Acceptable	# Minor Reservations	# Major Reservations	# Not Acceptable
Voting Members	48%	2	8	6	5
Non-Voting Members	N/A	1	0	0	1

Option 16: New restoration areas 3					
Description: This option is the same as the status quo except there is major restoration work in 5 additional tributaries. For each tributary, 8% of historic bottom is used as a proxy for how much area to restore. Hatchery spat is planted at a target density of 988 individuals per square meter and alternate substrate is planted at a target of 12 inches. The restoration sites in this option include poor performing sanctuaries in Herring Bay, Lower Chester, Calvert Shore, Miles River, and Wye River.					
	% Agreement	# Acceptable	# Minor Reservations	# Major Reservations	# Not Acceptable
Voting Members	33%	2	5	9	5
Non-Voting Members	N/A	1	0	0	1

Option 17: Sanctuary plantings option A					
Description: This option is the same as the status quo except restoration activity (i.e. hatchery spat and alternate substrate planting) is increased in all sanctuaries that are not part of the large-scale restoration tributaries. The target density for hatchery spat is 2 million per acre and the total amount spent each year on hatchery spat is the cost equivalent of 500,000 bushels of shell. No alternate substrate is planted in this option.					
	% Agreement	# Acceptable	# Minor Reservations	# Major Reservations	# Not Acceptable
Voting Members	44%	1	7	8	2
Non-Voting Members	N/A	1	1	0	0

Option 18: Sanctuary plantings option B					
Description: This option is the same as the status quo except that restoration activity (i.e. hatchery spat and alternate substrate planting) is increased in all sanctuaries that are not part of the large-scale restoration tributaries. The target density for hatchery spat is 2 million per acre and the total amount spent each year on hatchery spat is the cost equivalent of 1 million bushels of shell. No alternate substrate is planted in this option.					
	% Agreement	# Acceptable	# Minor Reservations	# Major Reservations	# Not Acceptable
Voting Members	45%	7	2	7	4
Non-Voting Members	N/A	0	2	0	0

Option 19: Sanctuary plantings option C					
Description: This option is the same as the status quo except restoration activity (i.e. hatchery spat and alternate substrate planting) is increased in all sanctuaries that are not part of the large-scale restoration tributaries. The target density for hatchery spat is 2 million per acre. For this option, each sanctuary gets planted with spat on shell every four years. This results in about 996 acres planted annually. No alternate substrate is planted in this option.					
	% Agreement	# Acceptable	# Minor Reservations	# Major Reservations	# Not Acceptable
Voting Members	39%	4	3	5	6
Non-Voting Members	N/A	0	2	0	0

Option 20: Sanctuary plantings option D					
Description: This option is the same as the status quo except that restoration activity (i.e., hatchery spat and alternate substrate planting) is increased in all sanctuaries that are not part of the large-scale restoration tributaries. The target density for hatchery spat is 2 million per acre and target height for artificial substrate is 6 inches. For this option, the amount spent each year is the cost equivalent of 500,000 bushels of shell, which is split evenly between hatchery spat and alternate substrate.					
	% Agreement	# Acceptable	# Minor Reservations	# Major Reservations	# Not Acceptable
Voting Members	45%	5	4	7	4
Non-Voting Members	N/A	0	1	1	0

Option 21: Sanctuary plantings option E					
Description: This option is the same as the status quo except restoration activity (i.e, hatchery spat and alternate substrate planting) is increased in all sanctuaries that are not part of the large-scale restoration tributaries. The target density for hatchery spat is 2 million per acre and the target height for artificial substrate is 6 inches. For this option, the amount spent each year is the cost equivalent of 1 million bushels of shell, which is split evenly between hatchery spat and alternate substrate.					
	% Agreement	# Acceptable	# Minor Reservations	# Major Reservations	# Not Acceptable
Voting Members	45%	6	3	7	4
Non-Voting Members	N/A	1	0	1	0

Option 22: Sanctuary plantings option F					
Description: This option is the same as the status quo except restoration activity (i.e. hatchery spat and alternate substrate planting) is increased in all sanctuaries that are not part of the large-scale restoration tributaries. For this option, alternate substrate is placed in medium-high salinity sanctuaries at a target height of 6 inches. The amount spent each year is the cost equivalent of 500,000 bushels of shell. No hatchery spat is planted in this option.					
	% Agreement	# Acceptable	# Minor Reservations	# Major Reservations	# Not Acceptable
Voting Members	45%	5	4	5	6
Non-Voting Members	N/A	1	0	1	0

Option 23: Sanctuary plantings option G					
Description: This option is the same as the status quo except restoration activity (i.e. hatchery spat and alternate substrate planting) is increased in all sanctuaries that are not part of the large-scale restoration tributaries. For this option, alternate substrate is placed in medium-high salinity sanctuaries at a target height of 6 inches. The amount spent each year is the cost equivalent of 1 million bushels of shell. No hatchery spat is planted in this option.					
	% Agreement	# Acceptable	# Minor Reservations	# Major Reservations	# Not Acceptable
Voting Members	45%	3	6	5	6
Non-Voting Members	N/A	1	0	1	0

Option 24: 30% bottom in sanctuaries					
Description: This option is the same as the status quo except that the total amount of area in sanctuaries is increased from 24% to 30%. The additional 6% was not selected from the fishery 'best bars', but was high quality bottom. A total of 19,270 acres was placed into sanctuaries.					
	% Agreement	# Acceptable	# Minor Reservations	# Major Reservations	# Not Acceptable
Voting Members	25%	0	5	3	12
Non-Voting Members	N/A	0	0	1	1

Option 25: No fishing (no oyster harvest) and no plantings					
Description: In this option all public fishery areas are changed to sanctuaries, and no planting is done.					
	% Agreement	# Acceptable	# Minor Reservations	# Major Reservations	# Not Acceptable
Voting Members	0%	0	0	2	18
Non-Voting Members	N/A	0	0	0	2

Option 26: Everything open to fishing (oyster harvest)					
Description: This option is the same as the status quo except all oyster bars are open to fishing (oyster harvest). The gear assigned to each bar was based on the gear with the greatest reported harvest or the gear assigned to the nearest bar if no harvest was reported. Areas with artificial substrate present were assigned diver as the harvest gear.					
	% Agreement	# Acceptable	# Minor Reservations	# Major Reservations	# Not Acceptable
Voting Members	20%	1	3	0	16
Non-Voting Members	N/A	0	0	0	2

Option 27: 4-yr rotational harvest by region					
Description: All oyster bars not in sanctuaries in the large-scale restoration tributaries (i.e., Harris Creek, Tred Avon, Little Choptank, Manokin, St. Mary's) are open to harvest on a rotating schedule with 25% of bars open each year. In this option, the Maryland portion of the bay is divided into 4 different regions, which all are composed of multiple NOAA Codes. Within each region, all bars within a NOAA Code are open to harvest every four years.					
	% Agreement	# Acceptable	# Minor Reservations	# Major Reservations	# Not Acceptable
Voting Members	11%	1	1	2	14
Non-Voting Members	N/A	0	0	0	2

Option 28: 4-yr rotational harvest in NOAA codes					
Description: All oyster bars not in sanctuaries in the large-scale restoration tributaries (i.e., Harris Creek, Tred Avon, Little Choptank, Manokin, St. Mary's) are open to harvest on a rotating schedule. In this option, 25% of bars within each NOAA Code are opened to harvest every four years on a rotating schedule. The bars are chosen randomly based on the reported harvest during 2010-2018 monthly harvester reports.					
	% Agreement	# Acceptable	# Minor Reservations	# Major Reservations	# Not Acceptable
Voting Members	11%	1	1	2	14
Non-Voting Members	N/A	0	0	0	2

Option 29: Opt. 27 + shell and spat					
Description: All oyster bars not in sanctuaries in the large scale restoration tributaries (i.e., Harris Creek, Tred Avon, Little Choptank, Manokin, St. Mary's) are open to harvest on a rotating schedule with 25% of bars open each year and bars are replanted with shell and hatchery spat after they are closed to harvesting. In this option, the Maryland portion of the bay is divided into 4 different regions, which all are composed of multiple NOAA Codes. Within each region, all bars within a NOAA Code are open to harvest every four years. Replanting occurs after a bar is closed and each year there are 250,000 bushels of shell and 400 million hatchery spat planted on bars that recently closed to harvest.					
	% Agreement	# Acceptable	# Minor Reservations	# Major Reservations	# Not Acceptable
Voting Members	24%	2	3	3	13
Non-Voting Members	N/A	0	0	0	2

Option 30: Opt. 28 + shell and spat					
Description: This option is the same as the status quo except all oyster bars not in sanctuaries in the large-scale restoration tributaries (i.e., Harris Creek, Tred Avon, Little Choptank, Manokin, St. Mary's) are open to harvest on a rotating schedule. In this option, 25% of bars within each NOAA Code are opened to harvest every four years on a rotating schedule. The bars are chosen randomly based on the reported harvest during 2010-2018 monthly harvester reports. Replanting occurs after a bar is closed and each year there are 250,000 bushels of shell and 400 million hatchery spat planted on bars that recently closed to harvest.					
	% Agreement	# Acceptable	# Minor Reservations	# Major Reservations	# Not Acceptable
Voting Members	24%	2	3	3	13
Non-Voting Members	N/A	0	0	0	2

Option 31: Constrain to target fishing rates					
Description: This option is the same as the status quo except harvest in each NOAA Code is limited to the target fishing rates from the Maryland Oyster Stock Assessment.					
	% Agreement	# Acceptable	# Minor Reservations	# Major Reservations	# Not Acceptable
Voting Members	43%	6	3	5	7
Non-Voting Members	N/A	0	2	0	1

Option 32: Constrain to 75% target fishing rates					
Description: This option is the same as the status quo except harvest in each NOAA Code is limited to 75% of the target fishing rates from the Maryland Oyster Stock Assessment.					
	% Agreement	# Acceptable	# Minor Reservations	# Major Reservations	# Not Acceptable
Voting Members	40%	6	2	4	8
Non-Voting Members	N/A	0	1	1	0

Option 33: Seed and Shell 1M bu/yr					
Description: This option is the same as Option 2, except the amount of shell planted is 1 million bushels per year.					
	% Agreement	# Acceptable	# Minor Reservations	# Major Reservations	# Not Acceptable
Voting Members	43%	7	2	6	6
Non-Voting Members	N/A	0	1	1	0

Option 34: Seed and Shell 500k bu/yr					
Description: This option is the same as Option 2, except the amount of shell planted is 500,000 bushels per year.					
	% Agreement	# Acceptable	# Minor Reservations	# Major Reservations	# Not Acceptable
Voting Members	33%	3	4	7	7
Non-Voting Members	N/A	0	1	1	0

Option 35: 14.a - 14 except using shell as substrate					
Description: This option is the same as option 14 except shell is used for restoration activities instead of artificial substrate.					
	% Agreement	# Acceptable	# Minor Reservations	# Major Reservations	# Not Acceptable
Voting Members	37%	1	6	7	5
Non-Voting Members	N/A	0	1	1	0

Option 36: 15.a - 15 except using shell as substrate					
Description: This option is the same as option 15 except shell is used for restoration activities instead of artificial substrate.					
	% Agreement	# Acceptable	# Minor Reservations	# Major Reservations	# Not Acceptable
Voting Members	38%	1	7	7	6
Non-Voting Members	N/A	0	1	1	0

Option 37: 16.a - 16 except using shell as substrate					
Description: This option is the same as option 16 except shell is used for restoration activities instead of artificial substrate.					
	% Agreement	# Acceptable	# Minor Reservations	# Major Reservations	# Not Acceptable
Voting Members	33%	1	6	7	7
Non-Voting Members	N/A	0	1	1	0

Option 38: Little Choptank rotation with $600,000 spat on shell/yr					
Description: This option is the same as the status quo except there is a rotating harvest schedule for oyster bars in the tributaries (prongs) of the Little Choptank sanctuary where no restoration work was completed. There are a total of 7 bars used with all bars open for harvest every 2 years and planted with the equivalent of $600,000 worth of hatchery spat after they are closed to harvest. The bars are divided up so that 3 bars are open all together in one year, and the other 4 bars are open to harvest the following year.					
	% Agreement	# Acceptable	# Minor Reservations	# Major Reservations	# Not Acceptable
Voting Members	52%	9	2	4	6
Non-Voting Members	N/A	1	1	0	0

Option 39: Little Choptank rotation with $600,000 shell/yr					
Description: This option is the same as the status quo except there is a rotating harvest schedule for oyster bars in the tributaries (prongs) of the Little Choptank sanctuary where no restoration work was completed. There are a total of 7 bars used with all bars open for harvest every 2 years and planted with the equivalent of $600,000 worth of shell after they are closed to harvest. The bars are divided up so that 3 bars are open all together in one year, and the other 4 bars are open to harvest the following year.					
	% Agreement	# Acceptable	# Minor Reservations	# Major Reservations	# Not Acceptable
Voting Members	52%	9	2	4	6
Non-Voting Members	N/A	1	1	0	0

Option 40: Little Choptank rotation with $150,000 spat on shell/yr					
Description: This option is the same as the status quo except there is a rotating harvest schedule for oyster bars in the tributaries (prongs) of the Little Choptank sanctuary where no restoration work was completed. There are a total of 7 bars used with all bars open for harvest every 2 years and planted with the equivalent of $150,000 worth of hatchery spat after they are closed to harvest. The bars are divided up so that 3 bars are open all together in one year, and the other 4 bars are open to harvest the following year.					
	% Agreement	# Acceptable	# Minor Reservations	# Major Reservations	# Not Acceptable
Voting Members	48%	7	3	3	8
Non-Voting Members	N/A	1	0	1	0

Option 41: Little Choptank rotation with $150,000 shell/yr					
Description: This option is the same as the status quo except there is a rotating harvest schedule for oyster bars in the tributaries (prongs) of the Little Choptank sanctuary where no restoration work was completed. There are a total of 7 bars used with all bars open for harvest every 2 years and planted with the equivalent of $150,000 worth of shell after they are closed to harvest. The bars are divided up so that 3 bars are open all together in one year, and the other 4 bars are open to harvest the following year.					
	% Agreement	# Acceptable	# Minor Reservations	# Major Reservations	# Not Acceptable
Voting Members	45%	5	4	3	8
Non-Voting Members	N/A	1	0	1	0

Option 42: Eastern Bay $1M for rest. (spat), $500K fishery (shell and spat)					
Description: This option is the same as the status quo except there is additional shell and hatchery seed plantings on sanctuary and fishery bars in Eastern Bay. For this option $1,000,000 was spent each year on planting hatchery spat in sanctuaries with 250 million hatchery spat planted annually at 6 million per acre. An additional $500,000 was spent each year on planting shell and hatchery spat in public fishery areas: $200,000 was spent on planting 50 million hatchery spat at 1 million per acre, and $300,000 was spent on planting 30 acres with shell at 2000 bushels per acre.					
	% Agreement	# Acceptable	# Minor Reservations	# Major Reservations	# Not Acceptable
Voting Members	81%	6	11	2	2
Non-Voting Members	N/A	2	0	0	0

Option 43: Eastern Bay $1M for rest. (spat), $1M fishery (shell and spat)					
Description: This option is the same as the status quo except there is additional shell and hatchery seed plantings on sanctuary and fishery bars in Eastern Bay. For this option $1,000,000 was spent each year on planting hatchery spat in sanctuaries with 250 million hatchery spat planted annually at 6 million per acre. An additional $1,000,000 was spent each year on planting shell and hatchery spat in public fishery areas: $400,000 was spent on planting 100 million hatchery spat at 1 million per acre, and $600,000 was spent on planting 60 acres with shell at 2000 bushels per acre.					
	% Agreement	# Acceptable	# Minor Reservations	# Major Reservations	# Not Acceptable
Voting Members	86%	8	10	1	2
Non-Voting Members	N/A	2	0	0	0

Option 44: Combo 19 + 3					
Description: This option is a combination of options 19 (Sanc. plantings option C) and 3 (Complete Restoration).					
	% Agreement	# Acceptable	# Minor Reservations	# Major Reservations	# Not Acceptable
Voting Members	45%	6	3	7	4
Non-Voting Members	N/A	0	2	0	0

Option 45: Combo 14 + 3					
Description: This option is a combination of options 14 (New restoration areas 1) and 3 (Complete Restoration).					
	% Agreement	# Acceptable	# Minor Reservations	# Major Reservations	# Not Acceptable
Voting Members	43%	7	2	6	6
Non-Voting Members	N/A	0	1	1	0

Option 46: Combo 19 + 3 + 31					
Description: This option is a combination of options 19 (Sanc. plantings option C), 3 (Complete Restoration), and 31 (Constrain to target fishing rates).					
	% Agreement	# Acceptable	# Minor Reservations	# Major Reservations	# Not Acceptable
Voting Members	43%	6	3	4	8
Non-Voting Members	N/A	0	0	2	0

Option 47: Combo 14 + 3 + 31					
Description: This option is a combination of options 14 (New restoration areas 1), 3 (Complete Restoration), and 31 (Constrain to target fishing rates).					
	% Agreement	# Acceptable	# Minor Reservations	# Major Reservations	# Not Acceptable
Voting Members	38%	6	2	4	9
Non-Voting Members	N/A	0	0	2	0

Option 48: Combo 21 + 3					
Description: This option is a combination of options 21 (Sanc. plantings option E) and 3 (Complete Restoration).					
	% Agreement	# Acceptable	# Minor Reservations	# Major Reservations	# Not Acceptable
Voting Members	43%	7	2	2	10
Non-Voting Members	N/A	1	0	1	0

Option 49: Combo 21 + 3 + 31					
Description: This option is a combination of options 21 (Sanc. plantings option E), 3 (Complete Restoration), and 31 (Constrain to target fishing rates).					
	% Agreement	# Acceptable	# Minor Reservations	# Major Reservations	# Not Acceptable
Voting Members	43%	6	3	2	10
Non-Voting Members	N/A	0	0	2	0

Option 50: 2.a Seed and Shell (no seed)					
Description: This option is the same as option 2, but no natural seed is removed or planted.					
	% Agreement	# Acceptable	# Minor Reservations	# Major Reservations	# Not Acceptable
Voting Members	38%	5	3	7	6
Non-Voting Members	N/A	0	1	0	1

Option 51: 33.a Seed and Shell $1M (no seed)					
Description: This option is the same as option 33, but no natural seed is removed or planted.					
	% Agreement	# Acceptable	# Minor Reservations	# Major Reservations	# Not Acceptable
Voting Members	38%	4	4	4	9
Non-Voting Members	N/A	0	0	1	1

Option 52: 34.a Seed and Shell $500K (no seed)					
Description: This option is the same as option 34, but no natural seed is removed or planted.					
	% Agreement	# Acceptable	# Minor Reservations	# Major Reservations	# Not Acceptable
Voting Members	38%	3	5	1	12
Non-Voting Members	N/A	0	0	1	1

Option 53: Combo 3 + 7					
Description: This option is a combination of options 3 (Complete Restoration) and 7 (Low harvest bars -> sanctuaries).					
	% Agreement	# Acceptable	# Minor Reservations	# Major Reservations	# Not Acceptable
Voting Members	48%	1	9	1	10
Non-Voting Members	N/A	0	1	1	0

Option 54: Rotational harvest Upper Bay sanctuary (no planting)					
Description: This option is the same as the status quo, except all sanctuaries (Upper Chester River, Chester ORA, Lower Chester River, Man-O-War Shoals, and Magothy) above the bay bridge are removed and converted to public fishery areas with a rotating harvest schedule. Each bar is open every 4 years, with different bars open during different years so there are always some bars open to harvest in a given year.					
	% Agreement	# Acceptable	# Minor Reservations	# Major Reservations	# Not Acceptable
Voting Members	25%	2	3	5	10
Non-Voting Members	N/A	0	0	1	1

Option 55: Rotational harvest Upper Bay sanctuary (w/ spat)					
Description: This option is the same as the status quo, except all sanctuaries (Upper Chester River, Chester ORA, Lower Chester River, Man-O-War Shoals, and Magothy) above the bay bridge are removed and converted to public fishery areas with a rotating harvest schedule. Each bar is open every 4 years, with different bars open during different years so there are always some bars open to harvest in a given year. In this option, each bar is planted with hatchery spat the year after it is open to fishing. Hatchery spat are planted at a density of 1 million per acre, and only up to 50 million are planted on each bar.					
	% Agreement	# Acceptable	# Minor Reservations	# Major Reservations	# Not Acceptable
Voting Members	43%	4	5	3	9
Non-Voting Members	N/A	0	1	0	1

Option 56: Remove low productivity sanctuaries (categories C&D)					
Description: This option is the same as the status quo except low performing sanctuaries (categories C & D) are removed and converted to public fishery areas. Data on the rank of each sanctuary from the MD DNR Oyster Management Review 2016-2020 [@MDDNR2021] was used to select poor performing sanctuaries that were converted to public fishery areas.					
	% Agreement	# Acceptable	# Minor Reservations	# Major Reservations	# Not Acceptable
Voting Members	38%	3	5	5	8
Non-Voting Members	N/A	0	0	0	2

Option 57: Remove low productivity sanctuaries (replace w/ other bottom)					
Description: This option is the same as the status quo except low performing sanctuaries (categories C & D) are removed and converted to public fishery areas and then sanctuary area increased back to 20%. The new sanctuary area was not selected from the fishery 'best bars', but did have high quality bottom. Data on the rank of each sanctuary from the MD DNR Oyster Management Review 2016-2020 [@MDDNR2021] was used to select poor performing sanctuaries that were converted to public fishery areas.					
	% Agreement	# Acceptable	# Minor Reservations	# Major Reservations	# Not Acceptable
Voting Members	14%	1	2	4	14
Non-Voting Members	N/A	0	0	0	2

Option 58: Low productivity sanctuaries become rotational areas (categories C&D)					
Description: This option is the same as the status quo except low performing sanctuaries (categories C & D) are removed and converted to public fishery areas on a rotationg harvest schedule. Data on the rank of each sanctuary from the MD DNR Oyster Management Review 2016-2020 [@MDDNR2021] was used to select poor performing sanctuaries that were converted to public fishery areas. Each bar in the rotating harvest schedule was open once every five years, and the year a given bar was open was chosen so there were bars open for harvest each year. There were no plantings after a bar had been opened to harvest.					
	% Agreement	# Acceptable	# Minor Reservations	# Major Reservations	# Not Acceptable
Voting Members	29%	4	2	5	10
Non-Voting Members	N/A	0	0	0	2

Option 59: Upper Patuxent sanctuary to 4 yr. rotational harvest (no planting)					
Description: This option is the same as the status quo except sanctuary areas in the upper Patuxent River were converted to public fishery areas on a rotating harvest schedule. Each bar is open every 4 years, with different bars open during different years so there are always some bars open to harvest in a given year. There were no plantings after a bar had been opened to harvest.					
	% Agreement	# Acceptable	# Minor Reservations	# Major Reservations	# Not Acceptable
Voting Members	33%	2	5	5	9
Non-Voting Members	N/A	0	0	0	2

Option 60: Upper Patuxent sanctuary to 4 yr. rotational harvest (spat)					
Description: This option is the same as the status quo except sanctuary areas in the upper Patuxent River were converted to public fishery areas on a rotating harvest schedule. Each bar is open every 4 years, with different bars open during different years so there are always some bars open to harvest in a given year. After being open to harvest, bars were planted with hatchery spat at a density of 1 million individuals per acre.					
	% Agreement	# Acceptable	# Minor Reservations	# Major Reservations	# Not Acceptable
Voting Members	48%	6	4	3	8
Non-Voting Members	N/A	0	0	2	0

Option 61: All 51 sanctuaries open to public fishery					
Description: This option is the same as the status quo except that all sanctuaries are converted to public fishery areas (same as option 26).					
	% Agreement	# Acceptable	# Minor Reservations	# Major Reservations	# Not Acceptable
Voting Members	43%	8	1	0	12
Non-Voting Members	N/A	0	0	0	2

Option 62: All 51 sanctuaries open to public fishery as rotational areas					
Description: This option is the same as the status quo except all sanctuaries are converted to public fishery areas on a rotating harvest schedule. Each bar is open every 4 years, with different bars open during different years so there are always some bars open to harvest in a given year. There were no plantings after a bar had been opened to harvest.					
	% Agreement	# Acceptable	# Minor Reservations	# Major Reservations	# Not Acceptable
Voting Members	43%	7	2	2	10
Non-Voting Members	N/A	0	0	0	2

Option 63: Combo 2+3+4+13+14 (some options modified)					
Description: This option is a combination of options 2, 3, 4, 13, and 14 with some modifications. Option 3 is included with the addition of the completion of the St. Mary's and Manokin Rivers using only shell and hatchery seed. Gear allowed on each bar, including bars that allow no gear (i.e., sanctuaries) are based on the 2019-2020 fishing season except for the Upper Bay. Option 14 is included with restoration in Eastern Bay, South River, Severn, Upper Patuxent River, Herring Bay, with no alternative substrate used in restoration activities. Option 4 was included with 2018 fishing regulations: 5 days a week fishing and pre-2019 bushel limits for all gears. The author of this option intended for shell to be recovered from low performing oyster bars, but it was not possible to implement in the model. Therefore, the option assumes enough shell is available for the management. Hatchery spat on shell and wild Seed from Virginia are planted in public fishery areas. All sanctuary bars north of the Bay Bridge are converted to public fishery areas, and all bars in the upper bay are placed in a rotating harvest schedule with 25% of bars open every four years. Each bar is planted with hatchery seed at a density of 1 million per acre with a maximum of 50 million individuals planted on a bar in a given year.					
	% Agreement	# Acceptable	# Minor Reservations	# Major Reservations	# Not Acceptable
Voting Members	52%	6	5	5	5
Non-Voting Members	N/A	0	1	1	0

Option 64: Combo 2+3+14+54+59 (w/ modifications)					
Description: This option is a combination of options 2, 3, 14, 15, 54, and 59 with some modifications. This option includes completion of the St. Mary's and Manokin Rivers using only shell and hatchery seed. Complete large-scale restoration in the following current sanctuaries: Severn, South, Herring Bay, Up. Choptank & ORA, Breton Bay, Miles, Calvert Shore. Remove Up Patuxent sanctuary and do rotational harvest with out-of-state seed and SOS replenishment plantings. Remove all sanctuaries above Bay Bridge and conduct a rotational harvest schedule with replenishment on a 4 yr cycle. Remove Wicomico River West sanctuaries, and conduct rotational harvest with out-of-state seed and spat on shell replenishment plantings on a 4 yr cycle. Conduct the old shell program (no seed) on fishery bars in med-high salinity areas of Dorchester, St Marys, Calvert, Somerset, Wicomico, Talbot. Conduct the old seed program (out-of-state seed and spat on shell) in low-med areas of Kent, Baltimore, Charles, Anne Arundel, and Queen Annes fishery bars. Uses pre-2019 fishing regulations.					
	% Agreement	# Acceptable	# Minor Reservations	# Major Reservations	# Not Acceptable
Voting Members	38%	6	2	8	5
Non-Voting Members	N/A	0	0	1	1

Option 65: 3 + Rotational harvest in unrestored part of Manokin					
Description: This option is the same as the status quo except some oyster bars in the Manokin River are converted to public fishery areas on a rotating harvest schedule. There are a total of 7 bars used in the rotating harvest schedule with all bars open for harvest every 2 years. Four bars are open in year one, and the remaining three bars are open in the second year. All bars converted to public fishery areas do not have any planned restoration activity. There were no plantings after a bar had been opened to harvest.					
	% Agreement	# Acceptable	# Minor Reservations	# Major Reservations	# Not Acceptable
Voting Members	42%	3	2	2	5
Non-Voting Members	N/A	0	0	1	1

Option 66: 2 with seed from VA					
Description: This option is the same as option 2 except that all seed planted is either seed from Virginia or hatchery seed.					
	% Agreement	# Acceptable	# Minor Reservations	# Major Reservations	# Not Acceptable
Voting Members	62%	10	3	3	5
Non-Voting Members	N/A	0	1	1	0

Option 67: Sanctuary seed areas					
Description: This option is the same as the status quo except some oyster bars in sanctuaries in the Honga, Naticoke, and Manokin Rivers, are used as seed bars for planting of wild seed on other bars throughout Maryland. A total of seven bars are used as seed bars. On these bars, wild seed is removed every seven years, and prior to the year of removal 40,000 bushels of shell are planted on each bar. The seed removed from these bars are planted in Eastern Bay, the mainstem, the lower and mid Choptank River, Tred Avon River, Miles River, the lower Patuxent River, the South River, and the Wicomico River. All wild seed is planted in public fishery areas.					
	% Agreement	# Acceptable	# Minor Reservations	# Major Reservations	# Not Acceptable
Voting Members	60%	11	1	1	7
Non-Voting Members	N/A	1	0	0	1

Option 68: SOAR plant aquaculture adults in sanctuaries					
Description: This option is the same as the status quo except oysters are purchased from aquaculture operations and planted in sanctuaries. For this option, there are 2 million small oysters (> 1 year old and less than 3 inches long) planted each year. The plantings are divided evenly among 10 sanctuary bars each year.					
	% Agreement	# Acceptable	# Minor Reservations	# Major Reservations	# Not Acceptable
Voting Members	48%	4	6	4	7
Non-Voting Members	N/A	0	1	1	0

Option 69: Combo 10 + 33					
Description: This option is a combination of options 10 (Man O War Shoals 50% in Harvest) and 33 (Seed and Shell 1M bu/yr).					
	% Agreement	# Acceptable	# Minor Reservations	# Major Reservations	# Not Acceptable
Voting Members	57%	8	4	4	5
Non-Voting Members	N/A	0	1	1	0

Note: there is no model option # 70

Option 71: Combo 16 + 33					
Description: This option is a combination of options 16 (New restoration areas 3) and 33 (Seed and Shell 1M bu/yr).					
	% Agreement	# Acceptable	# Minor Reservations	# Major Reservations	# Not Acceptable
Voting Members	19%	1	3	7	10
Non-Voting Members	N/A	0	0	1	1

Option 72: Combo 31 + 33					
Description: This option is a combination of options 31 (Constrain to target fishing rates) and 33 (Seed and Shell 1M bu/yr).					
	% Agreement	# Acceptable	# Minor Reservations	# Major Reservations	# Not Acceptable
Voting Members	0%	0	0	4	17
Non-Voting Members	N/A	0	0	1	1

Option 73: Combo 32 + 33					
Description: This option is a combination of options 32 (Constrain to 75% target fishing rates) and 33 (Seed and Shell 1M bu/yr).					
	% Agreement	# Acceptable	# Minor Reservations	# Major Reservations	# Not Acceptable
Voting Members	5%	1	0	2	18
Non-Voting Members	N/A	0	0	1	1

Option 74: Opt 10 but use 7 Foot Knoll (500k bu/yr)					
Description: This option is the same as the status quo except Seven Foot Knoll is dredged every 2 years. Each time dredging takes place there are 500,000 bushels of shell removed. Fifty percent of the dredged shell is planted in public fishery areas and 50% is planted in sanctuaries.					
	% Agreement	# Acceptable	# Minor Reservations	# Major Reservations	# Not Acceptable
Voting Members	35%	3	4	5	8
Non-Voting Members	N/A	0	0	1	1

Non-Modeled Options

Option A.1: DNR should evaluate and develop cost effective strategies for identifying sources of shells and substrate.					
	% Agreement	# Acceptable	# Minor Reservations	# Major Reservations	# Not Acceptable
Voting Members	100%	15	10	0	0
Non-Voting Members	N/A	3	0	0	0

Option A.2: DNR should review the current state regulations and evaluate potential strategies, including providing economic incentives to retain shell in the state of Maryland and to reuse it.					
	% Agreement	# Acceptable	# Minor Reservations	# Major Reservations	# Not Acceptable
Voting Members	100%	13	12	0	0
Non-Voting Members	N/A	2	1	0	0

Option A.3: DNR should support a Bay-wide substrate committee to evaluate strategies and costs for substrate enhancement.					
	% Agreement	# Acceptable	# Minor Reservations	# Major Reservations	# Not Acceptable
Voting Members	64%	8	8	7	2
Non-Voting Members	N/A	0	2	1	0

Option A.3a: DNR should support a Bay-wide (MD) substrate action subcommittee of OAC to evaluate strategies, costs, and benefits for substrate.					
	% Agreement	# Acceptable	# Minor Reservations	# Major Reservations	# Not Acceptable
Voting Members	68%	7	10	7	1
Non-Voting Members	N/A	0	3	0	0

Option A.4: DNR should conduct pilot projects to study the efficiency of different substrates (e.g., small stones and mixed shell) and the effect of height and sedimentation rates.					
	% Agreement	# Acceptable	# Minor Reservations	# Major Reservations	# Not Acceptable
Voting Members	64%	4	12	8	1
Non-Voting Members	N/A	1	0	0	2

Option A.5: DNR should evaluate the costs/benefits of dredging Man-O-War Shoals.					
	% Agreement	# Acceptable	# Minor Reservations	# Major Reservations	# Not Acceptable
Voting Members	60%	10	5	3	7
Non-Voting Members	N/A	0	0	3	0

Option A.6: DNR should use bagless dredging to clean shell in preparation for spat sets.					
	% Agreement	# Acceptable	# Minor Reservations	# Major Reservations	# Not Acceptable
Voting Members	64%	8	8	8	1
Non-Voting Members	N/A	0	0	3	0

Option A.7: DNR should use bar cleaning (done with a dredge with the bag on it) to clean shell in preparation for spat sets.					
	% Agreement	# Acceptable	# Minor Reservations	# Major Reservations	# Not Acceptable
Voting Members	56%	10	4	9	2
Non-Voting Members	N/A	0	1	2	0

Option A.7a: OAC should work with DNR to create a collaborative broad-scale study to evaluate bar cleaning (done with a dredge with the bag on it) to clean shell in harvest areas in preparation for spat.					
	% Agreement	# Acceptable	# Minor Reservations	# Major Reservations	# Not Acceptable
Voting Members	76%	13	6	6	0
Non-Voting Members	N/A	1	2	0	0

Option B.1: Begin electronic daily harvest reporting.					
	% Agreement	# Acceptable	# Minor Reservations	# Major Reservations	# Not Acceptable
Voting Members	84%	10	11	3	1
Non-Voting Members	N/A	2	1	0	0

Option B.2: Monitor effort using vessel monitoring systems or hail-in hail-out systems.					
	% Agreement	# Acceptable	# Minor Reservations	# Major Reservations	# Not Acceptable
Voting Members	68%	7	10	3	5
Non-Voting Members	N/A	1	1	1	0

Option B.2a: Monitor effort using hail-in hail-out systems.					
	% Agreement	# Acceptable	# Minor Reservations	# Major Reservations	# Not Acceptable
Voting Members	68%	7	10	3	5
Non-Voting Members	N/A	1	1	1	0

Option B.3: Enhance marker systems to mark navigation hazards and oyster management boundaries.					
	% Agreement	# Acceptable	# Minor Reservations	# Major Reservations	# Not Acceptable
Voting Members	71%	6	11	6	1
Non-Voting Members	N/A	0	2	1	0

Option B.3a: Develop tools to mark navigation hazards and oyster management boundaries.					
	% Agreement	# Acceptable	# Minor Reservations	# Major Reservations	# Not Acceptable
Voting Members	79%	6	13	4	1
Non-Voting Members	N/A	0	2	1	0

Option B.4: Update the Fall Dredge Survey (e.g., new locations, fall dredge survey before start of fishery, cooperative survey with industry).					
	% Agreement	# Acceptable	# Minor Reservations	# Major Reservations	# Not Acceptable
Voting Members	84%	8	13	3	1
Non-Voting Members	N/A	1	1	1	0

Option C.1: Use catch shares.					
	% Agreement	# Acceptable	# Minor Reservations	# Major Reservations	# Not Acceptable
Voting Members	44%	3	8	6	8
Non-Voting Members	N/A	0	0	1	0

Option C.2: Develop fishery or aquaculture co-ops with shared equipment and/or shared plantings (particularly in areas with low current spat set).					
	% Agreement	# Acceptable	# Minor Reservations	# Major Reservations	# Not Acceptable
Voting Members	56%	6	8	7	4
Non-Voting Members	N/A	1	2	0	0

Option C.3: Use stratified fishing rights with different license types that allow harvest with different gears (similar to crabs).					
	% Agreement	# Acceptable	# Minor Reservations	# Major Reservations	# Not Acceptable
Voting Members	56%	4	10	7	4
Non-Voting Members	N/A	0	0	1	0

Option C.4: Manage using quotas and in-season monitoring.					
	% Agreement	# Acceptable	# Minor Reservations	# Major Reservations	# Not Acceptable
Voting Members	56%	9	5	4	7
Non-Voting Members	N/A	0	0	1	0

Option C.5: Make annual changes in regulations in response to stock assessment.					
	% Agreement	# Acceptable	# Minor Reservations	# Major Reservations	# Not Acceptable
Voting Members	64%	8	8	8	1
Non-Voting Members	N/A	2	1	0	0

Option C.6: Develop better minimum abundance thresholds and more precautionary target harvest rate reference points.					
	% Agreement	# Acceptable	# Minor Reservations	# Major Reservations	# Not Acceptable
Voting Members	56%	10	4	8	3
Non-Voting Members	N/A	2	0	0	1

Option C.7: Consider limited entry or other actions to limit effort (e.g., attrition).					
	% Agreement	# Acceptable	# Minor Reservations	# Major Reservations	# Not Acceptable
Voting Members	63%	10	5	7	2
Non-Voting Members	N/A	1	2	0	0

Option D.1: Create reefball sanctuaries in areas that do not interfere with other uses.					
	% Agreement	# Acceptable	# Minor Reservations	# Major Reservations	# Not Acceptable
Voting Members	45%	3	6	6	5
Non-Voting Members	N/A	1	1	0	0

Option D.2: Permanent protection of sanctuaries.					
	% Agreement	# Acceptable	# Minor Reservations	# Major Reservations	# Not Acceptable
Voting Members	35%	3	4	3	10
Non-Voting Members	N/A	1	0	0	1

Option E.1: Improve organization and cooperation among groups and integrate projects across the 3 sectors (fishery, aquaculture, restoration).					
	% Agreement	# Acceptable	# Minor Reservations	# Major Reservations	# Not Acceptable
Voting Members	85%	10	7	3	0
Non-Voting Members	N/A	1	1	0	0

Option E.2: Improve processor capabilities and techniques (e.g., more shucking houses, develop frozen product).					
	% Agreement	# Acceptable	# Minor Reservations	# Major Reservations	# Not Acceptable
Voting Members	100%	15	5	0	0
Non-Voting Members	N/A	1	1	0	0

Option E.3: Use bars in the north as “investments” against disease outbreaks in lower Bay.					
	% Agreement	# Acceptable	# Minor Reservations	# Major Reservations	# Not Acceptable
Voting Members	90%	8	10	1	1
Non-Voting Members	N/A	1	1	0	0

Option E.4: Use nutrient trading to support the aquaculture industry.					
	% Agreement	# Acceptable	# Minor Reservations	# Major Reservations	# Not Acceptable
Voting Members	60%	8	4	6	2
Non-Voting Members	N/A	1	1	0	0

Option E.5: Use nutrient credit opportunities to help finance restoration and replenishment work in upper Bay.					
	% Agreement	# Acceptable	# Minor Reservations	# Major Reservations	# Not Acceptable
Voting Members	90%	5	13	0	2
Non-Voting Members	N/A	1	1	0	0

Option F.1: Special effort should be placed on outreach and education in minority communities to enhance awareness of the oyster resource and associated career opportunities and environmental benefits.					
	% Agreement	# Acceptable	# Minor Reservations	# Major Reservations	# Not Acceptable
Voting Members	85%	12	5	3	0
Non-Voting Members	N/A	2	0	0	0

Option G.1: Conduct a comprehensive survey of the Maryland Bay bottom with a focus on describing the current amount, quality, and location of oyster habitat.					
	% Agreement	# Acceptable	# Minor Reservations	# Major Reservations	# Not Acceptable
Voting Members	90%	13	5	2	0
Non-Voting Members	N/A	2	0	0	0

Option G.2: Develop the ability to make stock assessment forecasts of abundance and harvest.					
	% Agreement	# Acceptable	# Minor Reservations	# Major Reservations	# Not Acceptable
Voting Members	75%	8	7	5	0
Non-Voting Members	N/A	1	0	1	0

Option G.3: Improve science on oyster filtration.					
	% Agreement	# Acceptable	# Minor Reservations	# Major Reservations	# Not Acceptable
Voting Members	60%	4	8	8	0
Non-Voting Members	N/A	1	1	0	0

Option G.4: Determine ways to reduce sedimentation.					
	% Agreement	# Acceptable	# Minor Reservations	# Major Reservations	# Not Acceptable
Voting Members	100%	12	8	0	0
Non-Voting Members	N/A	2	0	0	0

Option G.5: Evaluate bagless dredging and power dredging.					
	% Agreement	# Acceptable	# Minor Reservations	# Major Reservations	# Not Acceptable
Voting Members	60%	6	6	6	2
Non-Voting Members	N/A	1	0	1	0

Option G.6: Modify management boundaries to coincide with reporting and data collection areas.					
	% Agreement	# Acceptable	# Minor Reservations	# Major Reservations	# Not Acceptable
Voting Members	50%	4	6	9	1
Non-Voting Members	N/A	2	0	0	0

Option G.7: Conduct studies to estimate the loss rates of shell (both newly planted and existing bottom).					
	% Agreement	# Acceptable	# Minor Reservations	# Major Reservations	# Not Acceptable
Voting Members	85%	7	10	3	0
Non-Voting Members	N/A	2	0	0	0

Option G.8: Conduct studies to estimate the loss rates of artificial substrate.					
	% Agreement	# Acceptable	# Minor Reservations	# Major Reservations	# Not Acceptable
Voting Members	75%	4	11	4	1
Non-Voting Members	N/A	2	0	0	0