

CONSERVATION

Reconsidering the Consequences of Selective Fisheries

S. M. Garcia,^{1*} J. Kolding,^{1,2*} J. Rice,^{1,3*} M.-J. Rochet,^{4,*†} S. Zhou,^{5*} T. Arimoto,⁶ J. E. Beyer,⁷ L. Borges,⁸ A. Bundy,⁹ D. Dunn,¹⁰ E. A. Fulton,¹¹ M. Hall,¹² M. Heino,^{2,13,14} R. Law,¹⁵ M. Makino,^{1,16} A. D. Rijnsdorp,¹⁷ F. Simard,¹⁸ A. D. M. Smith¹¹

Concern about the impact of fishing on ecosystems and fisheries production is increasing (1, 2). Strategies to reduce these impacts while addressing the growing need for food security (3) include increasing selectivity (1, 2): capturing species, sexes, and sizes in proportions that differ from their occurrence in the ecosystem. Increasing evidence suggests that more selective fishing neither maximizes production nor minimizes impacts (4–7). Balanced harvesting would more effectively mitigate adverse ecological effects of fishing while supporting sustainable fisheries. This strategy, which challenges present management paradigms, distributes a moderate mortality from fishing across the widest possible range of species, stocks, and sizes in an ecosystem, in proportion to their natural productivity (8), so that the relative size and species composition is maintained.

Selectivity: Rationale, Undesirable Effects

Fishers select species and sizes for various practical, economic, and regulatory reasons. The idea of increasing size-selectivity to increase yields is centuries old (9). The concept of growth overfishing (loss of yield when small fish are caught) has been a cornerstone of modern fisheries management since the 1950s (10). Avoiding juveniles has been justified to let fish reproduce at least once before they are harvested (11). Protecting rare and charismatic species has also gained currency (12). New guidelines from the United Nations Food and Agriculture Organization (FAO) reiterate the objective of “minimizing the capture and mortality of species and sizes

which are not going to be used,” i.e., by-catch (13). Fisheries worldwide have used species and size limits (9, 14), gear technology (5, 15), and spatial and temporal fishing restrictions (16) to reduce fishing impacts while pursuing human benefits.

But selective removals will inevitably alter the composition of a population or community and, consequently, ecosystem structure and biodiversity. Old individuals contribute the most to reproduction (17). Even moderate fishing reduces the proportion of

Balanced harvesting ... distributes a moderate mortality from fishing across the widest possible range of species, stocks, and sizes in an ecosystem.

large and old fish in a population. Selectively fishing large individuals amplifies this effect, and although it does not provide the expected yield benefits (9), it results in ecological and evolutionary side effects. Removal of older age classes can increase fluctuations in population abundance (18), which, in turn, increase the risks associated with low abundance. Increased and selective fishing has been predicted to drive stocks toward earlier maturation and smaller adult body size (19). Such changes appear common (20), although their environmental and genetic causes are not fully disentangled (21).

Community effects of heavy, selective exploitation include alteration of trophic structure on the Eastern Scotian Shelf (6), and a shift from large- to smaller-sized

Balanced fishing across a range of species, stocks, and sizes could mitigate adverse effects and address food security better than increased selectivity.

species and individuals in the North Sea (22) (fig. S1). By contrast, in several African small-scale inland fisheries, the fish size spectrum (23) has been maintained under intense and diverse fishing activities that cause high mortality with low selectivity (5, 24) (fig. S1).

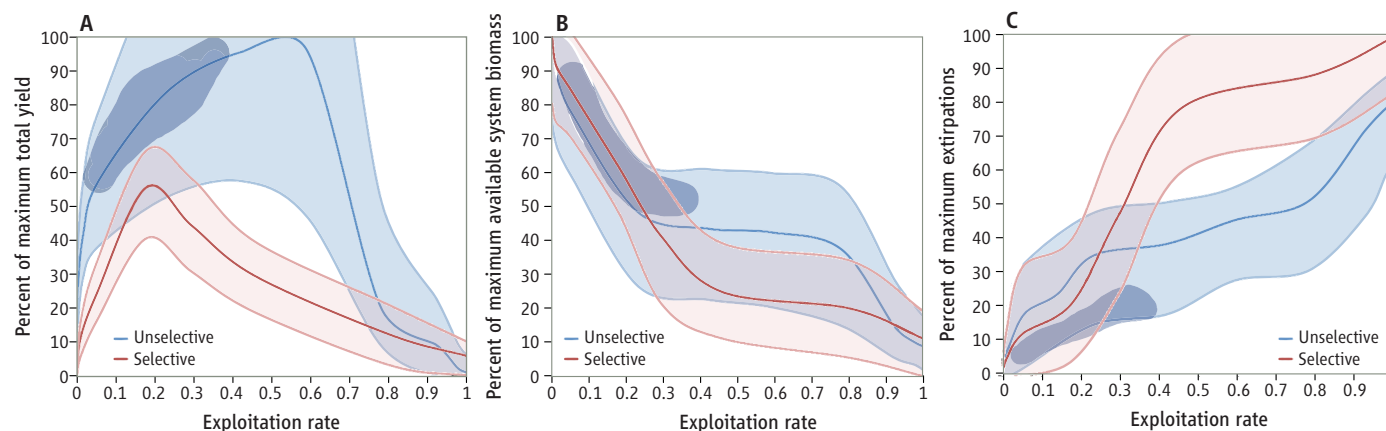
Results from models suggest that moderating fishing mortality across a wide range of species and sizes maximizes overall catch summed across species while better conserving biodiversity. Multispecies fishery models

show that increased mesh sizes may reduce total yield, owing to increased predation by large fish (25), and that targeting a limited range of species or sizes will not maximize diversity at most fishing mortalities (26). In size-based models, depletion of particular sizes by fishing affects smaller-size groups because their predation mortality is reduced and impinges on larger-size groups by both reduced food for predators of the harvested sizes and faster growth rates of the survivors of the selective fishing. This causes destabilizing fluctuations in biomass that are wider when the size range fished is narrower and/or the sizes fished are large (27). When models allow for some diversity in properties other than size within size classes, fluctuations persist but are dampened (28).

Synthesizing across ecosystem models from 30 systems [see supporting online material (SOM) for details] suggests that the biodiversity benefits from selective fishing occur only at fishing mortalities so low that yield is not economically sustainable (see the graph). With fishing spread over more groups and sizes, yields are higher and impacts of fishing—such as population extirpations (local extinctions) and biomass depletion—are lower across a broad range of fishing mortalities.

¹Commission on Ecosystem Management, International Union for Conservation of Nature (IUCN-CEM), Fisheries Expert Group, 1000 Brussels, Belgium. ²Department of Biology, University of Bergen, 5020 Bergen, Norway. ³Fisheries and Oceans, Ottawa, Ontario K1A 0E6, Canada. ⁴L'Institut Français de Recherche pour l'Exploitation de la Mer (IFREMER), 44300 Nantes, France. ⁵CSIRO Marine and Atmospheric Research, Brisbane, Queensland 4001, Australia. ⁶Tokyo University of Marine Science and Technology, Tokyo 108-8477, Japan. ⁷Danish National Institute of Aquatic Resources (DTU Aqua), Charlottenlund Castle, 2920, Denmark. ⁸FishFix, Brussels, Belgium. ⁹Bedford Institute of Oceanography, Dartmouth, Nova Scotia B3B 1A5, Canada. ¹⁰Duke University Marine Geospatial Ecology Lab, Beaufort, NC 28516, USA. ¹¹CSIRO Marine and Atmospheric Research, Hobart, Tasmania 7000, Australia. ¹²Inter-American Tropical Tuna Commission, La Jolla, CA 92037, USA. ¹³Institute of Marine Research, 5005 Bergen, Norway. ¹⁴International Institute for Applied Systems Analysis, 2361 Laxenburg, Austria. ¹⁵Biology Department, University of York, York YO10 5DD, UK. ¹⁶Fisheries Research Agency, Yokohama, 220-6115, Japan. ¹⁷Institute for Marine Resources and Ecosystem Studies (IMARES), 1976 IJmuiden, Netherlands. ¹⁸Global Marine Programme, IUCN, 1196 Gland, Switzerland.

*These authors contributed equally to this work. †Author for correspondence. E-mail: Marie.Joelle.Rochet@ifremer.fr



Effects of conventionally selective (red), unselective (blue), and balanced (dark blue) fishing. Unselective fishing harvests all exploitable nonmicrofauna and nonlarval ecosystem components. Balanced fishing mortality rates are set in proportion to productivity per biomass for each group. **(Left)** Results for total catch weight (as a percentage of the maximum total yield for a system across all fishing scenarios), **(middle)** total available biomass (i.e., biomass that could be harvested), and **(right)** extirpations (number of groups that have dropped below 10% of their unfished levels). All values are plotted against the maximum sys-

tem level exploitation rate (i.e., roughly total catch as a proportion of total available biomass). For each fishing type (conventionally selective or unselective), the solid line is the average across 36 ecosystem models, and the lower and upper bounds of the lightly shaded areas represent the 5th and 95th percentiles across models. The darker blue shaded areas encompass >90% of the balanced harvest scenarios across the ecosystems. See SOM for details; the selective fishing results were part of supplementary fig. S1 in (2).

Toward Balanced Harvesting

The conventional “increased selectivity” paradigm may be inconsistent with objectives of an approach that considers all ecosystem consequences while managing fisheries. Balanced harvest is selective, but it broadens the selectivity perspective from scales of fishing operations and stocks to the integrated scale of ecosystem productivity and impacts.

Conventionally selective removal of parts of the ecosystem leads to unintended consequences that are inconsistent with a range of international conventions and agreements, including the international commitment to rebuild world fish stocks to their maximum sustainable yield (MSY) (29, 30). It is increasingly recognized that all stocks within an ecosystem cannot be rebuilt to biomasses consistent with their single-species MSY levels (31). If the focus is on how much to fish as calculated from reducing fishing mortality (1, 2), MSY’s dependence on what type of fishing is done—size-selectivity within stocks and species-selectivity at the community level (32)—is overlooked. Balanced harvesting requires adjusting selectivity regulations to balance the impact of all fisheries in an area with the relative productivities of the species and sizes of fish in the ecosystem; MSYs are subject to that constraint.

Regulations in many jurisdictions promote selectivity as an intended outcome, e.g., by using mesh-size limits. Our results suggest that such regulations often will be inconsistent with goals to maintain biodiversity as well as fish yield. Implementing balanced harvesting requires coordinated

management across multiple fisheries with consideration of ecosystem structure, consequences of current fishing selectivity, and implications for future yields. This involves quantifying patterns of fishing activities and ecological consequences aggregated at the fish-community and ecosystem levels.

We propose that fisheries management should address community properties such as the size-spectrum slope, for which acceptable levels would be agreed (33, 34). Ecosystem modeling could help in determining appropriate patterns of fishing mortality and selectivity to conserve these properties, and constraints on removals (including discards), not just landings. Perhaps the greatest changes required for a balanced harvesting approach concern by-catch and markets. As each ecosystem component is to be caught in appropriate amounts, by-catch ceases to be an operational nuisance to be minimized and becomes part of the management strategy. Markets and the processing sector will need incentives to accommodate a wider range of catch components, including many not currently utilized in Western countries but commonly used in multispecies, multigear fisheries (5, 35) in the Mediterranean, Asia, and the Southern Hemisphere: for example, (i) enhancing industrial processing for animal feed or human consumption (36), (ii) status change from by-catch to target (14), and (iii) consuming less-utilized fish species (37).

Issues regarding the potential benefits and implementation of balanced harvesting remain. However, consideration of food security and minimizing ecosystem impacts suggest that the time has come to take action.

References and Notes

1. E. K. Pikitch *et al.*, *Science* **305**, 346 (2004).
2. B. Worm *et al.*, *Science* **325**, 578 (2009).
3. S. M. Garcia, A. A. Rosenberg, *Philos. Trans. R. Soc. London Ser. B* **365**, 2869 (2010).
4. S. M. Garcia *et al.*, Selective fishing and balanced harvest in relation to fisheries and ecosystem sustainability: Report of a scientific workshop in Nagoya, Japan, 14 to 16 October 2010 (IUCN and European Bureau for Conservation and Development, Gland, Switzerland, and Brussels, 2011); <http://data.iucn.org/dbtw-wpd/edocs/2011-001.pdf>.
5. O. A. Misund, J. Kolding, P. Fr  on, in *Handbook of Fish Biology and Fisheries*, vol. 2, Fisheries P. J. B. Hart, J. D. Reynolds, Eds. (Blackwell, Malden, MA, 2002), pp. 13–36.
6. A. Bundy, P. Fanning, K. C. T. Zwanenburg, *ICES J. Mar. Sci.* **62**, 503 (2005).
7. S. Zhou *et al.*, *Proc. Natl. Acad. Sci. U.S.A.* **107**, 9485 (2010).
8. Biological productivity is the amount of new organic matter produced per biomass unit during a given period of time.
9. R. G. Halliday, A. T. Pinhorn, *Fish. Res.* **57**, 211 (2002).
10. R. J. H. Beverton, S. J. Holt, On the dynamics of exploited fish populations, Fishery Investigations, Series 2 (Her Majesty’s Stationery Office, London, 1957).
11. M. P. Sissenwine, J. G. Shepherd, *Can. J. Fish. Aquat. Sci.* **44**, 913 (1987).
12. R. L. Lewison, L. B. Crowder, A. J. Read, S. A. Freeman, *Trends Ecol. Evol.* **19**, 598 (2004).
13. FAO, Report of the technical consultation to develop international guidelines on by-catch management and reduction of discards, Rome, 6 to 10 December 2010 (FAO Fisheries and Aquaculture Report no. 957, FAO, Rome, 2011).
14. S. J. Hall, B. M. Mainprize, *Fish. Res.* **6**, 134 (2005).
15. S. J. Kennelly, M. K. Broadhurst, *Fish. Res.* **3**, 340 (2002).
16. D. C. Dunn, A. M. Boustany, P. N. Halpin, *Fish. Res.* **12**, 110 (2011).
17. C. Birkeland, P. K. Dayton, *Trends Ecol. Evol.* **20**, 356 (2005).
18. C. N. Anderson *et al.*, *Nature* **452**, 835 (2008).
19. R. Law, *ICES J. Mar. Sci.* **57**, 659 (2000).
20. C. J  rgensen *et al.*, *Science* **318**, 1247 (2007).
21. A. Kuparinen, J. Meril  , *Trends Ecol. Evol.* **22**, 652 (2007).
22. N. Daan, H. Gislason, J. G. Pope, J. C. Rice, *ICES J. Mar. Sci.* **62**, 177 (2005).
23. The size spectrum is the relative proportion of biomass per size-class in the fish community (see fig. S1). Increased spectrum slope reflects relative increase in biomass in

- smaller-size classes compared with larger classes.
24. E. Jul-Larsen, J. Kolding, J. R. Nielsen, R. Overa, P. A. M. van Zwieten, Management, co-management or no management? Major dilemmas in southern African freshwater fisheries (Tech. Rep. 426/1–2, FAO, Rome, 2003).
 25. J. G. Pope, *ICES Mar. Sci. Symp.* **193**, 22 (1991).
 26. M.-J. Rochet, J. S. Collie, S. Jennings, S. J. Hall, *Can. J. Fish. Aquat. Sci.* **68**, 469 (2011).
 27. M.-J. Rochet, E. Benoît, *Proc. Biol. Sci.* **279**, 284 (2012).
 28. K. H. Andersen, M. Pedersen, *Proc. Biol. Sci.* **277**, 795 (2010).
 29. United Nations, Report of the World Summit on Sustainable Development, Johannesburg, South Africa, 26 August to 4 September 2002 (Tech. Report No.A/CONF.199/20*, United Nations, New York, 2002).
 30. MSY calculations assume that, by applying a constant fishing mortality with a given selectivity (externally deter-

- mined by fisheries), a constant yield can be taken from a stock over an indefinite period. There is one given fishing mortality rate that maximizes this yield, providing MSY.
31. M. N. Maunder, *Fish. Fish.* **3**, 251 (2002).
32. J. Link *et al.*, *Fish. Fish.* **12**, 152 (2011).
33. Ecosystem level constraints on target species catch limits have been agreed, e.g., in the Antarctic ecosystem (34).
34. A. J. Constable *et al.*, *ICES J. Mar. Sci.* **57**, 778 (2000).
35. B. Gobert, *Fish. Res.* **19**, 87 (1994).
36. I. Clucas, A study of the options for utilization of bycatch and discards from marine capture fisheries (FAO Fish. Circ., FAO, Rome, 1997).
37. Sainsbury's launches 'Switch the Fish' campaign, www.fishnewseu.com/latest-news/uk/5973-sainburys-launches-switch-the-fish-campaign.html.
38. This work results from a workshop sponsored by the International Union for the Conservation of Nature, the

Convention on Biological Diversity, the Census of Marine Life, the Ministries of Fisheries and Coastal Affairs and of Foreign Affairs of Norway, the Global Guardian Trust of Japan, the Ocean Alliance of the University of Tokyo, the Japan National Association for the Conservation of Fishing Ground, the Japan Fisheries Association, and the Technical University of Denmark. M.-J.R. received support from the Pew Charitable Trusts. The opinions expressed are those of the authors and do not necessarily reflect the views of the supporting organizations.

Supporting Online Material

www.sciencemag.org/cgi/content/full/335/6072/1045/DC1

10.1126/science.1214594

PUBLIC HEALTH AND BIOSECURITY

The Limits of Government Regulation of Science

John D. Kraemer^{1,2} and Lawrence O. Gostin^{2*}

Last summer, two research teams funded by the National Institutes of Health genetically modified H5N1 avian influenza viruses, making them capable of efficient respiratory transmission between ferrets. Ferrets are thought to be a good animal model for influenza in humans. A small number of genetic changes might be able to convert the presently zoonotic H5N1 virus into a pathogen with dangerous pandemic potential—transmissible

ology and results could become a blueprint for bioterrorism (1).

The U.S. government's request not to publish key scientific findings sparked considerable controversy. To many researchers, knowledge about what mutations enable respiratory transmission is essential to surveillance of and early action against variants of H5N1. They worry that government intrusion into scientific innovation would discourage vital research. However, security

A transparent institutional review process will balance scientific freedom and national security better than publication restrictions.

The court ruled that federally funded scientific research, especially at universities, should be free from prior restraint—calling into question the validity of CUI conditions on research grants.

from human-to-human, with a >50% case-fatality rate. The National Science Advisory Board for Biosecurity (NSABB), which advises the U.S. Department of Health and Human Services (HHS), recommended that two journals, *Science* and *Nature*, redact key information before publication. The NSABB and HHS expressed concerns that published details about the papers' method-

advocates believe the greater risk is that the mutated virus could escape or that knowledge about these mutations could get into the wrong hands. They suggest that research of this kind should not be funded or undertaken in the first place. Where, as here, the research has already been conducted, they urge scientific journals not to publish any sensitive methods or results (1).

The HHS request reveals a troubled relationship between security and science. This is not the first time a government has requested that a journal not publish information. In 1979, the U.S. Department of Energy secured an injunction against the magazine *The Progressive* to prevent the publication of an article

about building a hydrogen bomb, even though the information was in the public domain; the injunction was later vacated when the article was published elsewhere (2). In 2005, the *Proceedings of the National Academy of Sciences* refused to comply with an HHS request to decline publishing a mathematical model of botulism in the milk supply (3). The H5N1 case, however, is the first time government has sought to redact information after an institutionalized HHS review process.

Constitutional Limits on Government Restrictions of Scientific Publications

The First Amendment to the U.S. Constitution affords considerable protection to political, artistic, and scientific expression, that could trigger "strict scrutiny" by the Supreme Court (4). The court is most vigorous in reviewing government restraints on speech in advance of publication, which it calls "prior restraints." Prior restraints are uniquely threatening to First Amendment values because they prevent ideas from ever being heard (5).

Had the government compelled the H5N1 researchers to cease research or the journals to withhold publication—whether through the force of law or by creating adverse consequences such as loss of funding—it could have violated the First Amendment. Even informal systems of restraint can be unconstitutional, such as a government threat to prosecute publishers (5). In this case, however, HHS' request, by its own terms, was nonbinding, and the journals had discre-

¹Department of Health Systems Administration, Georgetown University School of Nursing and Health Studies, Washington, DC 20057, USA. ²O'Neill Institute for National and Global Health Law, Georgetown University Law Center, Washington, DC 20001, USA.

*Author for correspondence. E-mail: gostin@law.georgetown.edu