ECOLOGY

# Managing Evolving Fish Stocks

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

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 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

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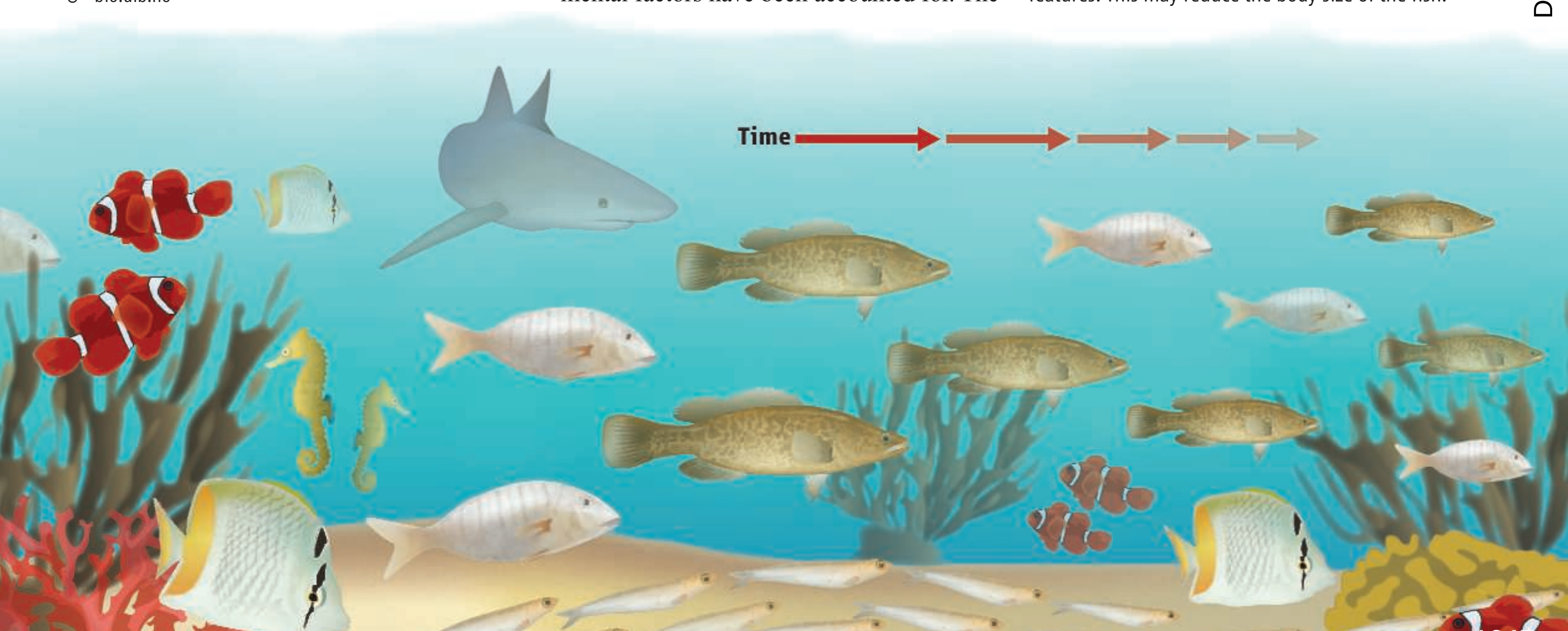


**Moving targets.** Fishing not only reduces the number of fish in the sea, but also changes their heritable features. This may reduce the body size of the fish.

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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*).

**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.

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, 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.

### References and Notes


1. S. R. Palumbi, *Science* **293**, 1786 (2001).
2. G. Mertz, R. A. Myers, *Can. J. Fish. Aquat. Sci.* **55**, 478 (1998).
3. M. Heino, O. R. Godø, *Bull. Mar. Sci.* **70**, 639 (2002).
4. T. Gjedrem, *Aquaculture* **33**, 51 (1983).
5. R. Law, D. R. Grey, *Evol. Ecol.* **3**, 343 (1989).
6. D. O. Conover, S. B. Munch, *Science* **297**, 94 (2002).
7. M. R. Walsh *et al.*, *Ecol. Lett.* **9**, 142 (2006).
8. M. Scheffer, S. Carpenter, B. de Young, *Trends Ecol. Evol.* **20**, 579 (2005).
9. M. V. Ashley *et al.*, *Biol. Conserv.* **111**, 115 (2003).
10. U.N. Food and Agriculture Organization (FAO), *Fisheries Management 2: The Ecosystem Approach to Fisheries* (FAO Technical Guidelines for Responsible Fisheries No. 4, Suppl. 2, FAO, Rome, 2003).
11. E. K. Pikitch *et al.*, *Science* **305**, 346 (2004).
12. R. C. Francis *et al.*, *Fisheries* **32**, 217 (2007).
13. J. R. Beddington, D. J. Agnew, C. W. Clark, *Science* **316**, 1713 (2007).
14. FAO, *Precautionary Approach to Capture Fisheries and Species Introductions* (FAO Technical Guidelines for Responsible Fisheries, No. 2, FAO, Rome, 1996).
15. The United Nations 2002 World Summit on Sustainable Development in Johannesburg, South Africa, declared that fish stocks shall be restored to produce the maximum sustainable yield by 2015.
16. A. D. Rijnsdorp, *Oecologia* **96**, 391 (1993).
17. E. M. Olsen *et al.*, *Nature* **428**, 932 (2004).
18. U. Dieckmann, M. Heino, *Mar. Ecol. Progr. Ser.* **335**, 253 (2007).
19. W. C. Lewin, R. Arlinghaus, T. Mehner, *Rev. Fish. Sci.* **14**, 305 (2006).
20. C. W. Clark, *The Worldwide Crisis in Fisheries* (Cambridge Univ. Press, Cambridge, UK, 2006).
21. R. Law, *Mar. Ecol. Progr. Ser.* **335**, 271 (2007).


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