QUANTIFYING CONNECTIVITY AMONG POPULATIONS AND COMMUNITIES: HOW DO WE GET CONNECTED?[1]

The White House' Interagency Ocean Policy Task Force published final recommendations in July , 2010 to better meet the nation's stewardship responsibilities for the ocean, coasts and the Great Lakes. The report emphasized the need to protect, maintain, and restore the health and biological diversity of ocean, coastal, and Great Lakes ecosystems and resources. To meet this need, NOAA is employing ecosystem-based approaches and marine spatial planning. Essential to their successful implementation is detailed knowledge of the distribution of organisms and habitats that support them, together with understanding spatial exchanges of organisms in the sea. While NOAA has made investments to characterize distributions of organisms and habitats, knowledge of the rates and consequences of exchanges among habitats is less well grounded. The Cooperative Institute for the North Atlantic Region (CINAR) is a regional consortium that focuses on the U.S. northeast continental shelf (NES) from Cape Hatteras to Nova Scotia and aims to conduct research that meets the needs of NOAA managers and that provides important information and tools for decision-making within the NES ecosystem.

A mechanistic understanding of connectivity among populations and communities requires resolution of biological and physical processes across temporal and spatial scales. The complexity of connectivity arises because the dynamic processes that determine connectivity occur at different physical scales and biological levels of organization. Connectivity at the individual level is often guided by processes such as larval dispersal or adult movements that serve to close life cycles. At the population level, patterns of dispersal and migratory behaviors promote ontogenetic and seasonal shifts, and exchanges among spatially distinct subpopulations that can promote resilience and sustainability of individual populations. At the ecosystem level, shifts in the productivity and invasions by non-endemic species and exchanges of taxa among neighboring ecosystems may impact the structure and function of fishery ecosystems. Hence, knowledge of connectivity and ecosystem processes is essential to enable sound ecosystem-based management and marine spatial planning to promote stable and resilient ecosystem functionality and services.

Marine spatial planning (MSP) can be conducted at a range of scales. The selection of appropriate scales for MSP is important for defining ecologically-based planning and management units; identifying their spatial extent, structure and composition; providing the basis to select biologically and ecologically important areas for protection; and establishing a spatial framework for environmental assessments. NOAA is implementing spatial management to optimize human uses of marine resources and achieve conservation in marine ecosystems, but the application of MSP is uneven across regions, species, and ecosystems. Spatially-explicit management strategies implicitly require accurate information on the spatial distributions of subpopulations of individual species. The lack of such information could lead to over-exploitation and potential collapse of key components of fishery ecosystems. Moreover, accommodating connectivity in MSP can reduce uncertainty in our understanding of the consequences of exploitation in fishery ecosystems. For example, the long-term effects of climate change may alter patterns of dispersal or changes in recruitment patterns, such as self- versus open-recruitment populations, with the potential for irreversible change.

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1. The workshop on population connectivity was sponsored by the Cooperative Institute for the North Atlantic Region in February 2011. The workshop was organized by Hongsheng Bi, Thomas Miller and Ed Houde from UMCES. Workshop participants include: Robert Cowen (U Miami), Bob Steneck (U Maine), Ken Able, Dale Haidvogel, Michael Deluca, Olaf Jensen (U Rutgers), Julie Kellner (WHOI), Jason Stockwell (GMRI), Ming Li, Elizabeth North, Michael Wilberg, Mike Roman (UMCES), Jon Manderson, Thomas Noji (NOAA).

Climate variability and change are major drivers of changes in connectivity for populations and key functional groups. Climate effects are observable and are progressing at a fast pace. Climate variability is likely to influence connectivity over decadal to longer-term temporal scales. In response to climate variability and change, adaptation and adaptive mitigation can occur at different levels: 1) adaptation by organisms e.g. shifts in biomass centroids; 2) adaptation by the fishery, e.g. shifts in location and seasonality of fisheries; and 3) adaptation by managers, e.g. adaptive spatial planning. The spatial scale of connectivity is pivotal to understanding how climate affects populations and ecosystems. Spatial dynamics of physical and biological processes responding to climate variability could have complex effects on connectivity, including but not limited to thermal limitation and physiological effects, changes in larval dispersal pathways, physiological condition during dispersal, suitability of habitat during settlement, and adult behavior/movement. Increased susceptibility to invasion and restructuring of communities are also likely to occur. Our ability to forecast these changes at each level can be amplified or dampened by our understanding of the pattern and degree of connectivity.

Research recommendations:

We recommend four principal focal areas for NOAA to expand and emphasize connectivity research to support management policies and strategies in the U.S. northeast continental shelf ecosystem. These areas are: 1) Quantification of rates of exchange and uncertainty in connectivity, 2) Simulation modeling to define the role of connectivity in life histories of individual species and future patterns may change, 3) Evaluation of connectivity among assemblages, biological communities, and ecosystems, and 4) Evaluation of management strategies. Below we provide examples of research capabilities within CINAR that can be leveraged to address NOAAs needs.

Research Theme 1: Quantifying connectivity

Existing techniques to investigate connectivity include 1) traditional tagging or modern acoustic arrays to trace adult movements, 2) analysis of morphometric and phenotypic variation to quantify stock structure, 3) genetic approaches to map patterns of subpopulation diversity, and 4) modeling approaches to a) quantify connectivity pathways, b) better understand the linkages among oceanographic processes, pelagic and benthic habitat, and life-history strategies, and c) predict the range of future responses by populations and communities to natural and anthropogenic variability. In general, we lack integrated, spatially-explicit models of entire populations over their life cycles. We recommend research that focuses on several functional groups with varying life-history strategies (e.g., shelf-estuary connectors, shelf spawners, and shellfish). Whereas some groups have relatively well-defined life-stage habitat requirements (e.g., winter flounder), others do not (e.g., some pelagic fishes such as Atlantic herring) and present different challenges in understanding population connectivity. A comparative research program, as suggested here, will lead to greater understanding of the diversity of responses.

Research by CINAR scientists to support this theme could involve targeted synthetic analysis of existing data using state of the art techniques and the collection of new data to fill gaps in our knowledge. CINAR institutions can implement a variety of approaches, including data synthesis of field programs (e.g., Marine Resources Monitoring, Assessment, and Prediction (MARMAP), Ecosystem Monitoring Program (ECOMON), and Coastal Collaboration on Recruitment (CCOR)) to identify spawning locations, nursery areas, suitability of benthic habitat types, phenologies, otolith-based reconstruction of habitat use, and larval transport modeling using hindcast simulations. Analyses and new research to test specific hypotheses (e.g., discrete population, dynamic balance, or metapopulation concepts) can be used to better understand connectivity pathways. For example, application of otolith analyses (shape, microstructure, and microchemistry), population genetics, morphometrics, and acoustic or traditional tagging of spatially and temporally discrete sub-populations and life-stages can be conducted to develop connectivity matrices. When coupled with physical process models (see Research Theme 3), such investigations can identify pathways of exchange and the potential for inter-annual variability.

Research Theme 2: Assessing current and future changes in connectivity patterns

Connectivity patterns will likely evolve because of climate variability; thus, assessing current and future changes in connectivity will enhance our understanding of climate-induced ecosystem variability. Approaches to forecasting impacts of changes in connectivity on sustainability of individual species and the structure and function of fishery ecosystems require integrated models of population dynamics and the physical and hydrodynamic environment.

CINAR partners have developed or have access to existing eddy-resolving (10 km) hydrodynamic and climate models for the NES region which could provide 100-year scenarios and include at least 20 years of hindcast scenarios. Larval transport models can use output of the hydrodynamic models to 1) project the influence of flow and larval behavior on dispersal trajectories, 2) characterize connectivity including spatial and temporal variability of larval dispersal between spawning and nursery areas, and 3) examine future connectivity patterns in the context of large-scale climate change. Recommended research would focus on functional groups such as shelf-estuary connectors (e.g., summer flounder), offshore ground fish (e.g., cod, haddock), shelf spawners (e.g., herring), and benthic invertebrates (e.g., surfclam, scallop). Models could be used to explore the impacts of interannual variability and episodic events (e.g. hurricanes) on trajectories of larvae between spawning and settling in nursery areas. They also could address changes to benthic habitat properties and the impact of changes in behavior and distribution of spawning adults. The modeling framework can be applied to predict future scenarios of how climate change may influence targeted species and functional groups. These existing models can also be used characterize ‘connectivity hubs’ for marine spatial planning (i.e., places in time where fish aggregate), and identify connectivity pathways and associated physical features in relation to climate effects.

Research Theme 3: Connectivity at the Assemblage and Ecosystem Level

Research themes described above have focused on comparative analyses of connectivity in individual species. However, we also recognize that the dynamics of assemblages and ecosystems can also reflect exchanges with neighboring assemblages and ecosystems to which they are connected. There are ongoing efforts within CINAR through CAMEO to describe and quantify patterns of connectivity at the assemblage and ecosystem-level but more are needed. Knowledge of ecosystem properties on functional groups and keystone species, as well as related biological and physical processes, is essential to construct a connectivity framework among different regions or subregions (ecosystems or subsystems). Analyses are being undertaken at broad scales, e.g., the mid-Atlantic, Southern New England and the Gulf of Maine.

CINAR partners recommend and have the capacity to implement expanded analyses to evaluate whether there are important patterns of exchange and connectivity within these broad spatial scales. We propose to utilize satellite data and survey data to perform geostatistical analyses and quantify the critical scales of physical and biological processes. Satellite observations will allow us to examine the related oceanographic features. From the survey data, we can examine assemblage and ecosystem structure, and the spatial and temporal scales at which physical and biological processes correlate or de-correlate. New companion research could be initiated that applies stable isotope analyses of archived or newly collected tissues of organisms throughout the region to quantify exchange rates among different domains.

Research Theme 4: Understanding the consequences of connectivity for management

Population connectivity presents a challenge to fisheries management because of potential mismatches between the scale of fisheries management and the scale of ecological processes that determine the dynamics of exploited species. Despite advances in understanding population connectivity, uncertainty about patterns of connectivity, its interannual variability, and how it will respond to climate change remain. Robust approaches to management are needed to buffer against uncertainty. Management strategy evaluation (MSE) is a state-of-the-art integrated modeling approach that evaluates performance of alternative strategies under a range of possible natural states (i.e., operating models about how the world works). MSE develops an understanding of the intergration of assessment, implementation of policy and resulting impacts on population dynamics, and subsequent feedback to assessment and management. Important aspects of biology and ecology, such as connectivity between subpopulations, can be included in the operating model. Performance measures can describe how management options achieve economic, social, and ecological objectives for a fishery under different assumptions about connectivity.

CINAR partners have the capability to develop operating models for selected species in the northwest Atlantic coastal ecosystem. These models could form the foundation for an MSE, to evaluate alternative hypotheses about stock structure and connectivity, including larval-mediated and adult-mediated connectivity, and factors that can affect connectivity such as fishing, climate change, and spatial management. We suggest that application of MSE to key species in the NWACS will permit NOAA to design assessment and management strategies robust to conditions of changing connectivity in larval or adult dispersal, uncertainty about system dynamics, and imperfect ability to predict future dynamics. Notably, toward this end it is implicit that a dialog between CINAR and NOAA scientists, including stock assessment experts, is critical to insure that CINAR products can easily be incorporated into the assessment process.