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PERSPECTIVE

When is a fishery sustainable?

Ray Hilborn, Elizabeth A. Fulton, Bridget S. Green, Klaas Hartmann, Sean R. Tracey, and Reg A. Watson

Abstract: Despite the many scientific and public discussions on the sustainability of fisheries, there are still great differences in both perception and definition of the concept. Most authors now suggest that sustainability is best defined as the ability to sustain goods and services to human society, with social and economic factors to be considered along with environmental impacts. The result has been that each group (scientists, economists, non-governmental organizations (NGOs), etc.) defines "sustainable seafood" using whatever criteria it considers most important, and the same fish product may be deemed sustainable by one group and totally unsustainable by another one. We contend, however, that there is now extensive evidence that an ecological focus alone does not guarantee long-term sustainability of any form and that seafood sustainability must consistently take on a socio-ecological perspective if it is to be effective across cultures and in the future. The sustainability of seafood production depends not on the abundance of a fish stock, but on the ability of the fishery management system to adjust fishing pressure to appropriate levels. While there are scientific standards to judge the sustainability of food production, once we examine ecological, social, and economic aspects of sustainability, there is no unique scientific standard.

Résumé : Malgré les nombreuses discussions scientifiques et publiques sur la durabilité des pêches, de grandes différences persistent quant à la perception et à la définition de ce concept. La plupart des auteurs suggèrent actuellement que la meilleure définition de la durabilité est la capacité de maintenir des biens et services pour la société humaine, en tenant compte de facteurs sociaux et économiques, ainsi que des impacts sur l'environnement. Il en découle que chaque groupe (scientifiques, économistes, ONG (les organisations nongouvernementales), etc.) définit les « poissons et fruits de mer durables » sur la base des critères qu'il juge les plus importants, et un produit donné peut être jugé durable par un groupe, alors qu'un autre groupe estime qu'il n'est pas du tout durable. Nous soutenons toutefois qu'il existe une vaste preuve à l'effet qu'une seule optique écologique ne garantit aucune forme de durabilité à long terme, et que la durabilité des poissons et fruits de mer doit uniformément reposer sur une perspective socioécologique pour constituer un concept efficace pour l'avenir, peu importe la culture. La durabilité de la production de poissons et fruits de mer dépend non pas de l'abondance d'un stock de poissons, mais de la capacité du système de gestion des pêches à ajuster la pression de pêche aux bons niveaux. S'il existe des normes scientifiques pour juger de la durabilité de la production alimentaire, il n'y a pas de norme scientifique unique pour l'évaluation des aspects écologiques, sociaux et économiques de la durabilité. [Traduit par la Rédaction]

Introduction

Everyone talks about sustainability — but how do we define it? Various layers of government have legislated mandates; international policy-makers and environmental non-governmental organizations (eNGO) have made statements, and consumers have formed opinions. Do they all talk about the same thing?

Legislation and policy on fisheries sustainability can be found in international agreements (Rice 2014), national legislation, and fisheries management agencies' policies. Opinions on sustainability can be found in a growing number of consumer seafood guides (Roheim 2009). All of them have a shared interest in maintaining sustainable fisheries (Jennings et al. 2014), but different interests use different objectives, measures, and definitions. The creation of ecosystem-based fisheries management (FAO 2003) was an attempt to define best practices that blended the concerns of the conservation community and fisheries managements agencies. At approximately the same time, eNGO-issued consumer seafood guides proliferated, offering a simple appraisal of whether or not the fish you had planned for dinner was sustainable. NGO guides have become an important force in retailers' choice of what they will sell and subsequently a powerful tool for marketing particular seafood (Johnston and Roheim 2006; Roheim et al. 2011).

Many perspectives on sustainability extend beyond biological resources to social and economic sustainability of dependent human communities (Wilson et al. 2007). A report by the US National Academy of Sciences (Kates and Clark 1999) emphasized that sustained benefits to society are the crux of sustainable development, with the obvious proviso that the productive capacity of natural ecosystems must be maintained to assure the goods and services people desire. Economic growth, environmental protection, and social development were identified as the three pillars of sustainability in a report to the IUCN (Adams 2006). There clearly is a divide between those who define sustainability in strictly ecological terms and those who focus on people. As we will see later, almost all definitions used in the context of seafood sustainability have dealt only with environmental protection. We argue against a purely ecological focus to sustainability and that seafood sustainability (and sustainability more broadly) must take on a socio-ecological perspective if it is to cope with global change and be effective across cultures, social drivers, and with the increasing number of uses of the ocean.

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R. Hilborn. School of Fisheries and Aquatic Sciences, Box 355020, University of Washington Seattle, WA 98195, USA.
E.A. Fulton. CSIRO Oceans & Atmosphere Flagship, GPO Box 1538, Hobart, Tasmania 7001 Australia; Centre for Marine Socioecology, University of Tasmania, Private Bag 49, Hobart, 7001, Tasmania, Australia.
B.S. Green, K. Hartmann, S.R. Tracey, and R.A. Watson. Institute for Marine and Antarctic Studies, University of Tasmania, Private Bag 49, Hobart, 7001, Tasmania, Australia.
Corresponding author: Ray Hilborn (e-mail: rayh@u.washington.edu).

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The remainder of this paper evaluates the perspectives and evidence on sustainability from single-species, multispecies, and ecosystem theory, models, and observations. From these we draw conclusions regarding sustainability and its socio-ecological nature.

Defining sustainability

There is now a multitude of meanings of sustainability and how to define "sustainable" seafood. Definitions of sustainability are almost always linked with the term "sustainable development", since it is the development of resources for human use that modifies natural ecosystems. A number of conservation groups, including the International Union for the Conservation of Nature, the United Nations Environment Program, and the World Wildlife Fund (WWF), have defined sustainable development as "improving the quality of human life while living within the carrying capacity of supporting eco-systems" (Munro and Holdgate 1991). Perhaps the most widely used definition comes from the World Commission on Environment and Development (1987), commonly known as the Brundtland Commission: "Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs." However, Kates et al. (2005) summarized the situation as "In the years following the Brundtland Commission's report, the creative ambiguity of the standard definition … also created a veritable industry of deciphering and advocating what sustainable development really means."

A common theme to all discussions on sustainability is living within limits and the capacity of natural ecosystems to indefinitely produce the goods and services we want. For example, Murawski (2000) discusses how ecosystem-level sustainability implies "systems are managed for the highest net benefits to society consistent with other biological objectives." Any population, or system, that is harvested to maintain forever maximum sustainable yield or near it would meet many definitions of sustainability. If future generations wanted to return such a population to an unfished state, they would have the option of ceasing all harvest, and in theory, the population would return to its preharvest condition. Now consider a fishery where the annual exploitation rate is higher than would produce long-term maximum yield so that the population fluctuates at a lower level than would produce maximum yield. If such a fishery can be sustained indefinitely, then it too would seem to meet the Brundtland definition; future generations could choose to harvest at a lower rate and the population would increase. This could be called "sustainable overexploitation".

The concept of sustainable overexploitation is far from simply an academic construct. Management of salmon in Alaska is regarded as among the best in the world and is among the first to receive certification by the Marine Stewardship Council. The managing system attempts to assure a target number of fish escape the fishery and are allowed to spawn. Maximum sustainable yield (MSY)-based escapement goals are called biological escapement goals (BEG), but some systems are managed with sustainable escapement goals (SEG), defined as escapement goals that have proven to be sustainable even if they are lower than BEGs (Mundy 1998). In essence, SEGs recognize that stocks may be sustainably overfished.

Major differences in perspectives on sustainability revolve around the extent to which the use of a resource modifies other components of the ecosystem. In a fishery that is harvested to produce long-term maximum sustainable yield, fish abundance will be lower than it would be if not harvested at all. However, add to this scenario the unintentional catch of another species, commonly called bycatch. If the level of unintentional catch is low enough, the impact of this fishery on the bycatch species may simply be to reduce the mean abundance of the nontarget species, but if the unintentional catch is too high and the bycatch species has a low reproductive rate, that species may go locally or even globally extinct (Matsuda and Abrams 2006). In this case the targeted fish species is sustainable, but we will have eliminated options to take benefits from the bycatch species for future generations.

Much of the controversy over sustainability appears not to be centered on the potential for long-term yield of the resources but on how much alteration to the ecosystem we are willing to accept. Fishing undoubtedly changes the trophic structure of an ecosystem, and fishing one species may make other species more or less abundant even if not threatening local or global extinction. Groups concerned with the status of seabirds, for instance, may consider fisheries that reduce bird food availability beyond some point to be unsustainable (Cury et al. 2011; Wilson et al. 2007). In view of this, how do we measure the environmental sustainability of marine ecosystems?

Single-species population dynamics

The theory of exploited populations suggests that the mean abundance of the population will decline as the exploitation rate increases and that the long-term mean yield will be maximized at an intermediate exploitation rate. Managers seeking to maintain long-term MSY search for the exploitation rate with the highest long-term harvest, but in theory almost any exploitation rate that does not lead to extinction of the population or cause a flip to an alternative enduring state is sustainable (in the sense that they can be maintained indefinitely). Flipping into a permanent alternative state would deprive future generations of the potential benefits from the species. In many places, including the USA, exploitation rates above the level that would produce MSY are called "overfishing". As fishing mortality is increased, sustainable yield initially increases, then beyond some point it declines. This simple relationship is derived for a logistic growth model, but can be shown to result from a wide range of life histories and population dynamics (Hilborn and Stokes 2010). For instance, age-structured or size-structured models provide a similar relationship, the abundance declines with exploitation rate, and yield is maximized at an intermediate value (Hilborn 2010). It is an exceedingly reassuring view of how populations behave, because the exploitation rate can be reduced at any time and the population will rebuild to its higher levels and can, in theory, rebuild to its unexploited state if harvesting is stopped.

However, there are many ecological relationships that can provide different perspectives. The ones of most concern are thresholds or tipping points (Kelly et al. 2015) in either population size or exploitation rate that lead to irreversible changes. Perhaps of the greatest concern are mechanisms known as depensation that can lead to a threshold population size below which the population might never recover (Walters and Kitchell 2001; Hutchings and Reynolds 2004; Keith and Hutchings 2012). Concern about possible low abundance thresholds and the long recovery times to rebuild stocks from low abundance has caused management agencies to attempt to avoid low levels of abundance. Large-scale meta-analyses (Myers et al. 1995; Liermann and Hilborn 1997; Neubauer et al. 2013; Hilborn et al. 2014) suggest that there is little evidence for depensation, although it certainly cannot be ruled out in individual cases. Thus, while the weight of the evidence is that stocks depleted to low abundance will generally recover if fishing pressure can be sufficiently reduced, provided the environment has not changed, almost all past considerations of fisheries sustainability have suggested that there are lower limits on abundance below which stocks are not considered sustainable.

Quinn and Collie (2005) review four stages in thinking about sustainability of single-species fisheries. These include (1) the classical perspective as represented in the logistic growth model where any level of biomass can be sustained, (2) the neoclassical view that allows for depensation and thus implies lower thresholds on sustainable abundance, (3) the modern view that shifts the objective from maximization of food production to maintaining large spawning stock as a precautionary element, and finally (4) the postmodern view that "attempt to incorporate the economic and social aspects of fisheries and (or) ecosystem and habitat requirements. These definitions now involve "warm and fuzzy" notions (healthy ecosystems and fishing communities, the needs of future generations, diverse fish communities) and value judgements of desired outcomes."

Fishing exerts selective pressures on stocks, and one of the most ubiquitous and striking examples of life history responses to fishing is the lowering of the age and size at maturity of heavily exploited stocks (Barot et al. 2004; Dieckmann and Heino 2007). Fishing increases the total mortality rate, individuals are less likely to live to older ages, and individuals who delay reproduction until older ages are unlikely to survive to reproduce. This is almost certainly an evolutionary response to fishing pressure. The impact of such changes is twofold: the long-term yield available at any exploitation rate will be lower than the simple logistic theory, and the higher exploitation rates otherwise considered sustainable could lead to extinction of the population.

The logistic theory assumes long-term, stable relationships between key population parameters, and the models generally allow for random variation around these parameters. There is a considerable literature documenting major changes in fish stock abundance unrelated to fishing, and recent meta-analysis suggests that irregular and often abrupt changes frequently occur in the key parameters (recruitment, somatic growth, and natural mortality) either from natural or anthropogenic causes (Gilbert 1997; Vert-pre et al. 2013; Rogers et al. 2013). These abrupt changes are often called regime shifts, and such shifts can alter aspects of ecosystem dynamics and the sustainability of exploitation. For instance, if a stock shifts into a less productive regime because of changing ocean temperatures or a decreased food supply owing to fishing, the sustainable yield and exploitation rate that would maximize long-term yield may both decline. While this does not mean the stock is no longer "sustainable", it does mean that sustainable management in an unproductive regime will need to be different than management in a productive regime. If a population shifts into a more productive regime, previously unsustainable exploitation rates may become sustainable. This was observed in fish populations in the North Pacific in the late 1970s (Hare and Mantua 2000). Vert-pre et al. (2013) found increases in productivity to be slightly more frequent than declines.

In summary, all the single-species evidence available suggests that species can be sustained across a range of fishing pressure and that stocks will rebuild when fishing pressure is reduced, unless there have been externally induced changes in the environment or a tipping point has been crossed. Stocks may be sustainably overfished in that they can sustain exploitation rates in excess of those that would produce MSY and recover to MSY levels (and beyond) if fishing pressure is reduced (Neubauer et al. 2013), but whether such overexploitation is desirable is a societal matter. However, few fisheries catch a single target species; many fisheries capture a broad mix of species.

Multiple species caught in the same fishing gear

The classic example of a multispecies fishery would be mixed species bottom trawls in the Northern Hemisphere, capturing Atlantic cod (*Gadus morhua*), haddock (*Melanogrammus aeglefinus*), and a range of other species. On the west coast of the USA, up to 60 species of rockfish are captured in the bottom trawl fishery, and almost all tropical trawl fisheries capture dozens of species. Similarly, many artisanal fisheries, such as coral reef hook and line fisheries, catch a mix of species. While there is some ability to shift the mix of species by choice of area, gear, and time, many, if not most, of these fisheries will always capture multiple species.

The theory of mixed stock fishing can be divided into two parts: the technical interaction due to the fact that multiple species are caught with the same fishing effort and trophic interaction that considers the predator–prey and competitive dynamics of ecosystems. We will first address the question of technical interaction, then move onto trophic dynamics.

The theory of management and maximization of sustainable yield from mixed-stock fisheries has received ongoing consideration from Ricker (1958*b*), through Paulik et al. (1967), Hilborn (1976), and Collie et al. (1990) to the recent renaissance of exploration — e.g., Matsuda and Abrams (2006), Matsuda et al (2008), Kar and Ghosh (2013), Jacobsen et al (2014). The problem occurs when two (or more) stocks being jointly harvested have different optimum exploitation rates. To illustrate with a simplified example, we assume we have a productive stock where MSY would be achieved at a harvest rate of 30% per year and an unproductive stock where MSY would be achieved at 10% per year. If both stocks have the same potential yield, then long-term MSY is achieved by applying a harvest rate slightly higher than would maximize the unproductive stock so it would be slightly overexploited. However, if the potential yield of the unproductive stock is small in comparison with the productive stock, then long-term yield will be maximized by overfishing the unproductive stock, and, depending on the relative optimum exploitation rates and abundance, the long-term yield may be maximized by fishing so hard that the unproductive stock goes to local extinction.

This is a problem for nearly all mixed-stock fisheries, since there are almost always some unproductive and productive stocks in the mix of what is caught. Trying to capture the potential of the productive stock while protecting the unproductive stock has been an ongoing management concern in a wide range of fisheries, both within and between species. An intraspecies example is the Fraser river sockeye salmon (*Oncorhynchus nerka*), where some small stocks are listed as "at risk" and mixed in the fishery with some very large and much more productive stocks of the same species (Pestes et al. 2008). Many interspecies cases involve bottom trawl fisheries. For example, there are ongoing concerns about how to catch the productive and healthy haddock stocks in New England and the North Sea while avoiding the less productive cod stocks (Fernandes et al. 2011).

The response of the US federal fisheries has been that all stocks that are assessed must be fished at rates less than that which would produce maximum sustainable yield (F_{MSY}) (Restrepo and Powers 1999), resulting in substantial lost yield overall. Hilborn et al. (2012) estimated that to prevent the least productive stocks in the US west coast bottom trawl fishery of 33 stocks from being overexploited, 55% of the potential seafood production would be forgone. Modeling of the trawl fishery in southeastern Australia suggests as much as 75% or more of the catch would need to be forgone if no bycatch species were to be overexploited (Fulton et al. 2007). While some would hold such lost food production acceptable, those concerned with food security may not find it so. Consequently, a number of solutions that try to meet both expectations by reducing exploitation rates on unproductive stocks while allowing harvest of productive stocks have been proposed and implemented. Core habitat for the least productive stocks can be closed to provide a refuge. Gear modifications can be found that reduce the relative effectiveness of gear on the least productive stocks. Finally, individual incentives have been provided to fishermen to find time, places, and fishing methods that minimize catch of unproductive stocks, such as individual vessel quotas on both unproductive and productive stocks (Branch et al. 2006; Branch and Hilborn 2008; Pascoe et al. 2010). Using the concepts from single-species management discussed earlier, any fishing policy that may overfish unproductive stocks but allows them to recover in the future would meet the Brundtland definition of sustainability.

None of this, however, takes into account resilience to external perturbations such as climate change, and there is growing evidence that the long-term productivity of a mix of stocks depends on maintaining the portfolio of stocks over time (Hilborn et al. 2003; Schindler et al. 2010), so that while short-term yield may be maximized by severely depleting unproductive stocks, stocks that are unproductive during one regime may be the productive stocks of the next environmental regime.

Ecosystem dynamics

Model results

Fish stocks do not exist in isolation, affected only by removals from fishing; species in a marine ecosystem interact through predation and competition. Thus, if we fish a single species, the abundance of prey of that species would be expected to increase, whereas the predators of the target species might decline because their food supply is reduced. These interactions are assessed in the ecosystem approach to fisheries (EAF) or ecosystem-based fisheries management (EBFM) — the fourth phase of sustainability thinking discussed by Quinn and Collie (2005).

A range of ecosystem models that consider these trophic relationships have been used to evaluate ecosystem-wide impacts of fishing. The most widely used is Ecopath with Ecosim (EwE) (Pauly et al. 2000), followed by Atlantis (Fulton et al. 2011a), but numerous other models have also been used or proposed (e.g., Hall et al. 2006; Matsuda and Abrams 2006; Travers et al 2010; Blanchard et al 2014; Jacobsen et al 2014).

While the implementation of these ecosystem models differs in many ways, a common result is that the ecosystem-wide yield behaves much like a single-species model. As exploitation rate increases from zero to higher levels, long-term ecosystem yield increases, eventually reaching a maximum, and then as exploitation rates increase further, the total yield declines (Worm et al. 2009; Garcia et al. 2012). The exact shape of this rise and decline is quite sensitive to the form of fishing used — whether focused on traditional harvested fish stocks or a broader range of taxa. A modeling study by Garcia et al. (2012) found that when fishing broadly across an ecosystem (exploiting all non-microfauna, including jellyfish, macroalgae, small-bodied pelagics such as krill, finfish, and even high-trophic-level species like marine mammals), not only was the sustainable catch of this entire assemblage of species much higher (1.5–2 times greater than for selective fisheries typical of North American, Australian, and western European nations), but there was little if any decline in that yield until the exploitation rate was very high. The entire shape of the curve was (typically) more skewed to the right than seen when focusing on traditionally targeted finfish; this did mean, however, that when exploitation rates rose very high, the declines in catch were precipitous. There was always a biodiversity cost of high exploitation rates, with some of the traditionally preferred species disappearing and being replaced by other species that can sustain very high exploitation rates. However, the rate of loss and replacement was not so rapid when fishing broadly across the ecosystem than when selectively targeting traditional finfish. This is because the application of pressure across much of the system was not as destructive for system structure and connectivity as the selective removal of specific nodes.

This ecosystem-level result may explain the persistent overall productivity of intensively fished multispecies fisheries such as those in the Gulf of Thailand (Pauly 1988). However, the highly modified ecosystem structure in those areas are not in line with the intent of at least some of the sustainability definitions outlined above. Delving into the dynamics of the species within the ecosystem under either fishing strategy shows that a consequence of increasing fishing mortality is an early decline in the less productive stocks, so that at the fishing pressure that maximizes total yield, some of the less productive stocks will likely be heavily depleted. Trophic models show the same basic trade-off that is found in mixed, single-species models; if you want to maximize the yield from a mix of stocks, the less productive stocks will be overexploited (Hilborn 1976; Hilborn et al. 2012). Moreover the tension between objectives for different components of the ecosystem will remain (e.g., between targeting small pelagic fish and allowing for consumption by species of conservation concern; Jacobsen et al. 2014).

Consideration of alternative harvesting regimes (e.g., balanced harvesting) is a growing area of research because there is a need for open discussion of what different patterns of fishing mean across objectives — e.g., intentionally shifting to targeting smaller-bodied and more productive forage fish (Jacobsen et al. 2014) — and whether that is considered desirable by society. Even if concepts like balanced harvesting are found to be sound and desirable in theory, the practicalities involved are quite challenging, not the least of which is re-educating the palate (and markets) of more selective cultures and addressing the economic considerations of fishing fleets. Not all harvested biomass is equally sustaining (or attractive) to all people, further highlighting the social and economic aspects of sustainability.

Empirical results

It has been well documented that ecosystems subjected to intense fishing pressure show strong declines in abundance of the target species (Thorson et al. 2012). Ecosystems subjected to strong fishing pressure also show declines in mean size of targeted species, diversity of species, and a shift towards more productive species. But, interestingly, there is growing evidence that ecosystems do not show declines in sustainable yield when yield is made of up a range of taxa and trophic levels. As fishing pressure increased in African lagoons, total yield did not decrease but reached an asymptote (Lae 1997), and McClanahan et al. (2008) showed a similar result across a range of coral reef fisheries. Ultimately, it should be possible to completely deplete all species in an ecosystem, but within the range of fishing pressures seen in these studies it has not happened.

There has not been a meta-analysis of the relationship between fishing pressure and ecosystem-wide yield, but there is certainly evidence that yield (as measured in kilograms) can be sustained and potentially even maximized at very high fishing pressures. The structure of ecosystems under extreme fishing pressure will be highly modified (e.g., much reduced biodiversity), and the landed catch in such situations may not be desired in all cultures. The market for these fish may be limited and of less economic value than the yield that would be realized if fishing pressure were reduced and the ecosystem shifted back to species with higher market values. The history of such intensively modified marine systems is quite short in comparison with our experience and acceptance of highly modified terrestrial systems, and we know little about the long-term dynamics of such highly perturbed (and simplified) systems. However, evidence from nearshore marine ecosystems (e.g., coral reefs, kelp forests, seagrass meadows, and other coastal seas) suggests that system simplification due to overfishing can modify their structure substantially (e.g., causing shifts from kelp forests to barrens or reefs to algal-dominated states), which increases the vulnerability of such systems to the impacts of other human activities such as eutrophication due to excessive catchment run-off, invasive species introductions, and climate change (Folke et al. 2004).

Forage fish impacts

Another ecosystem impact of fishing is the potential reduction in marine predator abundance (fish as well as birds and mammals) when low-trophic-level fish, often called forage fish, are exploited. As they are fished more intensely, there may be less food available for high trophic levels and the abundance of the predators may decline. This is a rather straightforward impact of ecosystem interactions — reduce the abundance of the food and the species that eat that food will be less abundant. These models suggest that fishing forage fish is certainly sustainable by the Brundtland definition, but it does have impacts on other species that may be highly valued or in some cases may be legally protected.

The situation is further complicated by indirect ecosystem effects. For example, modeling work done by Smith et al. (2011) found that predators of competitors of targeted small pelagics could benefit from fishing small pelagics. Similarly, modeling work based on the southern Benguela Current (Smith et al. 2015) has suggested that competitors of fished small pelagics can benefit, and while piscivorous predators may still decline, these declines are not always substantial. For example, the biomasses of pelagic feeding sharks, seabirds, and mammals dropped by <5%–10% when the forage species were exploited at MSY. The increased biomass of competitors helped compensate for any losses of the fished pelagic species. In terms of realized yields, the volumetric dominance of the small pelagics in that system meant that when fished simultaneously, the increase in biomass resulting from the release from competition led to increases in catch among the forage species that swamped any loss in production from piscivores who suffered from a drop in prey biomass.

Bycatch and ecosystem impacts of fishing gear

Two further impacts of fishing on ecosystems are bycatch of nontarget species and impacts of fishing gear on benthic habitats. Bycatch, particularly of birds, mammals, turtles, and sharks, has become a major concern of most fisheries management agencies and brings an immediate warning "not to eat" in consumer guides. The international ban on high-seas drift-netting, declared in the early 1990s, was one of the highest profile management actions to ensue. The bycatch of dolphins in the eastern Pacific purse seine fishery for tuna caused major declines in several populations, and strong pressure, including the introduction of the "dolphin safe" label, was put on the fishing fleet to reduce bycatch (Hall 1998). It was strikingly successful. The kill of dolphins declined from 133 000 in 1986 to 2600 in 1996 through a number of changes in fishing practices. By the 1990s the mortality rate of dolphins by purse seining was comparatively negligible (well under 1% per year), and populations began to increase (Hall 1998). However, one way the dolphin catch was avoided was by moving to fishing floating objects called FADs, which has resulted in considerable bycatch of other species.

Two other well-studied examples of bycatch affecting threatened, endangered, or protected species are turtles caught in a variety of fishing gears (Hall et al. 2000; Lewison et al. 2004) and seabirds caught by longlines (Melvin et al. 2004; Dietrich et al. 2009). In both cases the bycatch caused major reductions in population abundance, potentially leading to extinction, and in both cases technical measures were taken to dramatically reduce bycatch mortality. These positive changes in fishing practice have generally taken place in developed countries with legal frameworks that protect the nontarget species and central governments with sufficient funding to monitor and enforce changes. In many other fisheries in the world, bycatch of these same or related species continues with likely negative impacts on the species.

Much of the annual global catch of marine fish is caught by gear that is dragged along the bottom of the ocean, particularly bottom trawls, dredges, and Danish seines (Watson et al. 2006). These gear types are well documented to modify benthic flora and fauna. The negative effects to the benthic ecosystems are considerable on hard sea floor that is rarely subject to natural disturbance (National Research Council 2002). However, there is considerable evidence that on soft sea floor that is subject to natural disturbance, there are few if any long-term negative effects of alteration by fishing gears (Watling and Norse 1998; Pitcher et al. 2009), and in some cases fisheries productivity may be increased (van Denderen et al. 2013).

Many eNGO consumer guides list almost any fish caught by mobile sea floor contact gear as seafood to avoid, and numerous NGOs have been advocating a total ban on bottom trawling in deep water (Watling 2013) without any distinction between sensitive and resilient sea floors. Banning trawling and therefore protecting all of the ocean floor has a negative effects on scavengers who depend on discards. For example, it was estimated that great skuas (*Stercorarius skua*) nesting in the UK consumed 80 000–90 000 t of fish in 1999–2001 and that discards were a major component of their food (Votier et al. 2004). With its disappearance, the pressure on other local seabird stocks rises as they become prey instead (Votier et al. 2007), since the great skuas could not be sustained at their current levels with a ban on trawling. While trawling changes marine benthic communities, that in itself does not mean that these fisheries are unsustainable.

The system must be considered as a whole. For instance, if there are area closures to protect key, vulnerable, or representative species, the system as a whole can remain sustainable in structure and function even if individual locations are impacted by fishing gear. The dynamic nature of ecosystems, both in time and space, is in part why sustainability must be thought of as a process not a simple stock target — it is far more like juggling than throwing darts at a bull's-eye.

There is mounting evidence (largely modeling, but with a growing database of empirical observations) that both seafood production and broader marine ecosystem form and function can be sustained at a wide variety of fishing pressures, including some very high levels of fishing. Although the highest exploitation rates likely come at the cost of a dramatically transformed and potentially less resilient ecosystem, this would make these systems less sustainable by many definitions of sustainability, but, as stated above, it is not yet clear where one would draw the line between a sustainably and an unsustainably exploited marine ecosystem. It is also unclear what level of ecosystem transformation could be considered sustainable. We live at a time when there is still room for such debate for marine ecosystems, in contrast with terrestrial systems where near complete ecosystem transformations and ecosystem simplification with highly productive exotic species are the norm in agriculture and are broadly accepted. While food security means that we are unlikely to dramatically change our agricultural system, we can still learn from the history of agriculture and what shaped it. First and foremost among those lessons is that to ignore social and economic pressures is to put considerations of environmental sustainability at risk.

Social and economic sustainability

The three pillars of sustainability include economic growth, environmental protection, and social development (Adams 2006). In a review of sustainability, Chapin et al. (2010) wrote "We integrate these approaches to address social–ecological sustainability, recognizing that people are integral components of social–ecological systems and that people both effect and respond to ecosystem processes. Efforts that fail to address the synergies and tradeoffs between ecological and societal well-being are unlikely to be successful." Despite this, sustainability in exploited fisheries has primarily been considered an ecological question by the biodiversity conservation community.

Almost all seafood guides and certification schemes consider only the biological and management aspects and do not consider social or economic impacts of the fishery management system. Economic and social sustainability are often identified in fisheries policies and legislation and targeted in performance measures, such as maximum economic yield (MEY). Much attention has been paid to the economic inefficiency of fishing fleets due to overcapacity (World Bank 2009) and subsidies (Clark et al. 2005). In general, the profitability of a fishery will be maximized at lower fishing pressure and higher mean abundance than would produce maximum biological yield (Grafton et al. 2007). This can produce a situation in which a stock is economically overfished (fishing pressure higher than would produce maximum economic profit), but not biologically overfished. Such a system can certainly be sustained — which is why governments, such as the Australian government, has switched to MEY from MSY as a target reference point — but as yet certification schemes and NGO recommendations have not considered economic management targets or maximizing benefit to the public. As an added benefit, targeting MEY rather than MSY can reduce other environmental impacts such as carbon footprint and water use (Farmery et al. 2014).

Considering economic return in isolation is not necessarily wise either, however. In many countries there are explicit or implicit social objectives involved in the fisheries management system often centering around maintaining traditional fishing communities (Degnbol and McCay 2007) and access to fishing as a mechanism for those displaced from agriculture or otherwise unemployed. In contrast, New Zealand has an explicit goal to maximize economic value to the nation without any social objectives. As a result, New Zealand fishery ownership has been centralized, and the social and community consequences have been of serious concern to some (Dewees 1998; Yandle and Dewees 2008). A similar case is the fisheries allocation system for the British Columbia trawl fisheries (Pinkerton and Edwards 2009). From the standpoint of local fishing communities and equitability, these systems might not be considered sustainable.

Forms of unacceptable working conditions and human trafficking have been identified in vessels chartered in New Zealand waters (Sylwester 2014) and Thailand (Simmons and Stringer 2014), and exchanging sex for access to fish has been revealed in sub-Saharan African fisheries (Béné and Merten 2008). Gender equality is a growing concern for many discussions of sustainability (Allison and Horemans 2006), as are issues of child labor, forced labor, violence, and unsafe working conditions (Ratner et al. 2014). Once we move from the restricted consideration of sustainability as a question of marine ecosystems to include the other two pillars of social and economic sustainability, the range of issues that would need to be considered in defining and categorizing sustainable seafood is much wider. Such breadth is undeniably daunting, but again is made more tractable if sustainability is thought of as a process rather than a set of fixed targets.

People have been trying to manage fisheries for more than 4600 years (Li et al. 2012) and making jokes about the state of fisheries for at least 1900 years (since Iuvenalis circa 100 AD). The history of fisheries management and analysis of the success of fisheries management have shown that a focus on the state of the resource is insufficient for achieving fisheries that meet environmental objectives, let alone environmental, social, and economic ones (Fulton et al. 2011*b*). Focusing on environmental status alone can result in a lack of compliance with negative stock outcomes (Peterson and Stead 2011). Externalities, multiple incentives, feedbacks, and behavioral responses can lead to unintended consequences. Moreover, global change has driven home the pervasive nature of change — ecosystems change, technology and behaviour change, societal desires and scientific understanding all change. As a result, any method of management relying on static measures or targets is either eventually irrelevant or at best delayed, both of which ultimately lead to fish stocks in a poor state (Brown et al. 2012). To be successful, the method of management must be dynamic and responsive, a process not an end result. At a minimum this means monitoring changes in the abundance of ecosystem components and adjusting fishing pressure on different elements of the ecosystem as their productivity varies over time.

Sustainability is a process

Many consumers and retailers simply want to know if a specific fishery is sustainable. Using ecological measures of abundance or biomass does not provide the most accurate answer to this question. Even beyond the myriad social and economic considerations listed above, fish stock abundance goes up and down with or without fishing, and paleontological evidence shows many stocks fluctuate greatly and even show widespread local extinction prior to human impacts (Schwartzlose et al. 1999; Rogers et al. 2013). A stock may be at high current abundance, but caught in a totally unregulated fishery and fished at rates that are not sustainable. Thus, the abundance of a fish stock does not necessarily say much about its sustainability, and sustainability definitions that rely on stock abundance as the primary indicator can often be misleading. A question with a more exacting answer is "Is it sustainably managed?" Sustainably managed stocks are far more likely to remain so and dynamically respond to changing circumstances and understanding. Thus, current exploitation rate would generally be a better measure of sustainability than current abundance.

The western theory of sustainable harvesting of fish stocks evolved during the first half of the 20th century and was codified in two major books of the 1950s (Beverton and Holt 1957; Ricker 1958*a*), but by the 1990s many fisheries in the developed world were considered overexploited (Worm et al. 2009). This started to change in the 1990s as more countries implemented fisheries management systems that had (*i*) specific objectives and targets for fishing pressure and abundance, (*ii*) monitoring of fishing pressure and abundance, (*iii*) assessments to determine if targets were being met, (*iv*) feedback management systems that adjusted regulations in response to the assessments and in particular restricted fishing pressure when it was too high, and (*v*) enforcement systems to assure compliance with regulations. These are the basic elements of a sustainable management system (for the fish stock at least), and without these elements there can be no assurance that the stock will be sustainably managed. This can be summarized quite simply as "sustainability is a process".

Certification and sustainability guides

There are now hundreds of seafood guides and several certification programs to provide guidance to consumers and retailers on what is sustainable. In this section we look specifically at two of the most widely recognized to evaluate what elements of sustainability they consider most important in providing consumer advice.

The Marine Stewardship Council (MSC) is an independent nonprofit organization founded originally by the WWF and Unilever to provide certification that fisheries are well managed. As of May 2013, 200 fisheries were certified, 103 were under assessment, and 22 fisheries have failed or withdrawn from the program (Agnew et al. 2014). The MSC has a transparent scoring process broken into three principles, dealing with (*i*) stock management, (*ii*) ecosystem effects of the fishery, and (*iii*) governance, policy, and the management system (Marine Stewardship Council 2010). Overall, the MSC has eight scoring criteria related to outcomes (state of stocks and ecosystem) and 23 that concern process. Thus, MSC evaluation is heavily weighted towards sustainability as a process rather than as a measure of ecosystem condition. However, the MSC scoring is completely confined to the fish stock and the management system, with no consideration of social or economic impacts nor of environmental impacts beyond the local marine ecosystem.

The Monterey Bay Aquarium's Seafood Watch program is the best known of over 200 seafood guides (Roheim 2009) and provides consumer advice for particular species, with each species and harvest method graded as "best choice", "good alternative", or "avoid". They have four criteria: (1) impacts on the species under assessment, (2) impacts on other species, (3) management effectiveness, and (4) impacts on the habitat and ecosystem. Within the first two criteria, all scoring is based on the state of the system, with measures of the biological vulnerability, the abundance, and the mortality. Criterion 3 has two process-related scoring factors, while criterion 4 has two state measures and one process measure. Overall Seafood Watch scoring is dominated by state measures (9), with only three measures of process.

As with MSC scoring, no scoring in Seafood Watch deals with social or economic impacts, nor are environmental impacts beyond the local marine ecosystem considered. This is perhaps best illustrated by the relative rankings of yellowfin tuna (*Thunnus albacares*) (ratings as of 26 December 2014), which can be a "best choice" if caught by US troll or poll-and-line fishing, "good alternative" if caught by imported troll or poll-and-line or US longline, or "avoid" if caught by purse seine. It is not the status of the stock or its management that distinguishes, but the bycatch of other species that is different among the different methods. Purse seining has significant bycatch of juvenile bigeye tuna (*Thunnus obesus*) and a range of other species. However, pole and line and longline fisheries produce three to five times more carbon footprint per ton of tuna landed than do purse seiners (Ardill et al. 2011) and rely on intense exploitation of "baitfish" from local coastal zones. Therefore, if there were more concerns about carbon footprint (broader environmental impacts) than bycatch impacts, purse seining would be elevated and pole and line fishing demoted in the scoring system.

While Seafood Watch is the best known of the seafood guides, and its scoring criteria are well documented, there is reasonable agreement across various seafood guides that were compared by Roheim (2009). These guides were predominantly oriented towards the state of the fish stock and assessments of the acceptability of various marine ecosystem impacts. They contain little consideration of the nature of the management system or the social or economic outcomes and essentially no consideration of environmental impacts beyond the marine ecosystem.

Impacts beyond the marine ecosystem and fishing communities

Consumer guides to many forms of consumables, not just food, are growing in number. Since seafood guides came first, fish retailers in the USA, Canada, and Europe can advise you on what seafood is "sustainable", but no such advice or guidance is available for other forms of food sold in the same stores. Changes have come with labeling as to whether food is organic, eggs are free range, or beef is grass-fed, but there is a deafening silence on sustainability of food stuff as measured by social impact, carbon footprint, water use, eutrophication and acidification, land transformation, and biodiversity. Consequently, consumers may be excused for thinking seafood is not such a good choice even though comparative studies show seafood to be one of the most sustainable, or lowest impact, foods across a range of sustainability measures (Tilman and Clark 2014; Sharpless and Evans 2013). As a result, we are now in a position that even though the transformation of marine ecosystems by fishing is in most places far less than the transformation of land by agriculture, and there are direct threats to human health from pesticides, herbicides, and antibiotics used in livestock production, many retail chains have stopped selling certain fish but continue to sell beef, chicken, and pork regardless of production practices.

In the future it may be common for seafood sustainability to be compared with agriculture, aquaculture, and other human activities in its broader impacts. However, as we are not there yet, we should make the most of our experience so far with an evolving understanding of what defines seafood sustainability, lending what we have learned to a wider consideration of which impacts could be used to define sustainability more broadly. For example, Australian fishermen must report any interaction with threatened, endangered, or protected species. In contrast, no Australian motorist has ever been asked to report any bycatch-by-car of threatened, endangered, or protected species (e.g., marsupials such as brushtail possums, pademelons (*Thylogale* spp.), wallabies, bandicoots, quolls (*Dasyurus* spp.), and Tasmanian devils (*Sarcophilus harrisii*)); despite more than approximately 300 000 deaths per year in the State of Tasmania (Hobday and Minstrell 2008) alone (summed across taxa) and roadkill having been identified as a major cause for the decline of the eastern quoll (*Dasyurus viverrinus*) and the Tasmanian devil. It is clear that the transferal of a simple, biological, target-based concept of sustainability to all aspects of humanity is unlikely to be feasible or to deliver the intended biodiversity, broader ecosystem services, or socio-ecological outcomes.

Conclusions

Once we examine aspects of sustainability beyond food production, we can find little basis for an agreed upon definition of social, economic, or ecological elements of sustainability. The standard in those dimensions depends on what an organization or individual believes is most important. There are some standards in these dimensions that could likely be widely agreed. For instance, bycatch that leads to extinction and use of slave labor, but any attempt to be all-inclusive will subject "sustainable fisheries" to being tweaked and pulled in all directions by different interest groups. Given such intractable, unwieldy complexities, it may be prudent to rein in the definition of sustainable fisheries. The Brundtland definition is already widely accepted, sound, and defensible. Consequently, if a management system can provide food for this generation without reducing the ability of future generations to produce food, let us call that "sustainable seafood".

Certainly consumer advice can and should incorporate environmental impacts, human rights, and social equity into their advice on what should be eaten, but either we have to abandon the term "sustainable seafood" in those dimensions or find broad agreement on what is acceptable.

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