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Mr. David Preble, Chair
Habitat Oversight Committee

Mr. Terry Stockwell, Chair
Groundfish Oversight Committee

New England Fishery Management Council
Water Street
Newburyport, MA

June 7, 2013

Dear Mr. Preble and Mr. Stockwell,

Thank you for the opportunity to comment on the development of the Habitat Omnibus Amendment. Environmental Defense Fund (EDF) wishes to express support and appreciation for the work done jointly by the CATT and the Habitat PDT, and particularly at their recent meeting on May 29-30, 2013. These groups have produced excellent analyses to assist the Council in developing a series of closed areas that will protect critical habitats and life stages, and build resilience in the face of climate change, all necessary components of healthy and productive fisheries.

At the recent meeting, the CATT and PDT developed a series of alternatives, each assembling a package of areas within four major regions managed by the Council. Dividing the options among four regions can ensure a broad network of coverage across New England waters. We support the approach that the CATT and PDT have taken to packaging alternatives, and believe these alternatives provide the Committees with several strong options for inclusion in the final alternatives. The options provided consider the conservation benefits of each package and weigh them against the social and economic tradeoffs of restricting fishing activity.

The CATT and PDT also developed rationales for why the proposed alternatives for each region do or do not meet the objectives of the Amendment as defined by the Council. We urge the Committees to thoroughly consider these rationales when deciding which alternatives to select. Generally, we feel that the CATT and PDT have done a good job of packaging alternatives, but we have a few recommendations for the Committees as they proceed in selecting the alternatives to be forwarded to the Council.

We strongly urge the Committees to select a package of alternatives that includes the new closed area developed for Eastern Maine. While this area currently supports only minimal fishing activity for groundfish, it has historically supported spawning populations cod, and has been an important fishing ground in past decades[1,2]. A closed area here will be important for rebuilding the cod population of the Eastern Gulf of Maine. As waters continue to warm in a changing climate, many fish stocks are moving northward[3,4,5]. Climate adaptation and resilience should be a key consideration in developing closed area alternatives, building on the recent commitment to addressing climate change expressed at the April Council meeting. The Eastern Maine groundfish closed area is well-positioned to become a refuge for seedling populations cod and other species in the coming years as they move north and take root. Ongoing efforts to restore river herring in eastern Maine will increase the forage base for these seedling cod populations, working with the protection from fishing mortality offered by a closed area to increase local productivity and accelerate local rebuilding.

A recent analysis[6] of potential cod larval dispersal in the Gulf of Maine found that larvae spawned in this area have a high probability of transport to the primary fishing grounds in the Western Gulf of Maine in some years, and a high probability of being retained locally in others. Therefore, the proposed Eastern Maine closed area can likely achieve the self-replenishment needed to increase local abundance, while also serving as an additional source of recruitment for the Western Gulf of Maine. A closed area in place in Eastern Maine to protect this shifting and rebuilding sub-population may be the key to once again having a strong groundfish fishery on the Maine coast and rebuilding on a stock-wide scale.

We are concerned that the existing Cashes Ledge Closed Area is not included in any of the alternatives proposed, other than the No Action alternative. The Cashes Ledge Closed Area should remain in any new set of closed areas developed by the Council. Cashes Ledge has been recognized as a critical area for groundfish in the Gulf of Maine, supporting a variety of life stages for different species because of the unique and varied habitats found here. The kelp beds provide habitat for young-of-year cod[7,8], and additionally the closed area provides suitable habitat for every life stage of cod[9], as well as many other

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groundfish species. In the 1990s, this area supported among the highest density of cod in the Gulf of Maine[10], and is poised to again become a hotspot again as species distributions shift and stock rebuilding progresses. Cashes Ledge is also home to a unique and highly localized resident population of red cod[11].

Cashes Ledge also contains healthy kelp forests which support intact food webs and significant biodiversity[12,13,14], and is a prime example of using a closed area to protect a habitat mosaic[15]. The existing Cashes Ledge closed area not only includes the kelp beds of Cashes Ledge itself, but also Fippennies Ledge and a variety of habitat types surrounding these areas important for feeding, spawning, and sheltering by a number of species. Cod and other species move among these areas over daily, seasonal and ontogenetic time scales, which underscores the importance of protecting a mosaic of habitats rather than isolated features. While there are proposed closed areas that include smaller subsets of the existing Cashes Ledge Closed Area, the biodiversity and fishery production value of the full Cashes Ledge Closed Area make this area is too important not to retain.

The process of defining and selecting a package of closed areas that best meet the objectives of the Habitat Omnibus Amendment has been a long and arduous process, but we commend the hard work done to date by the PDT and CATT. We urge inclusion of the existing Cashes Ledge Closed Area and a new Eastern Maine Closed Area among the preferred alternatives. Furthermore, we urge the Council to take seriously its commitment to addressing implications of climate change in developing alternatives.

Sincerely,

Sarah L. Smith

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| Sarah Smith, Ph.D. | Jake Kritzer, Ph.D. |
| Spatial Policy Specialist | Director of Spatial Initiatives |

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# Modeling Dispersal of Atlantic Cod Larvae in Coastal Waters of the Gulf of Maine

*Progress report*

May 2013

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## Introduction

Biomass of Atlantic cod *Gadus morhua* in the Gulf of Maine (GOM) is estimated to be at approximately 20% of the target $B_{MSY}$ (NEFSC 2012). However, the distribution of cod in the GOM show a pronounced spatial pattern, with much greater density and abundance in the Western Gulf of Maine (WGOM), inshore of approximately 70°W longitude (NEFSC 2012). Comparison of runs of the assessment model for the whole GOM with runs for the WGOM alone show nearly identical biomass estimates in recent years (NEFSC 2012). In fact, the WGOM model runs show that recent biomass is close to the highest levels observed in the last 30 years. This still falls well below the target $B_{MSY}$, but it does illustrate that the greatest need, and perhaps potential, for recovery lies in eastern waters. The concentration of cod in the WGOM also means that fishing effort is concentrated heavily in that area. The WGOM has therefore become the stronghold not only for the cod stock in the GOM, but also for the fishing fleet.

The limited distribution of cod in the GOM creates a tenuous situation since there is little for the stock to fall back if natural declines or mismanagement cause further depletion in the region. Even in the absence of further depletion, productivity in the WGOM might be limited by an absence of non-local recruitment sources. In other words, metapopulation structure and its stock-wide advantages (per Kritzer and Sale 2004) have likely been lost. Smedbol and Wroblewski (2002) have modeled similar loss of spatial structure and its costs for cod off Newfoundland and Labrador.

Closed areas represent one potential strategy for rebuilding spatial structure by alleviating fishing mortality in heavily depleted waters and allowing a greater chance for recovery. Once re-established, sub-populations within closed areas can serve as sources of additional recruitment to both nearby and more distant locales within the stock areas through connectivity processes (i.e., adult migration and larval dispersal). It is notable that the remaining concentration of cod in the GOM is situated adjacent to the WGOM Closed Area, which might be providing an important subsidy to the fishing grounds through spillover (Murawski et al. 2005). Closed areas further upstream could potentially further supplement the WGOM through longer distance larval dispersal.

Huret et al. (2007) examined larval dispersal potential in the WGOM, and Churchill et al. (2011) considered larval retention within the WGOM. Neither considered linkages further east due to the near extirpation of spawning populations in the area (Ames 2004). However, NEFMC is re-evaluating and considering reconfiguration of the closed area network in the GOM, including potential creation of new closed areas outside of the WGOM. Therefore, we expand upon the approach of Huret et al. (2007) and Churchill et al. (2011) to estimate potential dispersal linkages between coastal areas in the EGOM and WGOM. Specifically, we evaluate whether recovery in the EGOM might have benefits for the stability and productivity of the primary fishing grounds in the WGOM through recruitment subsidy, and whether subpopulations in the EGOM can be partially self-sustaining through larval retention.

## Methods

Simulation of cod egg/larval transport was done following the techniques of Huret et al. (2007) and Churchill et al. (2011). Particles, representing developing cod eggs and larvae, were tracked using velocity fields generated by the 'first generation' Finite Volume Coastal Ocean Model of the Gulf of Maine and Georges Bank (FVCOM-GoM/GB) (Chen et al., 2003, 2006, 2007). The model grid has a 0.5 to 2-km resolution within the Gulf of Maine coastal region and an order 5-km resolution within the basins. Egg/larval trajectories within the modeled flow field were generated with an explicit fourth order Runge–Kutta integration scheme with a 180-s time step.

In carrying out the transport simulations, it was assumed that cod eggs and larvae developed through 3 distinct stages: an early, fully passive, stage in which egg/larvae are positively buoyant and incapable of directed swimming; an intermediate stage in which larvae are capable of diel migration but are not sufficiently developed for settlement to a benthic habitat; and a final stage of both migration capability and sufficient development to colonize a suitable bottom habitat. Following Churchill et al. (2011), the first stage duration was set at 21 days during which the passive and buoyant eggs/larvae were maintained a depth of 2.5 m. Diel vertical migration, initiated at an age of 21 days, was simulated by shifting the vertical particle position between 2.5 and 30-m depth (or to within 1-m of the bottom) over the course of a day. Downward migration (to avoid day-time predation) was initiated at sunrise, while the start of upward migration was set at 1 hr before sunset. Both upward and downward migration time was set at 4 hr. The age of settlement capability was assumed to extend from 45 to 60 days (the last 15 days of simulated drift).

The simulated particle tracks were used to determine the probability of successful cod larval transport from a spawning area to a juvenile-suitable habitat. Termed the "transport success", *T*, (Huret et al., 2007; Churchill et al. 2011), this probability is defined as the percent of time that a particle (or ensemble of particles) is over a juvenile-suitable habitat during the range of particle age (time since release) for which the larvae are considered settlement capable. Given the above assumption of settlement capability age, *T* was taken as the percent of time that a particle, or group of particles, was over an area deemed to be a suitable habitat for juvenile cod over the final 15 days of the 60-day simulated drift.

In obtaining the results shown here, particles were released from 3911 locations distributed (at an interval of 0.02° in latitude and longitude) over the northern and western coastal region (depths < 70 m) of the Gulf of Maine (Figure 1a). The release locations incorporated the historical cod spawning grounds identified by Ames (2004) (Figure 2). Following Churchill et al. (2011), releases were initiated at an interval of 3-days, less than the correlation time scale of Gulf of Maine currents (Huret et al., 2007).

Two juvenile cod settlement areas have been considered (Figure 1b): one in the western Gulf of Maine and in second off of the central Maine coast (roughly centered on Penobscot Bay). Based on the distribution of newly-settled cod reported by Howe et al. (2002), as determined from 22 years of trawl survey data, Churchill et al. (2011) set the juvenile suitable habitat in the western Gulf of Maine as areas with bottom depth < 30 m. Accordingly, the maximum depth of the western Gulf of Maine settlement area has been set at 30-m (Figure 1b). The depth limit of the central Gulf of Maine settlement area, for which there is little or no information on newly-settled cod distribution, was set to 50 m to encompass the region's numerous offshore islands (Figure 1b).

Simulations have been carried out with releases extending over the spring spawning period (April-June) for six years, 2004-2009. Simulations for the winter spawning period (Nov-Dec) are ongoing.

## Results

### *Larval transport from the eastern/central coastal Maine region to juvenile habitat in the western Gulf of Maine*

To give a sense of the interannual variability of cod larval transport during the spring spawning period, a seasonal mean *T* was computed for each release site and each year by averaging the *T* values determined from the tracks of all particles released from the site during the spring spawning period of a particular year. Given the 3-day particle release interval, a total of 31 particles were set out at each site over the spring spawning period.

Fields of the seasonally averaged *T* to the western Gulf of Maine juvenile habitat (Figure 3) show considerable interannual variability. The field of 2005 stands out with particularly high probability of cod larval transport from the central and eastern Maine coastal region. High probabilities for such transport are also indicated by the fields of 2007 and 2008, while the fields of 2004 and 2009 show extreme low probability of this transport pathway.

For all simulation years, the *T* computed for eastern/central coastal Maine release sites show a tendency to decline through the spawning season, tending to be highest for April releases and lowest for June releases (Figure 4).

The mean *T* fields for April releases (Figure 5) show an interannual variability pattern similar to that exhibited by the seasonally-averaged fields. As would be expected, the connectivity indicated by the *T* fields is closely linked with the characteristics of the Gulf of Maine Coastal Current as simulated by the FVCOM-GoM/GB model (Figure 5). In particular, for the banner connectivity years of 2005 and 2007, model results show a very strong coastal current during April, extending the length of the Maine coast (the 'open-door' condition of Pettigrew et al., 2005). For the other years considered, the modeled representation of the coastal current is not as well defined as a pan-Maine flow.

### *Larval transport to the eastern/central coastal Maine settlement region*

Seasonally-averaged fields of *T* (Figure 6) to the central Gulf of Maine settlement region show a high degree of retention of larvae released in the central Gulf of Maine. The fields also show considerable interannual differences in those areas for which released larvae tend to be retained. For example, *T* fields of 2006 and 2008 show a high probability of retention of larvae released within, and offshore of, the Penobscot Bay region. By contrast, the *T* fields of 2004 and 2005 show only small areas for which released larvae tend to be retained in the central Gulf of Maine coastal region.

## Discussion

Our initial results suggest that subpopulations in the EGOM have the potential to both seed the WGOM and exhibit self-replenishment, with the relative strength of each process varying from year to year as a function of hydrodynamic processes. For example, 2005 was a strong year for downstream dispersal to the WGOM with less self-replenishment, whereas 2006 showed the opposite trend. This interannual variation means that different areas within the GOM can experience different degrees of independence and connectivity through time, therefore potentially realizing the benefits of each in a dynamic balance.

The relative importance of dispersal and retention for both local and regional dynamics will depend upon a variety of factors, especially local abundance and demography within different areas. At present, density and abundance are comparatively high in the WGOM, suggesting that local demography leads to relatively high productivity. The dearth of fish elsewhere in the stock areas reinforces this conclusion since the WGOM is unlikely to be receiving significant recruitment subsidy from elsewhere at present. In contrast, the much lower density and abundance in the EGOM suggests that both upstream supply and local demography are limiting, and perhaps that retention is insufficient in light of local demography.

This study is a work in progress and we seek guidance from technical bodies, management bodies and others on interpretation of the results to date, modification of the approaches adopted, and additional questions to pursue through continued analyses in order to best inform development of spatial management strategies.

## Acknowledgement

The velocity fields used in this study were generated by Marine Ecosystem Dynamics Modeling (MEDM) Laboratory of the University of Massachusetts at Dartmouth using the Finite Volume Coastal Ocean Model of the Gulf of Maine and Georges Bank. We extend our appreciation to MEDM for the access to these data.

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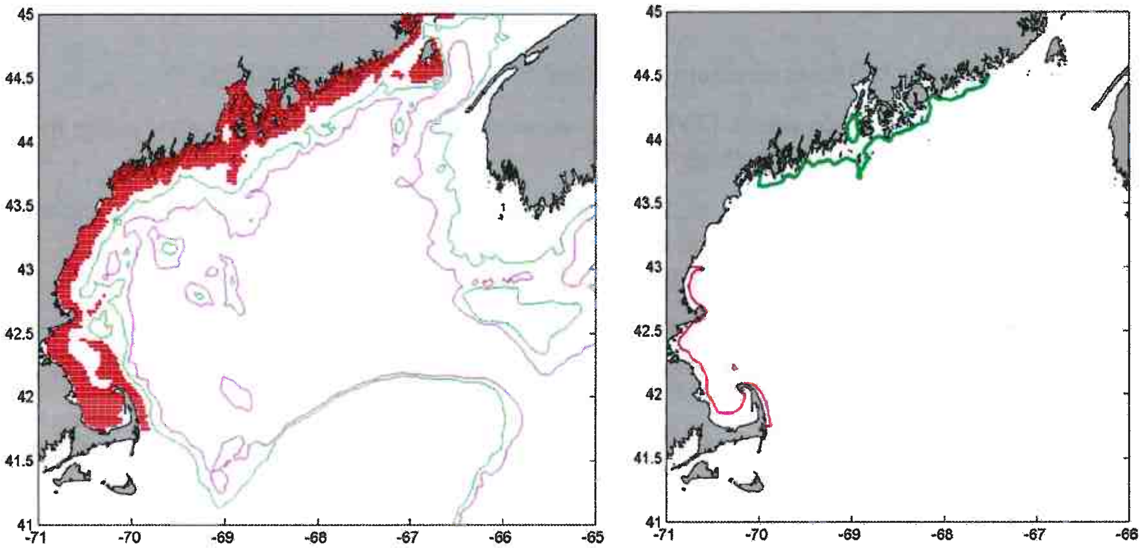

Figure 1. (a) Release locations for larval transport simulations. Locations are separated by 0.02° of latitude and longitude and are at bottom depths < 60 m. (b) Outer boundaries for the western (red) and central (green) Gulf of Maine larval cod settlement regions.

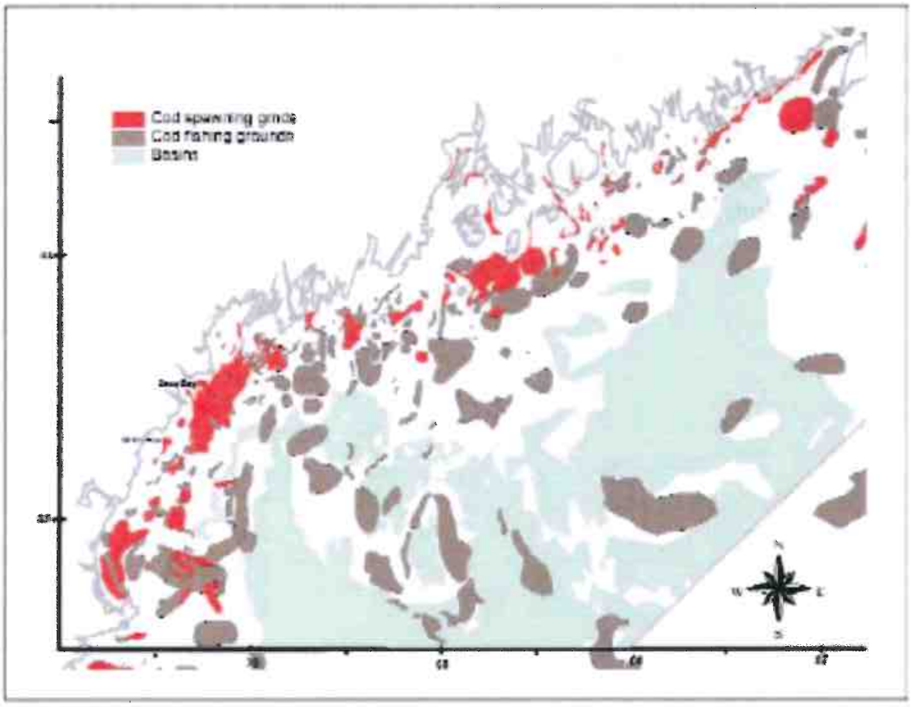

Figure 2. Representation of historical cod spawning grounds (red areas) in the Gulf of Maine (from Ames, 2004).

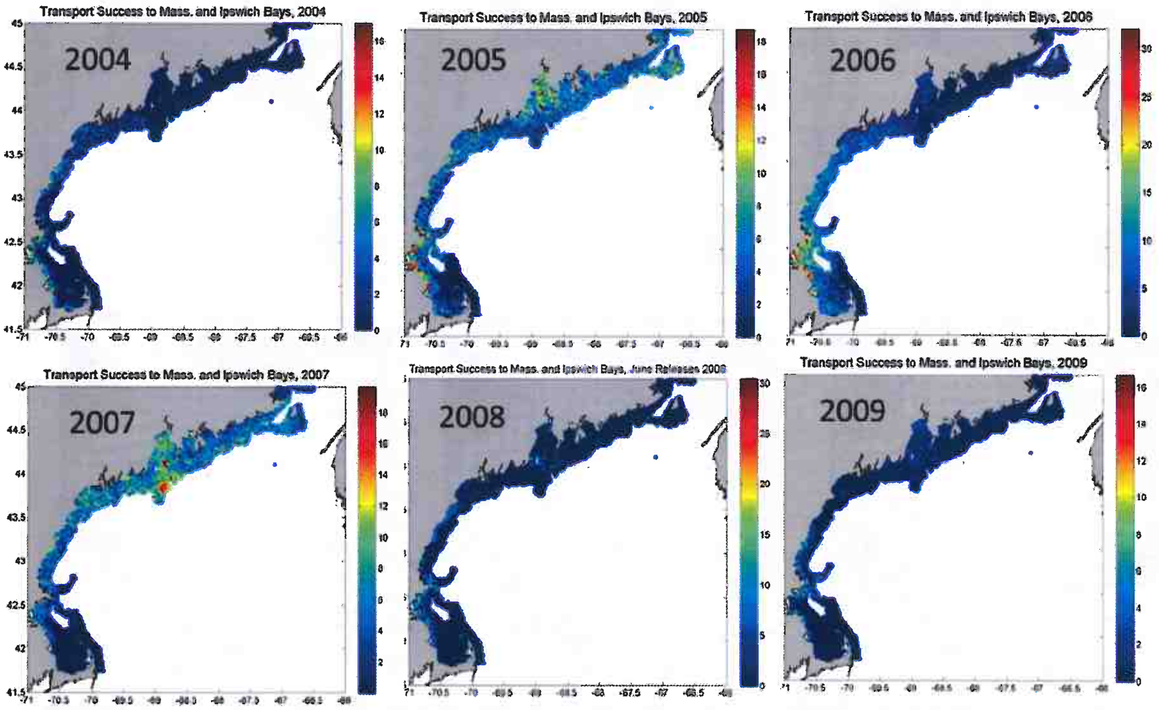

Figure 3. Fields of average transport success to the western Gulf of Maine settlement area (Figure 1b) for particles set out from each release location (Figure 1b) over the spring spawning period (April-June) of the indicated year.

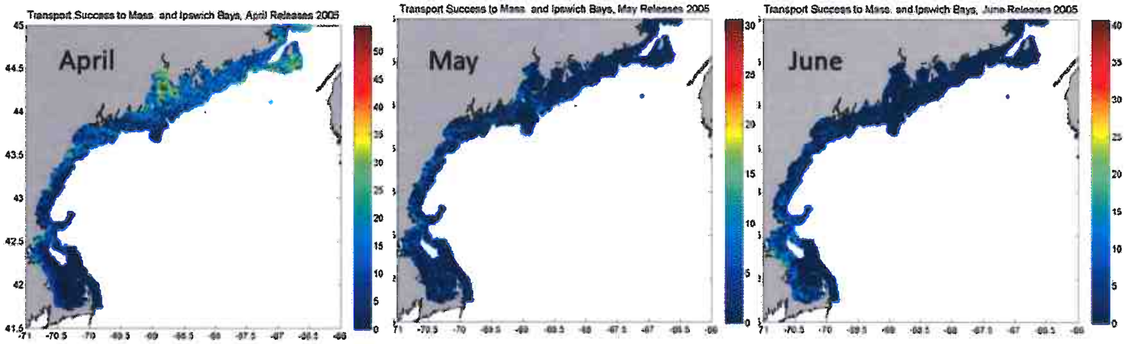

Figure 4. Fields of average transport success to the western Gulf of Maine settlement area (Figure 1b) for particles set out from each release location (Figure 1a) over the indicated months of 2005.

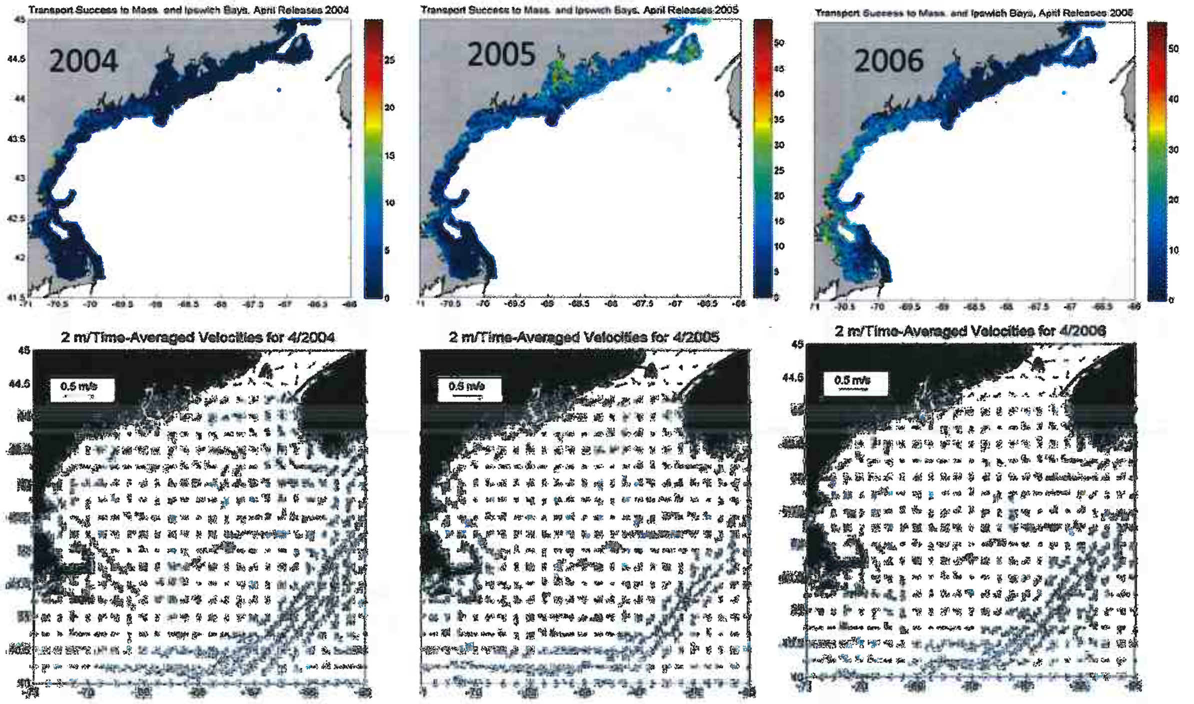

**Figure 5.** Top panels are fields of average transport success to the western Gulf of Maine settlement area (Figure 1b) for particles set out from each release location over April of the indicated year. Top panels are model-derived fields of velocity at 2 m averaged over April of the indicated year.

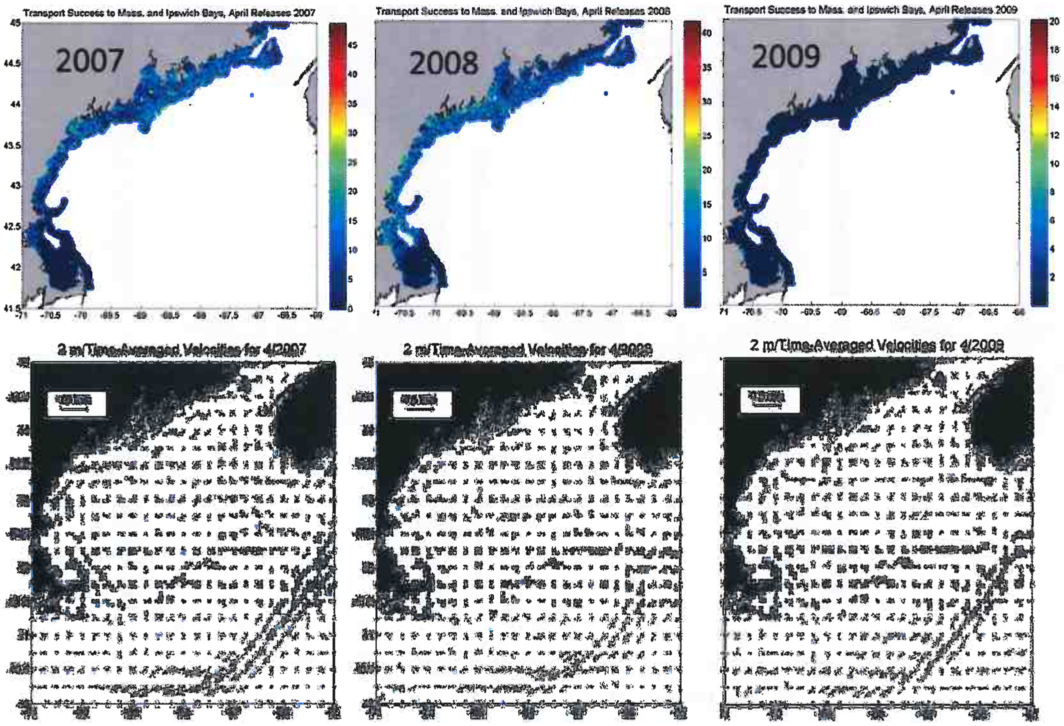

Figure 5. Continued.

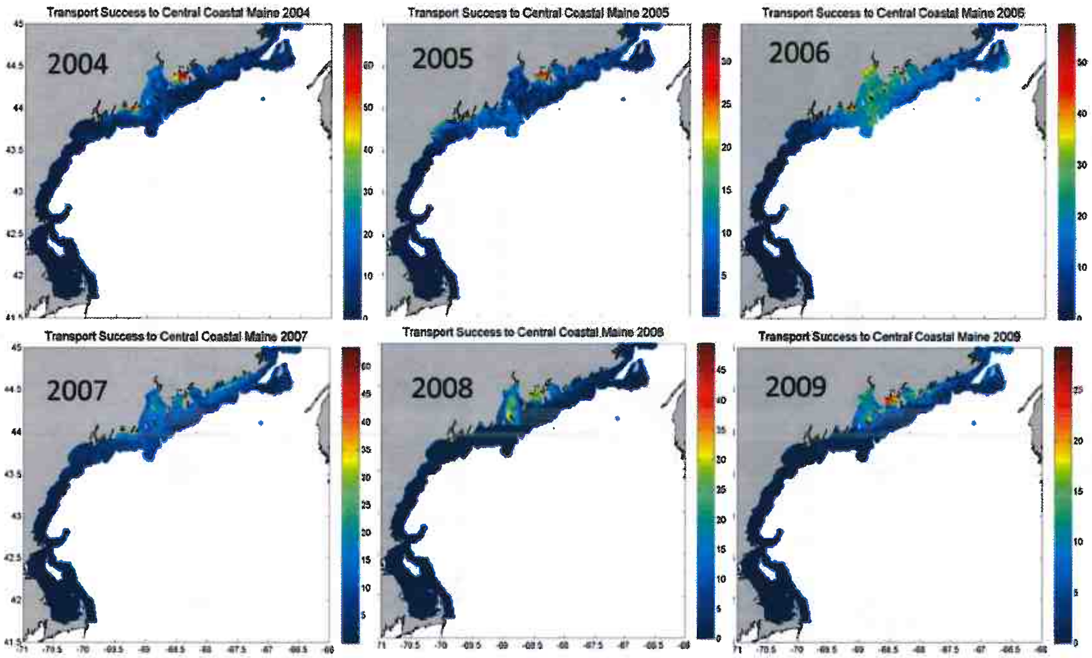

Figure 6. Fields of average transport success to the central Gulf of Maine settlement area (Figure 1b) for particles set out from each release location (Figure 1b) over the spring spawning period (April-June) of the indicated year.

# Scientific considerations for design of fishery closed areas

*Guidance for the New England Fishery Management Council*

May 2013

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## Executive summary

We propose that closed areas should remain an important tool in management of the groundfish fishery. Specifically, closed areas should be strategically designed to address stock attributes and ecosystem dynamics that are not addressed directly by ACLs. In other words, quotas and spatial management should evolve as complimentary rather than alternative strategies.

This paper outlines a range of issues that should inform closed area design, but are not dealt with well by other measures. We propose criteria that should be used to design and evaluate closed areas, and urge you to use this guidance as a filter through which to view alternatives:

- Retain the strongest benefits that have accrued from existing closed areas, and create new closed areas in response to new management needs and scientific understanding.
- Employ a combination of targeted spatial and temporal closures focused on spawning events and larger year-round closures that address a broader range of ecological attributes.
- Build larger closed areas as habitat mosaics combining multiple habitat types centered on the most vulnerable features.
- Distribute closed areas along current tracks and latitudinal and longitudinal gradients in order to rebuild metapopulation structure and increase resilience in the face of climate change.
- Consider adaptive management strategies, such as closed areas that expand and contract from a core conservation zone in response to pre-defined triggers linked to stock status.
- Develop and implement a strategic monitoring and research plan so that future evaluations can be conducted more readily and effectively.
- Develop strategies to address important attributes and drivers that are not addressed well by catch limits and closed areas, such as coastal zone and watershed management.

Well-designed closed areas can be valuable components of a management strategy that attend to a diverse array of ecological processes in ways that improve ecosystem function and fishery production.

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## Introduction

The New England Fishery Management Council is facing important challenges in building sustainable fisheries. Many of these challenges are rooted in the complexity inherent in the ecosystems on which New England's fisheries are based. Management of the groundfish fishery is particularly challenging due to the number and complex life histories of the harvested species. The structure of the fishery (i.e., diversity of vessels, gears, participants and ports) is another complicated system driver. Additionally, rapid changes underway in these ecosystems driven by climate change, coastal development, watershed impacts, and other factors create greater uncertainty, which makes understanding and predicting ecosystem status and resulting stock dynamics difficult.

Presently, the primary scientific tools used to estimate stock status and determine reference points are single-species assessment models. The primary management tool used in response to assessment outcomes is risk-averse annual catch limits (ACLs) set with buffers to account for scientific and management uncertainty. Closed areas are an additional management tool, originally designed as part of input control management in the groundfish fishery. Since there has been a fundamental shift to output control management, this has led to questions regarding the need for continued closure of these areas to fishing activity. However, continued challenges with the performances of stock assessment models, along with a range of critical biological and ecological processes not considered by those models, mean that ACLs still need to be paired with other management strategies, especially closed areas.

Many of the assessment models used in the management of New England fisheries are quite sophisticated, combining multiple data streams and characterizing the major demographic attributes of the stock (growth, mortality, maturity) to reconstruct long-term trends in biomass, recruitment and fishing mortality. However, most of these models by necessity do not consider the full breadth of relevant stock attributes (e.g., dependency upon other species and system components, behavior, spatial structure, age-specific reproductive value). These are important features of populations that have a stabilizing influence and confer resiliency when systems are perturbed. Experience around the world has shown that, despite these omissions, many models still work well if stock depletion has not been too severe and environmental variables fluctuate within reasonable bounds around average conditions. However, when a stock is depleted to very low levels, these features of populations can be critical to stock recovery. These features also play an essential role in the flexibility of species to respond to a changing ecosystem in which environmental variability is no longer bounded around a long-term average. This lack of stationarity in the data violates a key assumption in the models used to predict the dynamics of the fish populations.

There is potential for stock assessment models to evolve in ways that explicitly consider more complex stock attributes, such as spatial structure, and environmental drivers, such as temperature effects, which can result in more accurate determination of reference points and stock status, and effective management advice. However, there are limits to the range of factors that can be modeled, and many of the stock attributes that may contribute to resiliency can be addressed through closed areas. Moreover, for species with the highest economic, ecological and cultural value experiencing high levels of harvest in an altered ecosystem, the management response will need to be multi-dimensional. In addition to quotas, impacts of other activities, especially in watersheds and the coastal zone, need to be addressed outside of the fisheries management arena. Within the jurisdiction of fisheries management, ***closed areas can address a range of ecological attributes and drivers that ACLs do not.***

As the Council continues its efforts to re-evaluate and reconfigure fishery closed areas in New England waters, we offer the following guidance on key considerations and their implications for design of a robust closed area network.

## Habitat

Initial alternatives for new habitat closed areas in New England waters were developed by the Council's Habitat Plan Development Team (PDT) and were based on results of the regional scale swept-area seabed impact (SASI) modeling exercise along with information from extant literature and small scale map products. SASI used an extensive literature database to identify those features with the greatest potential to be adversely affected by fishing and the least potential to recover from those impacts. These are primarily hard-bottom patches, often with known or inferred biotic features (i.e., vegetation or sessile fauna). Hard-bottom areas such as those identified by SASI are necessary but not sufficient components of comprehensive habitat management system given that the timing between impacts and habitat use by fishes at critical life-history stages was not considered in this process. Furthermore, representation of a diversity of habitat types can help build resilience into the ecosystem (Jones 2002), a key component of a transition to ecosystem-based management (Crowder and Norse 2008).

Incorporating greater diversity of habitats within a network is more effective if a diversity of habitat types is incorporated into each closed area, thereby capturing habitat mosaics rather than distinct features in isolation. This is because most species utilize a variety of habitats over daily, seasonal and ontogenetic time scales. Different habitats can be important for feeding, sheltering and spawning, and the nature of each use can depend upon prevailing conditions. Therefore, protecting those habitats in proximity can allow their collective ecological function to be greater than the value of each in isolation.

For example, cod have been shown to move between structured habitat for shelter at night and soft substrate for feeding during the day (Clark and Green 1990). Between seasons, cod of different ages occupy different depths in response to temperature profiles (Swain et al. 1998). However, at any given point in time, cod modify habitat use in response to the presence of predators (Lindholm et al. 1999) and density of other cod (Laurel et al. 2004). Demographic modeling focused on habitat diversity in the Western Gulf of Maine Closed Area has demonstrated how creating closed areas that incorporate a diversity of contiguous habitats improve survival as a result of these dynamic patterns of use (Lindholm et al. 2002). The combination of mud, sand, bare rock, *Laminaria* kelp, *Agarum* kelp, and other benthic features on and around Amman Rock and Fippennies Ledge within the existing Cashes Ledge Closed Areas is a good example of a diverse habitat mosaic.

## Behavior

The concept of capturing habitat mosaics within closed areas builds a bridge between objectives for management of habitat in its own right and objectives for management of groundfish stock productivity. This linkage is mediated by behavior. The discussion above addresses changing patterns of habitat use at different times of day, seasons and life stages under different prevailing conditions. However, individuals of the same species can also exhibit very different behavioral strategies, even at the same time, location and life stage.

For example, Lindholm et al. (2007) and Sherwood and Grabowski (2010) documented resident and migratory strategies within the Gulf of Maine cod stock, distinguished by morphological and ecological traits. In this case, a single closed area could provide adequate protection to a resident cod within its borders, but less so for migratory cod. This has the potential to unintentionally shift fishing impacts disproportionately onto migratory cod. However, this imbalance can be corrected by creating a network of closed areas that provide "stepping stone" refuges for migratory fish. Additionally, year-round seasonal closure of known migratory corridors can reduce excessive impacts on migrants and maintain greater behavioral diversity. Life history diversity within a population (or a metapopulation) can confer resilience which may help to ensure high yields over the short term (e.g., the "portfolio effect" in the Alaskan sockeye salmon fishery; Schindler et al. 2010) and sustainability over the long-run. It is important to note that migratory components, either among or within populations, tend to be more productive (e.g., Robichaud and Rose 2004) and may be required to fuel stock rebuilding and high yields.

Movement is not the only behavior relevant for closed area design. Cod and other groundfish species exhibit complex courtship behaviors during spawning (Hutchings et al. 1999). Fishing activity can disrupt mating, even among fish that are not caught (Morgan et al. 1997; Dean et al. 2012), thereby compromising reproductive potential to a greater degree than predicted only by the direct removals. Closed areas timed and sited when and where spawning aggregations are known to exist can reduce this impact.

### Spatial structure

The benefits of protecting spawning behavior in some areas will be limited if distinct spawning groups are not maintained to preserve the complex internal spatial structure of most stocks. Although most assessment models assume a single, well-mixed, randomly mating population, more often fish are organized into distinct sub-populations. Historical structure of this type has been documented for cod in the Gulf of Maine (Ames 2004), although many sub-populations have been lost. Because these sub-populations supplement one another by migration of adults and export of pelagic larvae, localized losses can have stock-wide consequences (e.g., Smedbol and Wroblewski 2002). Accounting for population connectivity and its effects on stock-wide stability, productivity and recoverability requires greater attention to spatial resolution and scale in fisheries science and management.

In the Gulf of Maine, the dominant current, the Maine Coastal Current, runs northeast to southwest (Pettigrew et al. 2005; Runge et al. 2010), or from areas along the coast of Maine where cod have largely been extirpated to the last stronghold of modest abundance in the Western Gulf of Maine (WGOM). The WGOM closed area may be playing an important role as a reservoir for whatever upstream production is delivered to the area, and in turn supplying the remaining fishing grounds inshore. Whether this hypothesis is true or not, the WGOM as a whole might be at risk in the long-term due to an absence of upstream sources. Closed areas distributed more widely across the stock area and strategically placed within major current tracks can be one component of a strategy to recover depleted or extirpated sub-populations and rebuild stronger connections across the stock area.

### Age structure

Closed areas can also be a useful tool in rectifying the documented erosion of age structure in our groundfish stocks. Many assessment models are age-structured in that overall spawning stock biomass is composed of distinct age classes. However, reproductive potential, management targets, stock status and management strategies are ultimately based on aggregate biomass without consideration of age structure. This omission can be detrimental for two important reasons.

First, numerous studies have demonstrated that larger and older fish are disproportionately important for stock productivity. Not only do these individuals produce more eggs per unit of body weight per spawn (Marteinsdottir and Begg 2002), but they also spawn more frequently throughout the year (Scott et al. 2006). This increases total annual fecundity and the chances that vulnerable early life stages encounter favorable conditions (i.e., the 'match-mismatch' hypothesis; Cushing 1990). Additionally, eggs spawned by older and larger fish are often larger with greater nutritional stores, and consequently their offspring exhibit superior growth and survival after hatching (Marteinsdottir and Begg 2002). Considering these effects can dramatically change perceptions of stock dynamics (Murawski et al. 2001), but current assessment practice and management strategies do not.

Second, maintaining more complete age structure can be an effective strategy for enduring years when conditions are not conducive to recruitment success until conditions again become favorable. This bet-hedging strategy is known as the 'storage effect' because reproductive potential is "stored" through time across a broader range of age classes (Warner and Chesson 1985). The advantages of this stored reproductive potential are similar to the advantages of spawning over a longer duration within a given year in that it increases the probability of encountering favorable conditions for growth and survival. This strategy is inconsistent with the goals of maximizing both productivity and sustainability (Carr and Kaufman 2008). Unfortunately, for too many groundfish stocks, the spawning biomass is currently built largely upon a small number of young age classes.

Age structure can be rebuilt through management measures that allow greater numbers of fish to reach older ages and receive protection when they do. Slot limits are one approach, wherein retention of fish above a certain size is prohibited. This requires high post-release survival of fish above the maximum size, or gear modifications or other changes in fishing behavior to prevent their capture at all. However, even with such measures, sufficient numbers of fish must survive the harvestable slot to reach the protected age and size classes, but often the number will be low even with modest levels of fishing mortality (Berkeley et al. 2004). In contrast, closed areas can allow some sub-populations to experience higher survival and achieve more robust age structure (Berkeley et al. 2004). There is evidence that closed areas in the Gulf of Maine and on Georges Bank harbor older and larger cod (Sherwood and Grabowski, unpublished data[1]).

## Uncertainty and ecosystem change

Fisheries management is more effective when uncertainty in the underlying science is acknowledged and accommodated. The primary tool for addressing uncertainty in federally managed fisheries in the United States is risk-averse buffers incorporated into catch limits. Buffers are usually set through consideration of uncertainty in model inputs (e.g., discards, demographic rates), model performance (esp. retrospective patterns), and future stock trends (recruitment and stock growth estimated in projections). However, buffers and catch limits do not directly or effectively address the complexities of habitat dynamics, behavior, spatial structure or age structure, the absence of which represent an additional source of uncertainty. Therefore, closed areas in combination with risk-averse quotas can be a more effective strategy for managing in the face of uncertainty (see Stefansson and Rosenberg 2005 for an analysis of the combination of these tools).

Another significant component of uncertainty is change in the complex dynamics of the ecosystem as a whole as these are driven by regional and global processes (Liu et al. 2012, Glaser et al. *in* press). Our detailed understanding of cod and other species allows us to make predictions about potential effects of climate change (e.g., Fogarty et al. 2008). Still, ample uncertainties will remain, and closed areas can be part of a strategy for building adaptability and resilience. Specifically, closed areas distributed along both latitudinal and longitudinal gradients across the management area will create refuges for new

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[1] This study is currently being prepared for publication. However, the results are summarized in Framework Adjustment 48 to the Northeast Multispecies FMP.

ecological communities to establish and evolve as species distributions change under new environmental conditions with as little additional disturbance as possible (Planque et al. 2009).

Importantly, some changes underway may not be reversible and could limit the effectiveness of the best designed management strategies. For example, there is evidence that the distribution and abundance of certain zooplankton species are changing across the Gulf of Maine. Those changes might reduce the recruitment potential in certain areas because zooplankton species are key prey for larval groundfishes. Closed areas can help respond to those limitations by giving fish that are able to settle out of the plankton a better chance at growth and survival through alleviation of fishing mortality, and improved prey and habitat resources, especially for juveniles. However, the expected benefits of closed areas and other management actions will need to be gauged in light of constraints beyond the control of management.

## Natural attributes, management effects and monitoring

Ideally, a closed area network would be designed with complete information about the diversity and arrangement of habitats, structure of priority stocks, food webs, and other ecosystem dynamics. Of course, this is never the case. Decisions are made based on the best understanding at the time, which should then be re-evaluated on some schedule, as NEFMC is doing at the moment. New information will likely reveal that some closures were not placed in the ideal location originally, but the history of protection since they were created means that they may have developed attributes worth preserving (e.g., habitat complexity). Even with accumulated scientific research, some closed area outcomes will receive less attention, which means there are likely to be benefits that have accrued but are not documented. For example, while emergent epibenthic biota is often a focus of closed area studies (e.g., Stokesbury and Harris 2006), less attention is generally paid to infaunal invertebrate communities, even though these are known to be important drivers of productivity, diversity, and faunal composition.

This interplay between natural attributes, effects of management actions, and scientific understanding presents challenges in the re-evaluation and reconfiguration a closed area network. There are trade-offs between retaining accumulated effects and adapting design based on improved information. The former represents benefits being delivered immediately, whereas the latter represents potentially greater benefits to be delivered in the future. Generally, the best solution will likely be a combination of retaining existing benefits in some current closures, while potentially giving up others to move toward an overall improved design. However, evaluating those trade-offs is far from straightforward.

This conundrum does highlight the importance of a purposeful research and monitoring program as a core component of a closed area strategy. At the time of implementation, a program should be initiated that tracks key metrics that are indicative of priority objectives. That will enable performance to be understood more quickly and comprehensively, and adaptation to be more effective. Therefore, NEFMC should develop a research and monitoring plan as part of its ongoing efforts. Research and monitoring create the potential for management to be much more responsive to changes in the water, especially if contingent actions are defined from the outset. For example, some closed areas could shrink from a larger size down to a core size in response to localized increases in abundance in depleted areas, or overall stock-wide status.

## Conclusions and recommendations

Closed areas can be powerful management tools that address a wide range of ecological attributes that are too often absent from fisheries science and management, particularly when designed well and used in concert with science-based catch limits and other management actions. The troubling state of many groundfish stocks and rapid changes in the ecosystem call for greater attention to these attributes and development of strategies that account for their effects. In the context of designing the closed areas network, we recommend the following be taken into account:

- Retain the strongest benefits that have accrued from existing closed areas, and create new closed areas in response to new management needs and scientific understanding. Previous research and new analyses are lending insights into those trade-offs, but consideration should be given to benefits that are not well understood due to monitoring and research gaps.
- Employ a combination of targeted spatial and temporal closures focused on specific behavioral events, especially spawning aggregations, and larger year-round closures that address a broader range of key attributes, such as age structure and food webs.
- Build larger closed areas as habitat mosaics combining multiple habitat types centered on the most vulnerable features.
- Distribute closed areas across the stock area along current tracks and spanning latitudinal and longitudinal gradients in order to recreate metapopulation structure and build resilience to shifting species distributions driven by climate change.
- Consider adaptive management strategies, such as closed areas that expand and contract from a core conservation zone in response to pre-defined triggers linked to stock status.
- Develop and implement a strategic monitoring and research plan so that future evaluations of closed area performance and design can be conducted more readily by having the needed information and analyses in hand.
- Develop and implement a strategy to address important attributes and drivers that are not addressed well by catch limits and closed areas. For example, improved management of coastal development and watersheds will benefit groundfish, and the Council should work with states and municipalities on those issues.

Closed areas are an important complement to harvest management systems that can address a more complex array of spatially-explicit stock attributes and ecological processes not captured by stock assessments and quotas. When designed strategically, a closed area network can enhance productivity and accelerate rebuilding, to the benefit of the industry, while minimizing or offsetting costs to the industry. Reconfiguring a closed area network is generally done at infrequent intervals given the time needed for effects to emerge. Consequently, the Council should think broadly, creatively and carefully about the decisions at hand, and design a system that recognizes and responded to the ecological complexity, and change, evident in our marine ecosystems.

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