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Implications of Atlantic cod seasonal movements and population connectivity for fishery management and stock assessment in the Gulf of Maine

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Summary
The Gulf of Maine stock of Atlantic cod functions as a metapopulation with genetically-distinct spring- and winter-spawning subpopulations that are comprised of multiple finer-scale spawning components. Dominant mechanisms contributing to the development and maintenance of the observed metapopulation structure include dispersal of early life history stages and adult movement patterns. Tagging studies with a spring spawning component have documented cod residency and behaviour within a spawning closure, including fine-scale, multi-year spawning site fidelity and connectivity among spawning sites. Movements after the spawning season suggest that cod are primarily residential in the western Gulf of Maine. Cod movement patterns evidently play a major role in population dynamics. For example, spawning site fidelity reduces the reproductive connectivity among spawning sites and delays recolonization of abandoned spawning sites. There is sufficient connectivity among spawning sites via adult movements in order to promote gene flow within a subpopulation, but insufficient connectivity apparently exists to promote recolonization of abandoned spawning sites in other subpopulations. The complex metapopulation structure complicates the development of fishery management measures and stock assessment models which assume a homogeneous population. For example, the connectivity observed among spawning sites obscures determination of the appropriate spatial scales upon which to develop spawning protection measures.

Introduction
The Gulf of Maine stock of Atlantic cod can be described as a metapopulation consisting of genetically-distinct spring- and winter-spawning subpopulations which are each comprised of multiple finer-scale spawning components (Zemeckis *et al*., 2014a). The observed metapopulation structure appears to be developed and maintained primarily by the dispersal of early life history stages (Churchill *et al*., 2011) and adult movement patterns (Zemeckis *et al*., 2014b). In response to persistent difficulties with respect to managing rebuilding, recent research has focused on studying cod spawning dynamics (e.g. Dean *et al*., 2014) and population structure (Annala, 2012). However, significant knowledge gaps remain with respect to cod movement patterns in the Gulf of Maine. As a result, the objectives of this study were to describe the seasonal movements and population connectivity of a cod spawning component in the western Gulf of Maine, and to discuss the implications for fishery management and stock assessment.

Materials and Methods
From 2010-2013, spawning cod were captured using rod-and-reel fishing gear in the Spring Cod Conservation Zone (SCCZ), which is a seasonal fishery closure intended to prevent the extirpation of a remnant spawning component in the western Gulf of Maine (Armstrong *et al*., 2013). Cod were tagged with conventional t-bar tags (n=2,611), Vemco V16P coded acoustic transmitters (n=106), and Star-ODDI

milli-L data storage tags (DSTs) (n=266). Conventional tag recaptures were used to identify broad-scale migratory patterns and estimate the distribution of cod from the SCCZ spawning component. Acoustic telemetry receivers were deployed in the SCCZ and two other spawning sites to test for connectivity among spawning sites. In order to acquire fishery-independent movement information, geolocation methods were developed to assign daily positions to statistical areas based upon environmental data (depth, temperature, tidal signals) acquired from recovered DSTs.

Results and Discussion

Tag recapture positions (n=196) indicated that cod were generally residential in the western Gulf of Maine, with the mean distance travelled being 42.6 km ± 32.2 km (range = 0.1 – 166 km). Tag recaptures provided evidence of spawning site fidelity and connectivity among spawning sites with fish being recaptured on other spawning sites. Additional evidence of connectivity was provided by acoustic telemetry, whereas, 20.7% of fish were detected at the other monitored spawning sites up to 59 km apart. Acoustic telemetry data also documented spawning site fidelity to the SCCZ, as well as to another monitored spawning site 15 km from the SCCZ. Similarly, geolocation results indicated that cod were primarily residential in the western Gulf of Maine. However, more frequent movements to the eastern Gulf of Maine and Georges Bank were observed from the geolocation results, which were influenced by regional oceanographic conditions and the limitations of currently available geolocation methods.

Our results provided additional evidence of spawning site fidelity and connectivity to support previous observations (Zemeckis *et al*., 2014b). Both function as mechanisms contributing to the formation and maintenance of the observed metapopulation structure. Spawning site fidelity reduces the reproductive connectivity among spawning sites and delays recolonization of abandoned spawning sites. However, there is evidently sufficient connectivity to promote gene flow within a subpopulation, but insufficient connectivity to promote recolonization of abandoned spawning sites in other depleted subpopulations. The complex population dynamics complicates the development of fishery management measures and stock assessment models which assume a homogeneous population. For example, connectivity among spawning sites obscures determination of the appropriate spatial scales upon which to develop spawning protection measures. Also, the apparently limited connectivity among subpopulations presents important implications for stock identification and accurate evaluation of stock productivity and stability.

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