

ECOLOGY

Managing Evolving Fish Stocks

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Darwinian evolution is the driving process of innovation and adaptation across the world's biota. Acting on top of natural selection, human-induced selection pressures can also cause rapid evolution. Sometimes such evolution has undesirable consequences, one example being the spreading resistance to antibiotics and pesticides, which causes suffering and billion-dollar losses annually (1). A comparable anthropogenic selection pressure originates from fishing, which has become the main source of mortality in many fish stocks, and may exceed

natural mortality by more than 400% (2). This has, however, been largely ignored, even though studies based on fisheries data and controlled experiments have provided strong empirical evidence for fisheries-induced evolution over a range of species and regions (see table, page 1248). These evolutionary changes are unfolding on decadal time scales—much faster than previously thought.

Life-history theory predicts that increased mortality generally favors evolution toward earlier sexual maturation at smaller size and elevated reproductive effort. Fishing that is selective with respect to size, maturity status, behavior, or morphology causes further evolutionary pressures (3). Evidence that harvesting can bring about genetic changes comes from breeding programs in aquaculture, which have shown heritable genetic variation in numerous traits (4), and from experiments showing harvest-induced evolution in just a few generations (table S1). Furthermore, analyses of fisheries data spanning a few decades have detected widespread changes in maturity schedules that are unlikely to be explained by environmental influences alone (table S2). Although alternative causal hypotheses can be difficult to rule out, fisheries-induced evolution consistently arises as the most parsimonious explanation after environmental factors have been accounted for. The

Evolutionary impact assessment is a framework for quantifying the effects of harvest-induced evolution on the utility generated by fish stocks.

question is not whether such evolution will occur, but how fast fishing practices bring about evolutionary changes and what the consequences will be.

Life-history traits are among the primary determinants of population dynamics, and their evolution has repercussions for stock biomass, demography, and economic yield (5, 6). Fisheries-induced evolution may also be slow to reverse or even irreversible (5), with implications for recruitment and recovery (7). Consequently, predator-prey dynamics, competitive interactions, relative species abundances, and other ecological relationships will systematically change over time. Current management reference points are thus moving targets: Stocks may gradually become less resilient or may be erroneously assessed as being within safe biological limits. Some evolutionary trait changes will even have the potential to cause nonlinear ecological transitions and other unexpected outcomes (8). Fisheries-induced evolutionary changes are therefore pertinent beyond single-species management.

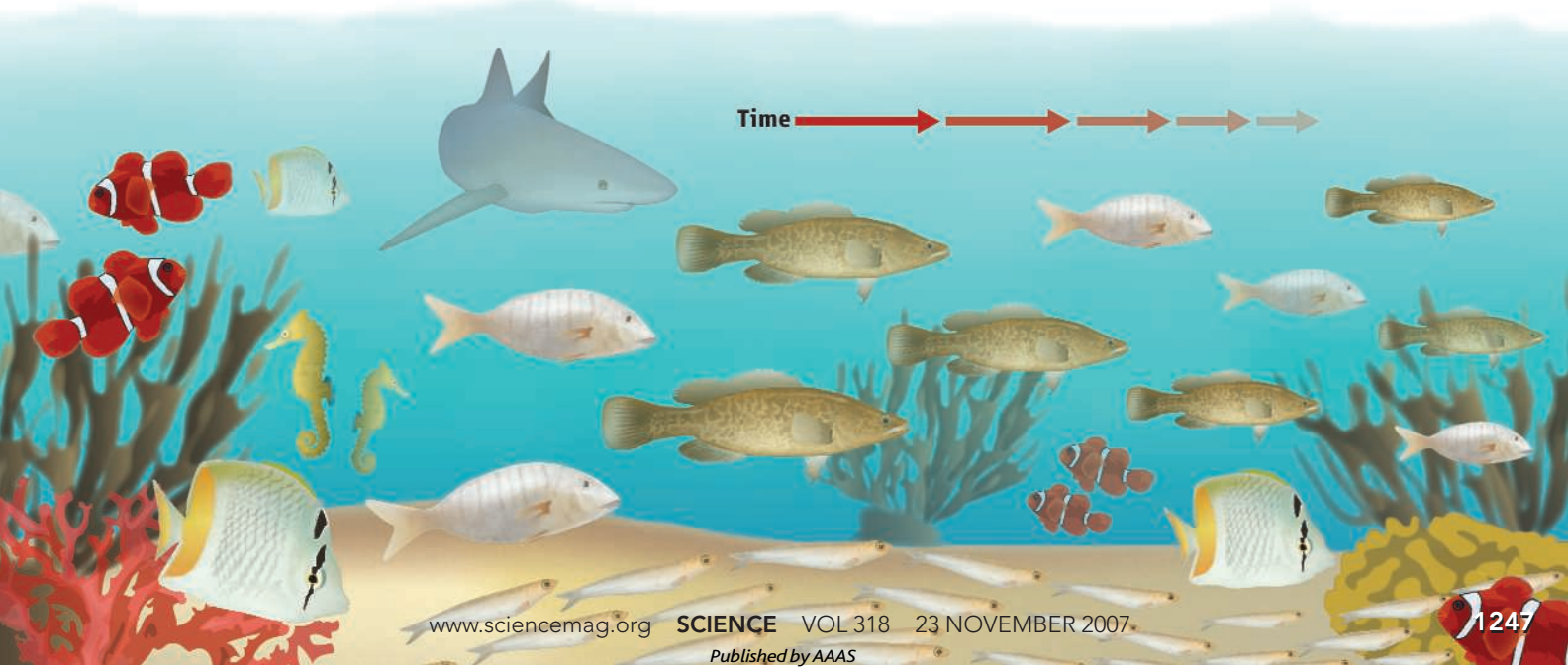
An evolutionarily enlightened management approach is needed (5, 6, 9). Although

Moving targets. Fishing not only reduces the number of fish in the sea, but also changes their heritable features. This may reduce the body size of the fish.

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some fish stocks will be managed primarily to maximize sustainable yield, successful management of fisheries-induced evolution will generally benefit from the recognition of a broader range of ecological services generated by living aquatic resources (fig. S1). This perspective emphasizes that evolution underlies ecology and influences economies. An evolutionary perspective will, therefore, (i) support the ecosystem approach to fisheries management (10–13) by considering how evolution alters ecological relations and management reference points, (ii) comply with the precautionary approach (14) by accounting for uncertainty and risk, and (iii) respect the Johannesburg summit's commitment to the restoration of sustainable fisheries (15).

Environmental impact assessments are commonly used to evaluate the consequences of human activities for ecosystems and society. We propose evolutionary impact assessment (EvoIA) as a tool for the management of evolving resources. Conceptually, an EvoIA involves two major steps. The first relies on biological information and describes how human actions, such as fishing, lead to trait changes. The second step addresses how trait changes affect the stock's utility to society. Any definition of utility has to reflect management objectives and needs to be developed with stakeholder involvement. Evolutionary impact is then assessed as the change in utility of a stock as a result of fisheries-induced evolution.

Economically valuable stocks typically have a long history of exploitation; for such stocks, a natural starting point to help prioritize management efforts is a retrospective assessment of past evolutionary change [e.g., (16, 17)]. Given suitable fisheries data, new statistical techniques can assess the extent to which evolutionary changes may have occurred (18).

A more detailed understanding will typically rely on evolutionary models. For example, Northeast Arctic cod was identified as being susceptible to large evolutionary changes in maturation, because offshore trawling, introduced in the 1920s, reversed earlier selection pressures (5).

An EvoIA goes a step further, linking evolution to an impact on utility. EvoIAs that look forward in time and compare alternative management options will have to rely on evolutionary models to provide quantitative predictions. In these prospective EvoIAs,

Harvest-induced evolutionary changes in marine and freshwater fish.

| Evolutionary change | No. of species | No. of studies | Change % (n) |
|----------------------------|----------------|----------------|--------------|
| Maturation at lower age | 6 | 10 | 23–24 (1) |
| Maturation at smaller size | 7 | 13 | 20–33 (3) |
| Lower PMRN midpoint | 5 | 10 | 3–49 (13) |
| Reduced annual growth | 6 | 6 | 15–33 (3) |
| Increased fecundity | 3 | 4 | 5–100 (3) |
| Loss of genetic diversity | 3 | 3 | 21–22 (2) |

Fisheries-induced evolution has been demonstrated in several species and studies, for some stocks (n) the magnitude of change could also be quantified. Analyzed time series covered between 13 and 125 years. PMRN, probabilistic maturation reaction norm (18). The documented evolutionary changes potentially affect fishery yield, recreational fishing experience, tourism revenue, trophic interactions, resilience to fishing, resilience to environmental fluctuations, and adaptability (e.g., to climate change). Further details are given in table S2 and fig. S1.

projections of future utility depend not only on how fishing affects traits, but also on how trait changes alter ecological relations, which in turn affect utility (fig. S2). Empirical and theoretical studies have shown that many life-history traits are prone to rapid harvest-induced evolution. These traits are important because they influence a population's demography and harvestable biomass. However, life-history traits are also shaped by, and have implications for, density-dependence, trophic interactions, geographical distribution, migration patterns, behavior, and sexual selection. Furthermore, the risk of adverse ecological consequences intensifies, because of nonlinear effects, as traits evolve further away from their historic distributions. Prospective EvoIAs will thus rely on life-history models that, ultimately, should address a broad range of mechanisms and traits influenced by fishing (19).

A baseline for comparison is the continuation of a business-as-usual scenario, with evolutionary and utility projections based on the current fishing regime. This allows the cost of inaction to be quantified for different time horizons. Further, utility can be calculated for alternative management scenarios. This identifies management regimes that have the least negative, or even positive, effects on utility (fig. S2). Cumulative utility and its net present value will depend on the choice of time horizons and discounting rates (20).

A central challenge to all EvoIAs is to define evolutionarily enlightened management objectives that can be translated into unified utility metrics integrating disparate social values. Pragmatically, such objectives are more likely to be implemented if they

harmonize with the pressing short-term goals of traditional fisheries management (21). In the context of fisheries-induced evolution, utility metrics might include yield and its variability and sustainability, conservation of genetic and phenotypic diversity, the role of a harvested species in ecosystem functioning, and implications for recreational fishing and tourism. The current state of each of these factors may be eroded either directly through fisheries-induced evolution or indirectly through the ecosystem-level implications of such evolution.

Fisheries-induced evolution is likely to diminish yield and degrade ecological services within decades, having an impact on species, ecosystems, and societies. Evolutionary effects could magnify the ecological challenges that already threaten sustainable harvesting. Successful management, therefore, will require the ecological and evolutionary consequences of fishing to be evaluated and mitigated. Adopting EvoIAs will enable fisheries managers to rise to this challenge.

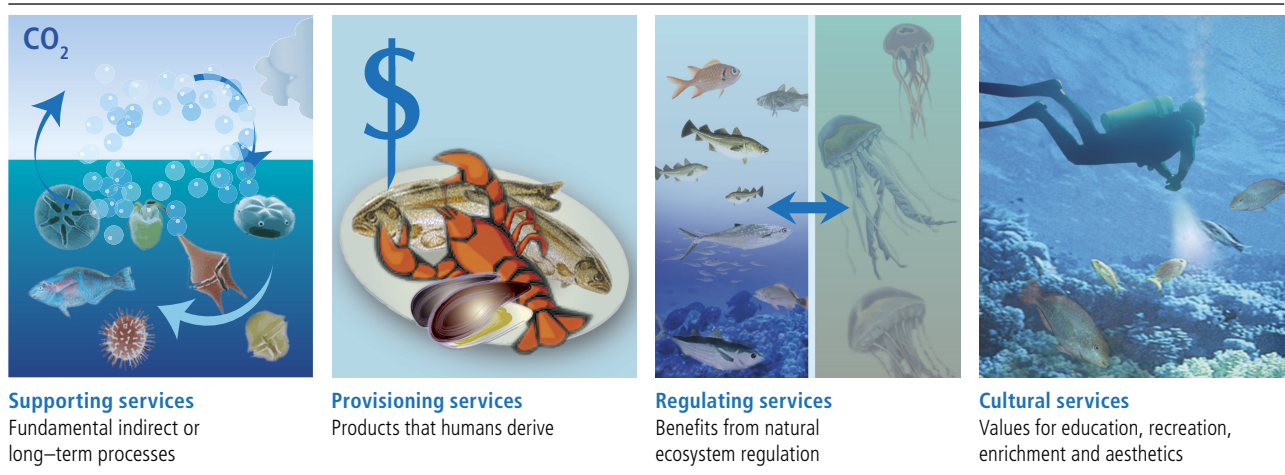
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Supporting Online Material

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Evolution toward smaller size and earlier maturation might alter:

- Top-down control of nutrient cycling
- Fisheries yield and stability
- Trophic interactions and geographical distributions
- Intrinsic value of species and ecosystems
- Recovery potential
- Presence or abundance of big fish of special value
- Pest and invasion control
- Recreational fishing experience

Erosion of natural genotypic and phenotypic diversity might affect:

- Structure of ecological niches
- Benefits to tourism industry
- Resilience to environmental fluctuations
- Enjoyment of nature
- Food product diversity
- Adaptability to climate change
- Indigenous and local culture

Fig. S1. Examples of utility components potentially affected by fisheries-induced evolution. Aquatic ecosystems produce four categories of ecological services of direct and indirect utility to society (ref. S1, S2). Using these definitions as a basic framework will facilitate discussions among stakeholders with different backgrounds and assist in the prioritization of objectives and actions. Potential effects are shown for the two most ubiquitous effects of fisheries-induced evolution: (i) reductions in body size and maturation age; and (ii) erosion of natural genotypic and phenotypic diversity.

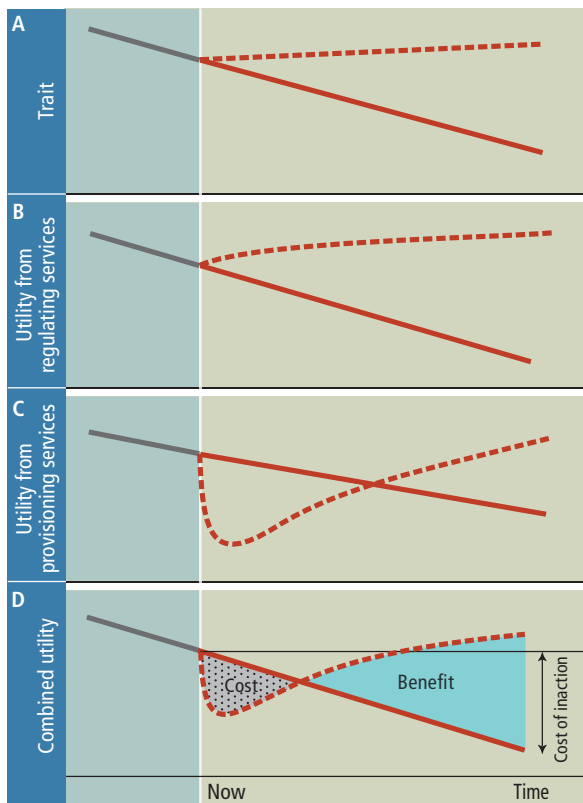


Fig. S2. Sketch of a prospective Evolutionary Impact Assessment (EvoIA) comparing two management scenarios. Using appropriate models, the consequences of fisheries-induced evolution can be quantified using a utility function. In this hypothetical scenario of an EvoIA, the red solid lines refer to business-as-usual: moderate overfishing causes continued evolution at a constant rate (A), resulting in steadily declining regulating services (B) and reduced catches (C) (see Fig. S1 for terminology and examples of how ecological services might be affected). In comparison (red dotted lines), a sufficiently strong reduction in harvest rate will in this example slowly reverse trends in trait evolution and thereby improve regulating services, while also causing a significant short-term loss of yield. When evaluating management strategies, the difference in combined utility (D) depends on the time horizon considered. The cost of inaction (vertical arrow) is defined as the loss of utility, relative to its present value, if current fishing practices are continued. In this example, reduced fishing leads to a temporary loss of combined utility that is compensated for by a long-term gain, as indicated by the areas marked 'Cost' and 'Benefit' in (D).

Table S1. Experimental studies demonstrating evolutionary changes caused by harvesting in aquatic animals.

| Species | Data period | Evolutionary change | Reference |
|--|---------------------------------|--|-----------|
| Atlantic silverside <i>Menidia menidia</i> * | 4 generations (4 years) | Decreased growth rate | S3 |
| | | Decreased fecundity, egg volume, larval size at hatching, larval growth rate, larval survival, food consumption, growth efficiency, food conversion efficiency, willingness to forage under threat of predation, and number of vertebrae | S4 |
| Water flea <i>Daphnia magna</i> * | 37 generations (148 days) | Decreased growth rate and delayed maturation | S5 |
| Guppy <i>Poecilia reticulata</i> § | 11 years (30–60 generations) | Smaller size and age at maturation, higher number of offspring, smaller offspring size, higher reproductive allocation, shorter time interval between successive litters | S6, S7 |
| Largemouth bass <i>Micropterus salmoides</i> # | 4 generations | Reduced parental care, reduced resting metabolic rate, poorer swimming performance | S8 |
| <i>Tilapia mossambica</i> | 75 months | Decreased growth rate | S9 |

*Effects are for lines in which large individuals were harvested. §Effects are for fish experiencing high predation pressure. #Effects are for treatments in which fish vulnerable to recreational fishing were removed.

Table S2. Empirical studies suggesting evolutionary changes caused by fisheries in wild populations. Inclusion criteria:

Studies were included that (i) documented changes in a quantitative trait over time or between populations that experienced different fishing regimes, (ii) attempted to account for environmental factors that could have caused the trend in the trait, and (iii) concluded that fisheries-induced evolution was a likely cause for the observed changes. We thus omitted negative findings, as well as reports of changes that might have been evolutionary but where the authors concluded otherwise or did not discuss evolution as a potential cause. Studies may be listed under more than one trait. The statistical procedures for estimating probabilistic maturation reaction norms are reviewed in ref. S10. *Quantification of evolutionary change:* For studies that included time series or compared different periods and contained quantitative information on the evolutionary change, we used either estimates from reported linear regressions with respect to time, or means of several years at the beginning and end of the data periods. Adjusted phenotypic trends were used where changes in environmental conditions were accounted for. Evolutionary changes in probabilistic maturation reaction norms were quantified as the mean displacement of the reaction norm midpoint (L_{P50}) for all ages for which the midpoint had been quantified at both the beginning and the end of the data periods. The magnitude m of evolutionary change was then calculated as $m = |z_2 - z_1| / z_1$ where z_1 and z_2 denote the considered quantitative trait at the beginning (t_1) and end (t_2) of the data period, respectively. The rate r of evolutionary change, in the standard unit ‘darwin,’ was calculated as $r = |\ln(z_2) - \ln(z_1)| / (t_2 - t_1)$, where $t_2 - t_1$ was measured in millions of years. Unless otherwise noted, we assumed linear trends throughout the data periods.

| Species | Population or stock | Data period | Evolutionary change: | | Reference |
|---|-----------------------------|--------------------------|----------------------|---------|-----------|
| | | | Magnitude | Rate* | |
| Maturation at younger age | | | | | |
| Atlantic cod <i>Gadus morhua</i> | Northeast Arctic | 1932–1998 | 23–24% | 4.0–4.1 | S11 |
| | North Sea, West of Scotland | 1969–1970, 2002–2003 | | | S12 |
| | Baltic | 1984–1997 | | | S13 |
| Bluegill <i>Lepomis macrochirus</i> | Lakes in Minnesota | 1989–1995, comparative | | | S14 |
| Brook trout <i>Salvelinus fontinalis</i> | 17 lakes in Canada | 1984, 1999, comparative | | | S15 |
| Grayling <i>Thymallus thymallus</i> | Several lakes in Norway | 1903–2000 (ca. 15 years) | | | S16 |
| Plaice <i>Pleuronectes platessa</i> | North Sea | 1957–2001 | | | S17–S19 |
| Red porgy <i>Pagrus pagrus</i> | South Atlantic Bight | 1972–1994 | | | S20 |
| Maturation at smaller size | | | | | |
| Atlantic cod <i>Gadus morhua</i> | Northeast Arctic | 1932–1998 | 22–24% | 3.9–4.4 | S11 |
| | North Sea, West of Scotland | 1969–1970, 2002–2003 | | | S12 |
| | Baltic | 1984–1997 | | | S13 |
| Brook trout <i>Salvelinus fontinalis</i> | 17 lakes in Canada | 1984, 1999, comparative | | | S15 |
| Coho salmon <i>Oncorhynchus kisutch</i> § | British Columbia | 1951–1975 | 24–26% | 10–11 | S21, S22 |
| Grayling <i>Thymallus thymallus</i> | Several lakes in Norway | 1903–2000 (ca. 15 years) | | | S16 |
| Pink salmon <i>Oncorhynchus gorbuscha</i> | British Columbia | 1951–1975 | 20–33% | 8.3–14 | S21, S22 |
| Plaice <i>Pleuronectes platessa</i> | North Sea | 1957–2001 | | | S17–S19 |
| Red porgy <i>Pagrus pagrus</i> | South Atlantic Bight | 1972–1994 | | | S20 |

Table S2 (continued).

| Species | Population or stock | Data period | Evolutionary change: Magnitude | Rate* | Reference |
|---|---|---------------------------------|--|---------|-----------|
| Reduction in the probabilistic maturation reaction norm midpoint | | | | | |
| American plaice <i>Hippoglossoides platessoides</i> | Labrador, Newfoundland | 1973–1999 | 22–47% | 12–31 | S23 |
| | Grand Bank | 1969–2000 | 19–49% | 10–32 | S23 |
| | St. Pierre Bank | 1972–1999 | 14–42% | 7.1–26 | S23 |
| Atlantic cod <i>Gadus morhua</i> | Northeast Arctic | 1932–1998 | 12% | 2.1 | S11 |
| | Georges Bank | 1970–1998 | 26–41% | 15–26 | S24 |
| | Gulf of Maine | 1970–1998 | 25–26% | 14–15 | S24 |
| | Northern† | (1977–)1981–2002 | – | 7–19# | S25 |
| | | | | 11–27% | S26 |
| | Southern Grand Bank† | 1971–2002 | 18% | 9.3–9.6 | S26 |
| | St. Pierre Bank† | 1972–2002 | 25–32% | 15–20 | S26 |
| | Baltic | 1988–2003 | 21% | 16 | S27 |
| Atlantic herring <i>Clupea harengus</i> | Norwegian spring-spawning | 1935–2000 | 3% | 0.7 | S28 |
| Plaice <i>Pleuronectes platessa</i> | North Sea | 1957–2001 | 13% | 4.7 | S19 |
| | | 1957–2001 | 14% | 4.6 | S29 |
| Sole <i>Solea solea</i> | Southern North Sea | 1958–2000 | 11% | 4.1 | S30 |
| Maturation at lower condition | | | | | |
| Atlantic cod <i>Gadus morhua</i> | Baltic | 1988–2003 | | | S27 |
| | Northern, St Pierre Bank, Southern Grand Bank | 1977–2002 | | | S31 |
| Bluegill <i>Lepomis macrochirus</i> | Lakes in Minnesota | 1989–1995, comparative | | | S14 |
| Brook trout <i>Salvelinus fontinalis</i> | 17 lakes in Canada | 1984, 1999, comparative | | | S15 |
| Whitefish <i>Coregonus clupeaformis</i> | Lesser Slave Lake | 1941–1975 | | | S32 |
| Reduced annual growth | | | | | |
| Atlantic cod <i>Gadus morhua</i> | Southern Gulf of St Lawrence | 1971–2002 | | | S33 |
| Atlantic salmon <i>Salmo salar</i> | Godbout River, Quebec | 1859–1983 | | | S34 |
| Coho salmon <i>Oncorhynchus kisutch</i> ‡ | British Columbia | 1951–1975 | 24–26% | 10–11 | S21, S22 |
| Pink salmon <i>Oncorhynchus gorbuscha</i> ‡ | British Columbia | 1951–1975 | 20–33% | 8.3–14 | S21, S22 |
| Whitefish <i>Coregonus clupeaformis</i> ‡ | Lesser Slave Lake | 1941–1975 | | | S32 |
| Whitefish <i>Coregonus lavaretus</i> ‡ | Lake Constance | 1947–1997 | 15% | 3.8 | S35 |
| Increased fecundity | | | | | |
| Atlantic cod <i>Gadus morhua</i> ** | North Sea, West of Scotland | 1969–1970, 2002–2003 | 25% | 8.2 | S12 |
| Haddock <i>Melanogrammus aeglefinus</i> ** | North Sea | 1976–1978, 1995–1996 | 33% | 15.5 | S36 |
| Plaice <i>Pleuronectes platessa</i> §§ | North Sea | 1900–1910, 1947–1949, 1977–1985 | 5–100% | 0.5–21 | S37, S38 |
| Loss of genetic diversity | | | | | |
| Brook trout <i>Salvelinus fontinalis</i> | 9 lake–stream population pairs in Canada | 1996, 1997, comparative | ## | – | S39 |
| Orange roughy <i>Hoplostethus atlanticus</i> | New Zealand | 1982/1983–1988 | 22% ## | – | S40 |
| Snapper <i>Pagrus auratus</i> (= <i>Chrysophrus auratus</i>) | Tasman Bay, New Zealand | 1950–2000 | 21% †† | – | S41 |
| Other trends | | | | | |
| Atlantic salmon <i>Salmo salar</i> | Rivers Asón, Pas, Nansa, and Deva, Spain | 1988–2000 | Later smolting, lower sea-age | | S42 |
| Common carp <i>Cyprinus carpio carpio</i> | Aquaculture lineages from China and Europe | Comparative between regions | Seine harvesting (China) selected for viability, lean body, escapement, early maturation | | S43 |
| Sockeye salmon <i>Oncorhynchus nerka</i> | Bristol Bay, USA | 1969–2003 | Earlier run timing | | S44 |
| Whitefish <i>Coregonus clupeaformis</i> | Lesser Slave Lake | 1941–1975 | Decreased condition | | S32 |

*In 10³ darwins, absolute values. §Assuming no change in maturation age. #Numbers from ref. S25. †Estimates based on pre-moratorium years only. ‡Weight. †Length. **Standardized by length and condition. §§Standardized by length. ##Heterozygosity loss. ††Allele loss.

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