The following supplements accompany the article

Effects of environmental change, fisheries and trophodynamics on the ecosystem of the western Scotian Shelf, Canada

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Supplement 1. Ecopath with Ecosim main features.

In Ecopath, for functional groups that are simple aggregate biomass pools, i.e. with no size/age structure representation, the flow to and from each functional group is described by the first Ecopath basic equation:

$$P_i = Y_i + B_i \cdot M2_i + E_i + BA_i + P_i \cdot (1 - EE_i) \qquad \text{(S1)}$$

where P_i is the total production; Y_i is the total fishery catch; B_i is the biomass; $M2_i$ is the predation mortality rate; E_i is the net migration rate (emigration – immigration); BA_i is the biomass accumulation rate; and EE_i is the 'ecotrophic efficiency' of *i,* with $P_i(1 - EE_i)$ being the other (non-predation) natural mortality term. Ecotrophic efficiency is the proportion of the production that is accounted for by fishing, predation, immigration and population growth.

The Ecopath master equation is usually expressed as:

$$B_i \cdot (P/B)_i - (P/B)_i \cdot B_i \cdot (1 - EE_i) - Y_i - E_i - BA_i - \sum_{j=1}^{n} B_j \cdot (Q/B)_j \cdot DC_{ji} = 0 \qquad \text{(S2)}$$

where P/B_i is the production/biomass ratio of *i*; B_j is the biomass of consumer or predator *j*; $(Q/B)_j$ is the consumption per unit of biomass of *j*; and DC_{ji} is the fraction of *i* in the diet of *j*.

In the second basic equation of Ecopath, the energy balance within each species or group is ensured using the equation:

$$Q_i = P_i + R_i + Q_i \cdot GS_i \qquad \text{(S3)}$$

where R_i and GS_i are the respiration and the proportion of food that is not assimilated, and the other parameters are as defined above.

In most cases, at least 3 of the 4 basic parameters (*B, P/B, Q/B* and *EE*) are required for the model parameterization. The fourth is then estimated by Ecopath. If all 4 basic parameters are entered, Ecopath then estimates either the *BA* or *E*.

Fully age/size-structured functional groups, representing ontogenetic changes in diet and changes in vulnerability to predation and fishing can be represented in Ecopath with Ecosim (EwE) as 'multi-stanzas'. In these cases, the user must enter the estimates of *B* and *Q/B* for the leading stanza, and total mortality, *Z,* for all stanzas. Note that for the functional groups represented by 2 or more stanzas, *Z* is used instead of *P/B*, since the equivalence between the 2 parameters is only valid for the population as a whole, i.e. the population averages of these parameters. In addition, estimates for *BA,* for the growth parameter *K* of the Von Bertalanffy growth function, the starting age in months of each stage and the ratio between the average weight at maturity and the asymptotic weight must be entered. The *B* and *Q/B* of the other stage(s) are then estimated by Ecopath.

The EwE multi-stanza representation is based on the following assumptions (Christensen et al. 2005): (1) body growth for the species as a whole follows a von Bertalanffy growth curve with weight proportional to length cubed; (2) the species population as a whole has had relatively stable mortality and relative recruitment rate for at least a few years, and so has reached a stable age–size distribution and (3) Q/B estimates for non-leading stanzas are estimated based on the assumption that feeding rates vary with age as the 2/3 power of body weight (a 'hidden' assumption in the von Bertalanffy growth model). For further details, see Christensen et al. (2005) and Araújo & Bundy (2011).
Ecosim is the time dynamic version of Ecopath, where Eq. (S1) is re-expressed as:

$$dB_i / dt = g_i \cdot \sum_j Q_{ji} - \sum_j Q_{ij} + I_i - (M_i + F_i + e_i) \cdot B_i \qquad \text{(S4)}$$

where dB_i/dt represents the growth rate of group i during the time interval dt in terms of its biomass (B_i); g_i is the net growth efficiency (production/consumption ratio); M_i is the non-predation $[(P/B)_i B_i(1 - EE_i)]$ natural mortality rate; F_i is the fishing mortality rate; e_i is the emigration rate; I_i is the immigration rate; and $e_iB_i–I_i$ is the net migration rate. The 2 summations estimate consumption rates, the first expressing the total consumption by group i, and the second the predation by all predators on the same group i.

For multi-stanza functional groups, Ecosim tracks numbers and biomass. Ecopath estimates of numbers and weight (N_s and W_s) per stanza are used to initialize this fully size-age structured simulation, which is performed in monthly time steps. Growth is parameterized in accordance with the von Bertallanfy growth equation curvature parameter provided (K), and the growth rates are dependent on body size and food consumption. Fecundity is assumed to be proportional to body weight, starting at the weight at maturity, which then affects egg production and recruitment of age-0 fish.

Predation and energy transfer is modelled in Ecosim using a 'foraging arena hypothesis' where only part of the population of prey i is vulnerable to predation by predator j. The flow rate between the 2 pools is called 'vulnerability', v_{ij}. As implemented, v_{ij} represents the maximum mortality that can be inflicted on prey i in the presence of infinite biomass of predator j: $v_{ij} = k_{ij}\ Q_{ijbase} / B_{ibase}$, where Q_{ijbase} is the Ecopath baseline estimate of the consumption of the species i by species j and B_{ibase} is the baseline biomass of i. The parameter $k_{ij,}$ determines the maximum Q_{ij} and is essentially a scaling factor. This parameter is a user-defined input to Ecosim and can vary from 1 to ∞, with a default value of 2. Low values cause bottom-up control, whereas high values result in top-down Lotka-Volterra predator–prey dynamics. With default handling time parameters, Ecosim calculates feeding rates of predators using the 'multispecies disc equation', a generalization of Holling's type II functional response model for multiple prey types. For additional information see, Walters & Martell (2004), Christensen et al. (2005), Araújo & Bundy (2011) and Ahrens et al. (2012).

To reduce the number of parameters to be estimated, not all groups of predators/consumers were included in the fitting procedure, and their k_{ij} were set with the default value (= 2). Groups excluded from the process comprised species for which there was either no biomass series or the series were incomplete. Preliminary tests showed that the exclusion of these parameters (18 out of 53) did not have large effects in the final results (<5% difference between runs) and had the advantage of reducing the number of parameters and of avoiding the issue of overparameterization. For groups which had their biomass forced, i.e. whales, seals and dogfish, the k_{ij} were set as 10, 100 and 10, respectively, to allow for the observed increased in their biomasses.

Supplement 2. Structure, species composition of the western Scotian Shelf/Bay of Fundy (WSS/BoF) model and additional details about data sources and methods for the modification of the 1995–2000 model to a model of the 1970s

A balanced 1995–2000 model was used as a base upon which to build the 1970s model; see Araújo & Bundy (2011) for further details of the 1995–2000 model. Here we detail the main changes made to adapt this model to a model for the 1970s.

Structural changes: Three functional groups, viz. demersal piscivores, large benthivores and flounders, were represented as single biomass pools instead of 2-stanza pools (see below).

Parameter estimation: Where available, Ecopath basic parameters, such as *B, P/B* (or *Z*) and *K* (for stanza groups), were estimated from the same data sources used for the 1995–2000 model. Where no new data were available, mainly for low trophic level groups, the values from the balanced 1995–2000 model were used.

Time-series data: This is detailed below for each functional group. When not stated, biomass/ abundance series were either not available or not considered sufficiently accurate to indicate temporal trends.

The initial percent diet composition for the 1970s model was estimated based on the food preferences from the 1995–2000 balanced model (see Araújo & Bundy 2011 for a description of this method). Since the method is based solely on the relationship between the biomass of prey groups and their proportion in the diets of predators and because the productivity and/or the relative importance of fishing mortality of some functional groups differed between the 2 periods, the 1970 model had to be balanced to account for those differences. Ten groups were unbalanced, i.e. had their $EE > 1$. Details of the necessary model adjustments both for balancing and fitting are given below.

1. Baleen whales: fin *Balaenoptera physalus*, humpback *Megaptera novaeangliae*, minke *B. acutorostrata*, right *Eubalaena glacialis* and sei whales *B. borealis*. As reported by Waring et al. (2002), current data and recent analysis suggest that the Gulf of Maine humpback whale stock is steadily increasing in size. This is considered consistent with an estimated average trend of 3.1% for the North Atlantic population in the period between 1979 and 1993, although there are no feeding-area-specific estimates. Analysis of population indices calculated from the individual sightings database for the years 1990 to 2003 suggests a positive trend in numbers for the Western Atlantic right whale population, with average growth rate of about 2% (Waring et al. 2009). There are insufficient data to determine population trends for the remaining cetacean species included in the model. An average, weighted by biomass, *BA* was estimated for the 1990s WSS/BoF model for the baleen whales. We used the *BA* (0.008 yr^{-1}) to estimate the series for the years prior to and after 1998, chosen as a baseline for the biomass, assuming that the group has been increasing steadily since the 1970s.

2. Toothed cetaceans: beaked whales *Ziphius cavirostris* and *Mesoplodon* spp., bottlenose dolphin *Tursiops truncatus*, common dolphin *Delphinus delphis*, Risso's dolphin *Grampus griseus*, harbour porpoise *Phocoena phocoena*, pilot whale *Globicephala melas* and whitesided dolphin *Lageno-rhynchus acutus*.

3. Seals: grey seal *Halichoerus grypus* and harbour seal *Phoca vitulina*. Time series of biomass for the WSS/BoF grey seals component was provided by K. Trzcinski (pers. comm.) and were derived from the modelling of grey seal–cod interactions in the eastern Scotian Shelf (ESS) and WSS populations (Trzcinski et al. 2009). Most WSS/BoF grey seals reside on the ESS and make seasonal movements onto the WSS to feed. There was no temporal trend estimates for harbour seals, hence the group’s time series trend was based solely on the grey seal model estimates.

4. Seabirds: black-legged kittiwake *Rissa tridactyla*, dovekie *Alle alle*, great black-backed gull *Larus marinus*, greater shearwater *Puffinus gravis*, herring gull *L. argentatus*, Leach's storm-petrel *Oceano-droma leucorhoa*, northern fulmar *Fulmarus glacialis*, sooty shearwater *Puffinus griseus*, thick-billed murre *Uria lomvia* and Wilson’s storm-petrel *Oceanites oceanicus*.

5. Sharks: this functional group is composed mainly of the porbeagle shark *Lamna nasus*, blue shark *Prionace glauca* and shortfin mako *Isurus oxyrinchus*. The porbeagle shark is the only species in this group for which there is a direct commercial fishery in Canadian coastal waters (Campana et al. 2009). Time series of biomass for sharks were derived from the porbeagle population model in the Northwest Atlantic (Campana et al. 2010), assuming that the WSS/BoF sharks biomass followed the same trend.

6. Large pelagics: the large pelagics are composed of highly migratory species such as swordfish *Xiphias gladius*, bluefin tuna *Thunnus thynnus*, yellowfin tuna *T. albacares*, albacore tuna *T. alalunga* and bigeye tuna *T. obesus*. A time series of biomass for this group is derived from the combined series of biomass for the north-western Atlantic bluefin tuna population (ICCAT 2008) and for the North Atlantic swordfish population biomass (ICCAT 2009), assuming that the WSS/BoF large pelagic biomass followed the same trend. The *P/B* ratio in the final model was increased by 30%.

7−10. Cod *Gadus morhua*: this group is represented by 4 stanzas or age groups: <1, 1–3, 4–6 and 7+ yr. The biomass series is based on the cod virtual population analysis (VPA) assessment data for the NAFO 4X Division cod stock (Clark & Emberley 2009). The VPA model uses a knife-edge increase in *M* for age 4+ cod from 0.2 to about 0.7 yr^{-1} in 1996 (Clark & Emberley 2009). To reproduce the total mortality trend in Ecosim and force the biomass estimates to better fit the VPA series, we used a 'fake' series of fishing mortality produced by adding 0.5 to the actual fishing mortality, for the years that VPA *M* was set equal to 0.7 yr^{-1} in the base scenarios for the time series fitting and then assessed the main hypothesis for the high level of unexplained natural mortality in a scenario that included predation by seals.

11−13. Silver hake *Merluccius bilinearis*: this group is represented by 3 stanzas: <2, 2–3 and 4+ yr. Input biomass for the leading stanza (4+) was increased by 10%, and the *Z* estimate for silver hake <2 yr was increased by 15%. The time series of biomass was derived from the DFO research summer survey data. The series was smoothed using a 3 yr running mean.

14−16. Halibut: the halibut functional group includes the Atlantic halibut *Hippoglossus hippoglossus* and Greenland halibut, or turbot, *Reinhardtius hippoglossoides*, which occurs sporadically and in very low numbers in the WSS/BoF area. The group is represented by 3 stanzas: <46, 46–81 and 82+ cm. Time series were derived from the Atlantic halibut population model in the NAFO Divisions 3NOPs4VWX5Zc, which were provided by K. Trzcinski (pers. comm.). Total mortality estimates (*Z*) for halibut halibut <46 and 46–81 cm were changed by –30 and +33%, respectively.

17−18. Pollock *Pollachius virens*: this group is represented by 2 stanzas: <4 and 4+ yr old. Time series data were derived from the pollock VPA model in the NAFO Divisions 4Xopqrs5Yb5Zc (Stone et al. 2009). The VPA series starts in 1982. The biomasses for the years 1970 to 1981 were estimated using landings data for the same year and the linear relationship between landings and biomass for the years 1982 to 2008. Biomass for pollock aged 4+ was reduced to 82% of the initial estimate, and *Z* estimates for pollock <4 and 4+ changed by –4 and +17%, respectively.

19. Demersal piscivores: this group comprised white hake *Urophycis tenuis*, cusk *Brosme brosme*, sea raven *Hemitripterus americanus* and monkfish *Lophius americanus*, all demersal, highly piscivorous species. The time series of biomass was derived from the DFO research summer survey data. The series was smoothed using a 3 yr running mean.

20. Large benthivores: this is a generic group composed of several demersal benthivore species with reported maximum sizes above 50 cm. The main species in the group are red hake *Urophycis chuss*, ocean pout *Macrozoarces americanus*, striped Atlantic wolffish *Anarhichas lupus* and lumpfish *Cyclopterus lumpus*. Biomass and *P/B* estimates were increased by 31 and 15%, respectively. The time series of biomass was derived from the DFO research summer survey data. The series was smoothed using a 3 yr running mean.

21–22. Skates: this group includes thorny skate *Raja ocelleta*, winter skate *R. radiata*, smooth skate *R. senta*, little skate *R. erinacea* and barndoor skate *R. laevis*. The group was split into small (<49 cm) and large (49+ cm). The time series of biomass was derived from the DFO research summer survey data. The series was smoothed using a 3 yr running mean.

23. Dogfish *Squalus acanthias*: the time series of biomass was derived from the DFO research summer survey data. The series was smoothed using a 3 yr running mean.

24–25. Redfish: the redfish functional group includes redfish *Sebastes* spp., which account for most of the biomass, and rosefish *Helicolenus dactylopterus*. The group is represented by 2 stanzas: <22 cm and 22+ cm. The time series of biomass was derived from the DFO research summer survey data. The series was smoothed using a 3 yr running mean.

26–27. American plaice *Hippoglossoides platessoides*: it is treated here as separate from the other flounder group because it is more piscivorous than the other species. The group is represented by 2 stanzas: <26 cm and large stanzas 26+ cm. The time series of biomass was derived from the DFO research summer survey data. The series was smoothed using a 3 yr running mean.

28. Flounders: this group includes the yellowtail flounder *Limanda ferruginea*, witch flounder *Glyptocephalus cynoglossus* and winter flounder *Pseudopleuronectes americanus*. Biomass and P/B estimates were increased by 21 and 10%, respectively. The time series of biomass was derived from the DFO research summer survey data. The series was smoothed using a 3 yr running mean.

29–30. Haddock *Melanogrammus aeglefinus*: the group is represented by 2 stanzas: <3 and 3+ yr old. The times series of biomass estimates were derived from survey data. Series of recruitment, natural mortality and average weight were derived from the haddock random-walk-*M* VPA model in the NAFO Divisions 4X (Mohn et al. 2010; R. Mohn pers. comm). The biomass for the leading stanza (aged 3+) was increased by 26%. Total mortality estimates for haddock <3 and 3+ were changed by +9 and –9%, respectively, and BA for the group was decreased from 0.05 to –0.02 yr^{-1}.

31–32. Longhorn sculpin *Myoxocephalus octodecemspinosus*: the group is represented by 2 stanzas: <25 and 25+ cm. Total mortality estimates for sculpin <25 and 25+ cm were decreased by 11 and 3%, respectively, and the BA for the group was increased from 0.05 to 0.1 yr^{-1}. The time series of biomass was derived from the DFO research summer survey data. The series was smoothed using a 3 yr running mean.

33–34. Herring *Clupea harengus*: the group is represented by 2 stanzas: <4 and 4+ yr. The time series of biomass estimates was derived from the NAFO Divisions 4WX herring stock VPA analysis, most recent results provided by M. Power (pers. comm.). Total mortality estimates for herring <4 and 4+ yr were changed by –7 and +22%, respectively.

35. Other pelagics: the other pelagic group includes several small to medium pelagic species such as Atlantic argentine *Argentina silus*, American shad *Alosa sapidissima*, alewife *A. pseudo-harengus*, sand lance *Ammodytes dubius* and capelin *Mallotus villosus*. The main species in the group in terms of biomass are Atlantic argentine, American shad and alewife. The P/B rate for the group was reduced by 5% and the BA changed from 0 to –0.05 yr^{-1}. The time series of biomass was derived from the DFO research summer survey data. The series was smoothed using a 3 yr running mean.

36. Mackerel: Northwest Atlantic Mackerel is currently assessed as a single stock unit, whose distribution ranges from North Carolina to Labrador (NAFO subareas 2 to 6). There are 2 major spawning areas, 1 located in the Gulf of St. Lawrence and a second in the Gulf of Maine and Georges Bank area. The species is highly migratory, and the seasonal distribution is influenced by temperature. Although biomass estimates for mackerel could be derived from the July Department of fisheries and Oceans research vessel survey, by July most 4X mackerel are in the inshore waters of the WSS, outside the surveyed area. Hence, VPA data for Northwest Atlantic mackerel (J. Deroba pers. comm.) were used to estimate mackerel biomass in the 4X division. The total population landings to biomass ratio (used as a proxy for the average population *F*) and the 4X landings were used to estimate the series of biomass for the 4X biomass from *L*/*F*. The initial biomass for the group was reduced by 30%.

37. Mesopelagic (mainly Myctophidae).

38. Small-medium benthivores: this is a generic group composed of several demersal benthivore species with reported maximum sizes around 40 cm. The main species in the group are longfin hake *Phycis chesteri*, fourbeard rockling *Enchelyopus cimbrius*, mailed sculpin *Triglops murrayi*, Arctic hookear sculpin *Artediellus uncinatus*, Atlantic hookear sculpin *A. atlanticus*, alligatorfish *Aspido-phoroides monopterygius*, marlin-spike grenadier *Nezumia bairdi* and snake blenny *Lumpenus lumpretaeformis*. The time series of biomass was derived from the DFO research summer survey data. The series was smoothed using a 3 yr running mean.

39. Squids: the dominant species of squid in the WSS/BoF region is the northern shortfin squid *Illex illecebrosus*. The time series of biomass was derived from the DFO research summer survey data. The series was smoothed using a 3 yr running mean.

40. Lobster *Homarus americanus*: lobsters and crabs were not systematically recorded in the summer DFO RV Groundfish survey before 1999, and data before this year are not considered a good indicator of species abundance (D. Pezzack pers. comm.). Stratified mean numbers per tow of American lobster in the Gulf of Maine (Northeast Fisheries Science Center, NFSC, autumn bottom trawl survey) have been recorded since 1981 and were available until 2006. The standardized (using the 1999 to 2006 average as the baseline) NFSC series trend (linear regression slope = 0.0348; 95% CI: 0.0156–0.0540) was quite similar to the standardized 4X landings series trend (linear regression slope = 0.0341; 95% CI: 0.0295–0.0387) for the period between 1981 and 2006. Hence, the relative index of abundance of lobster for the period between 1981 and 1998 was based on the NFSC. From 1970 and 1980 it was assumed that the abundance was constant, and after 1998 the index was derived from the DFO summer survey data. The 1970 biomass model estimate for lobster was increased by 60%, while its *P*/*B* and *Q*/*B* were reduced by 29%.

41−42. Large and small crabs: the large crabs group includes species with maximum carapace width that normally exceeds 100 mm, such as Jonah crab *Cancer borealis*, rock crab *C. irroratus*, snow crab *Chionoecetes opilio*, deep sea red crab *Geryon quinquedens*, toad crab *Hyas araneus*, porcupine crab *Neolithodes grimaldi* and northern stone crab *Lithodes maja*. The small-medium crabs group includes species such as lyre crab *Hyas coarctatus*, *Catapagurus gracilis* and hermit crabs *Pagurus acadianus* and *P. pubescens*. Similarly to lobsters, the crabs were not systematically recorded in the summer DFO RV Groundfish survey before 1999. The series for the large crabs group starts in 1999, and only those years are used in the fitting procedure.

43. Shrimps: this group includes several shrimp and some shrimp-like crustacean species. The taxa that have been identified in samples and/or local stomach contents data are: *Argis dentata*, *Axius serratus* (shrimp-like), *Crangon septemspinosa*, *Eualus pusiolus*, *Dichelopandalus letptoceras*, *Lebbeus groenlandicus*, *L. polaris*, *Pandalus borealis*, *P. montagui*, *P. propinquus, Pasiphaea multidentata*, *Spirontocaris liljeborgii* and *S. spinus*. Baseline estimates of *P*/*B* and *Q*/*B* were increased by 50%. The time series of biomass was derived from the DFO research summer survey data. The series has just a few years of observations.

44. Scallop *Placopecten magellanicus*: the WSS/BoF scallop aggregations are managed and assessed as discrete populations or stocks that occur within the scallop production areas (SPAs; DFO 2008). Population assessment models are available for some of these areas. The time series of biomass was derived from average exploitation rate parameters for the SPAs 1A, 1B, 3 and 4, which were provided by

S. Smith (pers. comm.). Hence, the biomass in each year was estimated from the biomass = landings/ exploitation rates for those SPAs and the total landings in the WSS/BoF area. Since exploitation rates were available only from 1983, biomass estimates prior to this were obtained by using a fixed average exploitation rate estimated from data in the years from 1983. The series was smoothed using a 3 yr running mean.

45. Bivalves: based on benthic data from Peer et al. (1980), Theroux & Wigley (1998) and Wildish et al. (1989), the 8 most important bivalve species in the WSS/BoF region in terms of biomass are: horse mussel *Modiolus modiolus*, ocean quahog *Arctica islandica*, *Astarte undata*, *Cyclocardia borealis*, *Astarte crenata subequilatera*, *Cytodaria sliqua*, *Astarte* sp., and *Tridonta borealis*.

46. Other molluscs: this functional group is composed of the Mollusca classes Gastropoda, Amphineura and Scaphopoda.

47. Other arthropods: this group is composed of small arthropods that live on or burrow into the benthic interface or swarm off the bottom such as Amphipoda (dominant group), Mysidacea, Cumacea, Isopoda, Tanaidacea and Pycnogonida.

48. Echinoderms: this group includes all echinoderms except the class Crinoidea, which was included in the sessile benthic functional group.

49. Sessile species: this is a very generic group composed of the taxa Ascidiacea, Brachiopoda, Bryozoa, Cnidaria, Cirripedia, Crinoidea and Porifera.

50. Worms: the dominant taxon in terms of biomass in this generic functional group are the annelids (polychaetes), followed by the taxon Sipuncula (peanut worms) and then by others that represented a small amount of the group's biomass (Chaetoderma, Nematoda, Nemertea, Pogonophora).

51. Meiofauna: meiofauna are defined as interstitial organisms that are retained on a 40 μm mesh sieve, but pass through a 1 mm sieve.

52–55. Zooplankton and micronekton: the zooplankton realm is composed of 4 functional groups: gelatinous, macro (>1 cm, mainly euphausiids), meso- (between 0.2 and 10 mm length, mainly copepods) and microzooplankton (<0.2 mm). Time series of abundance for macro- and mesozooplankton were derived from data provided by C. Johnson and E. Head (pers. comm.). The series are incomplete.

56–57. Microflora (bacteria and auto-/heterotrophic nanoflagellates) and phytoplankton.
In addition to the changes made to the parameters described above, changes were made to the diet input data. Largest average changes to diet data were made to silver hake <2 yr and herring 4+ yr, whose proportions were changed, on average, by about –27 and +16% in the diets of their predators, respectively. In most cases, 77% of food (prey) items, average changes for prey items were within –10 and +10% of initial diet data.

Supplement 3. Fish condition and recruitment

In order to examine how fish condition has changed over time, we calculated the standardized residuals (*Z*-scores) of observed condition for some of the most common finfish species in the WSS/BoF (Fig. S1). At the aggregate level, the average of the *Z*-scores in Fig. S1 was positively correlated with the primary production estimated by Ecosim ($r = 0.668$, $p < 0.0001$) and other low trophic level organisms (see Fig. 2 in the main text), indicating a positive, bottom-up relationship between productivity and condition.

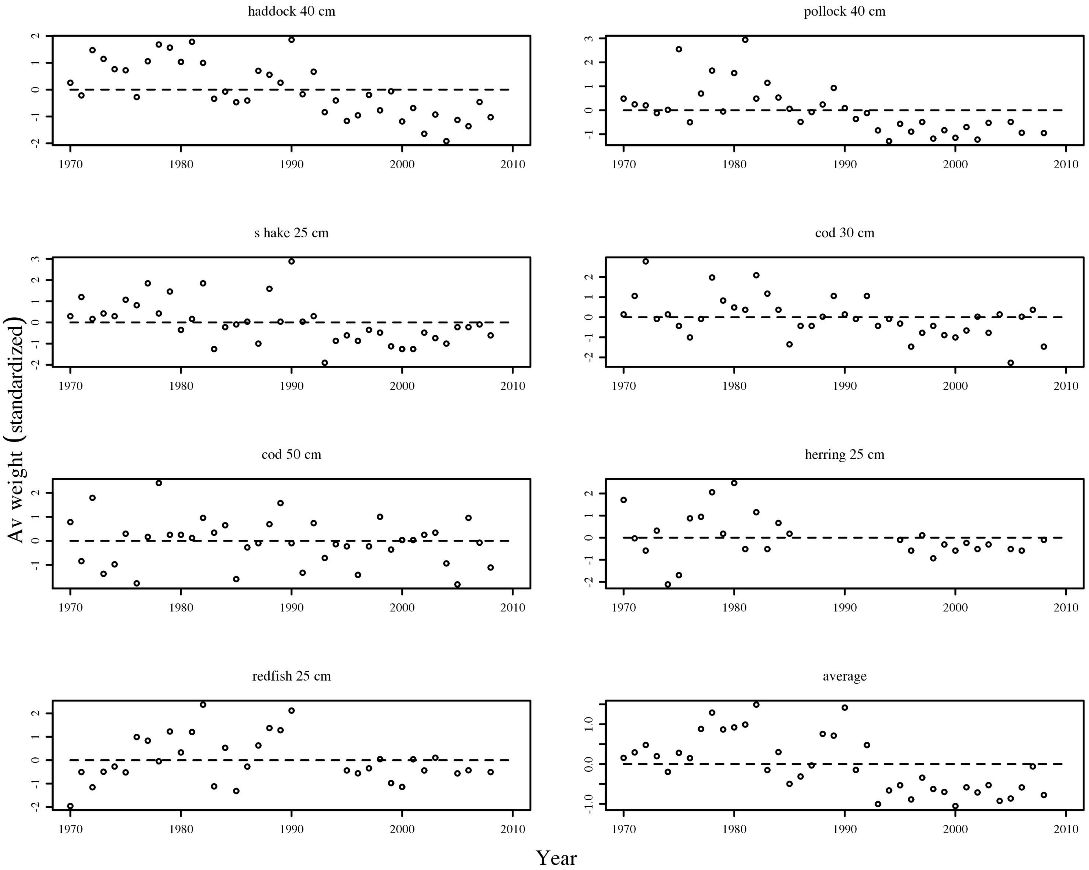

Fig. S1. Standardized condition residuals (*Z*-scores) for some of the most common finfish species in the WSS/BoF. Average of species was estimated using the data for all species except cod 50 cm: haddock *Melanogrammus aeglefinus*, pollock *Pollachius virens*, silver hake *Merluccius bilinearis*, cod *Gadus morhua*, herring *Clupea harengus*, redfish *Sebastes* spp.). Standardized residuals are estimated as $(X_i - \overline{X}) / SD$, where X_i is the observed variable, $\overline{X}$ is the series average, and *SD* is the standard deviation

We used the residuals from stock-recruitment functions as an index of relative survival in the first year of life (since fish recruitment is related to the level of the spawning biomass) and examined how this changed for 3 key species over time (only cod, herring and haddock have age-based estimates of spawning and recruitment extending back to the 1970s or earlier periods in the WSS/BoF). The standardized residuals of Beverton and Holt-type functions for these species (Fig. S2) suggest that survival of larvae and young fish was above average in the 1970s and early 1980s. Then there was a shift to below-average survival for herring and haddock from the early or mid-1980s to the late 1990s, followed by improved survival in the 2000s. Cod had a few good recruitment events after the early 1980s, but most residuals were negative and hence survival tended to be below average. These trends resemble the decadal trends observed for *Calanus* I–IV, *C. finmarchicus* V–VI and euphausiids (Head & Pepin 2010) and the predicted trends in the meso- and macrozooplankton in the Ecosim primary production forcing scenario. It is noteworthy that the best period for recruitment for all 3 species occurred in the 1970s and early 1980s, a time when most large fish piscivorous species were at their peak abundance (Zwanenburg et al. 2002).

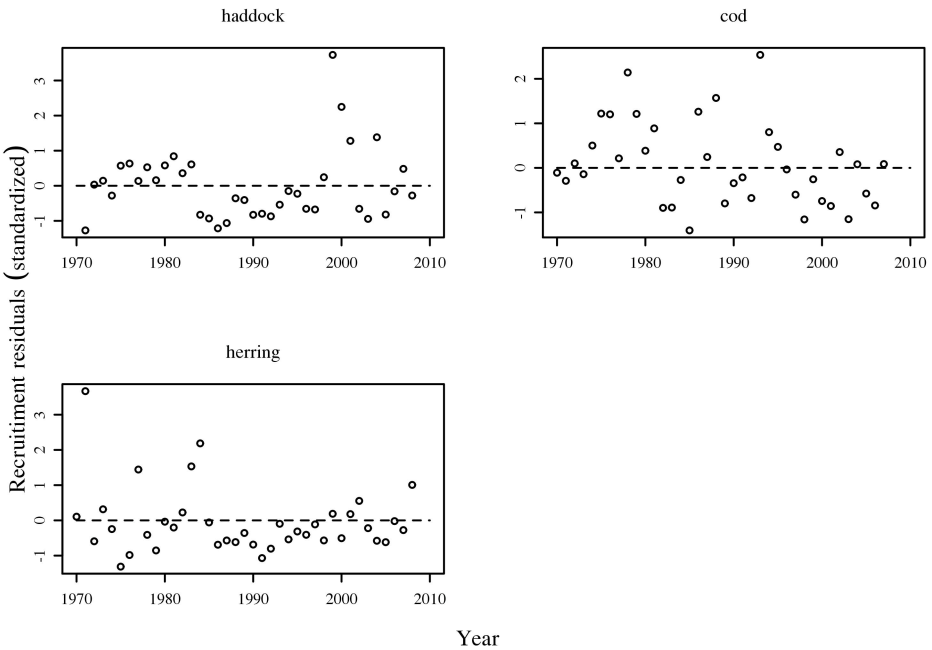

Fig. S2. *Melanogrammus aeglefinus*, *Gadus morhua* and *Clupea harengus*. Standardized residuals of Beverton and Holt-type functions for WSS/BoF haddock, cod and herring. Spawning stock biomass and recruitment data for herring were provided by M. Power (pers. comm.); for haddock by R. Mohn (pers. comm.) and for cod by D. Clark (pers. comm.). Standardized residuals are estimated as $(x_i - \bar{x}) / SD$, where X_i is the observed variable, $\overline{X}$ is the series average, and SD is the standard deviation

LITERATURE CITED

Ahrens R, Walters C, Christensen V (2012) Foraging arena theory. Fish Fish 13:41−59

Araújo JN, Bundy A (2011) Description of three Ecopath with Ecosim ecosystem models developed for the Bay of Fundy, western Scotian Shelf and NAFO Division 4X. Can Tech Rep Fish Aquat Sci 2952: xii + 189 p

Campana SE, Joyce W, Manning MJ (2009) Bycatch and discard mortality in commercially caught blue sharks *Prionace glauca* assessed using archival satellite pop-up tags. Mar Ecol Prog Ser 387:241−253

Campana SE, Gibson AJF, Fowler M, Dorey A, Joyce W (2010) Population dynamics of porbeagle in the northwest Atlantic, with an assessment of status to 2009 and projection for recovery. Collect Vol Sci Pap ICCAT 65(6): 2109–2182

Christensen V, Walters C, Pauly D (2005) Ecopath with Ecosim: a user's guide. Fisheries Centre, University of British Columbia, Vancouver, BC

Clark DS, Emberley J (2009) Assessment of cod in division 4X in 2008. Sci Advis Sec Res Doc 2009/018. Department of Fisheries and Oceans Canada, St. Andrews

DFO (Department of Fisheries and Oceans Canada) (2008) Assessment of Georges Bank scallops (*Placopecten magellanicus*). Sci Advis Sec Sci Advis Rep 2008/045. Department of Fisheries and Oceans Canada, Dartmouth

Head EJH, Pepin P (2010) Spatial and inter-decadal variability in plankton abundance and composition in the northwest Atlantic (1958−2006). J Plankton Res 32:1633−1648

ICCAT (International Commission for the Conservation of Atlantic Tunas) (2008) Report of the 2008 Atlantic bluefin tuna stock assessment session. ICCAT, Madrid

ICCAT (2009) Report of the 2009 Atlantic swordfish stock assessment session. ICCAT, Madrid

Mohn RK, Trzcinski MK, Black GAP, Armsworthy S, Young GA, Comeau PA, den Heyer CE (2010) Assessment of the status of division 4X5Y haddock in 2009. Sci Advis Sec Res Doc 2010/085. Department of Fisheries and Oceans Canada, Dartmouth

Peer D, Wildish DJ, Wilson AJ, Hines J, Dadswell M (1980) Sublittoral macro- infauna of the lower Bay of Fundy. Can Tech Rep Fish Aquat Sci 981:1–92

Stone H, Nelson C, Clark D, Cook A (2009) 2008 assessment of pollock in 4vwx+5. Sci Advis Sec Res Doc 2009/001. Department of Fisheries and Oceans Canada, St. Andrews

Theroux RB, Wigley RI (1998) Quantitative composition and distribution of macrobenthic invertebrate fauna of the continental shelf ecosystems of the northeastern United States. Tech Rep NMFS 140. US Department of Commerce, NOAA, Seattle, WA

Trzcinski MK, Mohn R, Bowen WD (2009) Estimating the impact of grey seals on the eastern Scotian Shelf and western Scotian Shelf cod populations. Sci Advis Sec Res Doc 2009/052. Department of Fisheries and Oceans Canada, Dartmouth

Walters CJ, Martell SJ (2004) Fisheries ecology and management. Princeton University Press, Princeton, NJ

Waring GT, Quintal JM, Fairfield CP (2002) US Atlantic and Gulf of Mexico marine mammal stock assessments—2002. Tech Mem NMFS NE 169. US Department of Commerce, NOAA,

Waring GT, Josephson E, Fairfield-Walsh CP, Maze-Foley K (2009) U.S. Atlantic and Gulf of Mexico marine mammal stock assessments—2008. Tech Mem NMFS NE 210. US Department of Commerce, NOAA, Woods Hole, MA

Wildish DJ, Wilson AJ, Frost B (1989) Benthic macrofaunal production of Browns Bank, Northwest Atlantic. Can J Fish Aquat Sci 46:584–590

Zwanenburg K, Bowen D, Bundy A, Frank K and others (2002) 4 decadal changes in the Scotian Shelf large marine ecosystem. In: Sherman K, Skjoldal HR (eds) Large marine ecosystems of the North Atlantic—changing states and sustainability, Vol 10. Elsevier, Amsterdam, p 105–150