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Climate and fishing: Disentangling factors affecting growth in Scotian shelf haddock (*Melanogrammus aeglefinus*)

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Abstract:

Fish growth is affected by variations in a number of factors including climate (temperature) and size-selective fishing. The effects of these factors on resulting size-at-age variation must be disentangled to allow for the development of successful management strategies. Of the factors impacting variation in growth, temperature is a controlling factor governing growth via reaction rates at the cellular (metabolic) level and the effects of temperature on size-at-age variation must be examined foremost. Disentangling effects of temperature on size-at-age requires a metric relevant to the integrated growth metric that is size-at-age. In previous work, we show this physiologically relevant metric is the growing degree-day (GDD, ºC d). Here we employ the GDD metric to quantify the influence of temperature variation on a 30-yr decline in length-at-age among mature, eastern Scotian Shelf (Northwest Atlantic Fisheries Organization statistical divisions 4VW) haddock (*Melanogrammus aeglefinus*). We present evidence that remaining, temperature-independent variation in length-at-age among year-classes is consistent with sustained size-selective fishing of large (i.e. fast-growing and late-maturing) fish. We argue that size-selective fishing is the most parsimonious explanation for the systematic declines in size-at-age and age-at-maturity found in Scotian Shelf haddock.

Fisheries management strategies differ depending on the sources contributing to variation in growth and thus require that the sources of variation be identified before successful strategies can be implemented. Factors affecting size-at-age in fish populations include climate (e.g. temperature) and size-selective fishing where the latter can represent a strong selective force on size-at-age variation and changes in population growth and maturation (Law 2000; Stokes and Law 2000; Engelhard and Heino 2004; Hutchings 2005). As temperature governs growth via reaction rates at the cellular (metabolic) level (Fry 1971), the effect of temperature on size-at-age variation must be examined foremost (Brander 1995). The effects of temperature variation on metabolism are near instantaneous and these effects are integrated over time to produce the observed size-at-age that is the growth integral. Thus, examining temperature effects on size-at-age variation requires a temperature metric that is also integrated over time. For up to 270 years in most areas of ectotherm research including agriculture and entomology (Seamster 1950; Atkinson 1994; Bonhomme 2000) the thermal integral estimated as the growing degree-day (GDD, ºC d) has been successfully employed to explain ectotherm size-at-age variation in a physiologically meaningful manner. Recently it has be shown to explain >90% of variation in fish size-at-age among 41 different datasets representing a range of species, stocks, environments, temperature regimes, and laboratory and field studies (Neuheimer and Taggart 2007). Thus, the GDD metric is the 'correct' measure for examining size-at-age variation among fishes and at the time-scale that is physiologically-relevant to the phenotypic expression of growth; thereby allowing one to disentangle size-at-age variation due to variation in climate (i.e. thermal history) from that which may be attributable to other factors such as food availability, fishing effects, etc.

Scotian Shelf haddock (Northwest Atlantic Fisheries Organization, NAFO, statistical divisions 4VW; *Melanogrammus aeglefinus*) demonstrate marked declines in both length- and weight-at-age for the 3+ ages over the period 1970 through 2003 (Frank et al. 2001, Mohn and Simon 2004). These declines were coincident with declines in length- and age-at-maturity and with high fishing pressure such that during the 1980s the fishing mortality on mature fish, age-5 though -10, was two- to three-fold greater than the management target, and the fishery has been closed since 1993 (Frank et al. 2001). The declines in size and maturity occurred along with changing environmental conditions including temperature (Choi et al. 2004). Here we employ the GDD metric to estimate year-class thermal history in the 4VW haddock stock and its relation to length-at-age and demonstrate that the thermal integral explains a surprisingly small portion of the length-at-age variation, even when stock distribution changes and associated varying thermal histories are incorporated into the analyses (Neuheimer et al. 2008). We explore the length-at-age variation that is unexplained by GDD and address the role that size-selective fishing may have had in generating the long-term decline in size and maturation schedules. We address possible density-dependence effects and examine the inferred size-selective fishing effects in light of the role changes in body condition (*K; sensu* Le Cren 1951) may have had on growth and maturity.

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