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Review

Low impact and fuel efficient fishing—Looking beyond the horizon

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ABSTRACT

Fishing provides high quality seafood and creates employment and income for people worldwide. Most of the capture methods used for fishing are, however, heavily dependent on the use of fossil fuels. For many important fisheries their high consumption of fuel constitutes a major constraint to their economic viability but also represents a significant source of greenhouse gas emissions. In addition, fishing activities can sometimes impact the marine environments through excessive removals of ecologically and economically valuable species and also by direct physical contact with critical habitats. Fishing practices and gears vary widely in their environmental impacts and fuel efficiency but, in general, the impacts of passive fishing gears such as pots, traps, and hooks are considered to be less severe, and the amounts of fuel required per kg of catch smaller, than for towed gears such as beam trawls, dredges and the many types of bottom trawls. Through technological improvements and behavioral changes, the fishing sector can substantially decrease the damage to aquatic ecosystems, reduce emissions and lower its fuel costs. Changes in fishing practices can result in more economical and sustainable fisheries thereby contributing to improved food security. Barriers to begin transition to the use of low-impact, less fuel-intensive practices and gears include a perception that cost-efficient and practical alternatives are not available; restricted access to capital; ineffective technology infrastructure support; and inflexible fisheries management systems that restrict the rapid development and uptake of alternative gears. This paper discusses some of the key capture technologies and identifies gaps, constraints, and opportunities that facilitate the development and adoption of Low Impact and Fuel Efficient (LIFE) Fishing. LIFE fishing addresses the complex dynamic of energy consumption and environmental impacts with the objective of improving the economic viability and environmental sustainability of fishing operations.

Contents

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1. Introduction

Global capture fisheries production in 2008 was approximately 90 million tonnes, with an estimated first-sale value of US$ 93.9 billion (FAO, 2010). While this level of production has been relatively stable over the past two decades, there have been marked fluctuations in the catches of major species and the stocks of many demersal high-value resources have diminished. Anticamara et al. (2011) estimated that over this period global fishing effort (in kilowatt days) has increased by roughly 20 percent with the most pronounced increases in Asia. Despite recent reductions of fleet sizes in many developed countries, the size of the global fishing fleet has doubled in the last 30 years and is estimated at some four million vessels (FAO, 2010), about 60% of these powered by some form of engine.

As many fish stocks have declined due to excessive fishing, vessels often need to search longer and/or fish in deeper offshore waters which has increased the fishing power of fishing vessels dramatically (World Bank and FAO, 2009) with greater amounts of gear being set over a larger area and depth range. Technological improvements have also contributed to an increase in effective fishing power and efficiency such as through advanced hydraulic power applications, stronger materials for fishing gears and better electronic aids for navigation, bottom mapping, fish finding, gear deployment and communication (Kristjonsson, 1971; von Brandt, 1984; Gabriel et al., 2005; Marchal et al., 2007). Many of these have become widely available, cheap and compact enough to be operated from almost any size of vessel. For a variety of reasons a significant part of global marine fish stocks are currently either fully exploited or overexploited (FAO, 2010) and the economic health of marine fisheries has generally declined (World Bank and FAO, 2009).

Most fishing techniques in use today have their origin in an era when fisheries resources were abundant, energy costs were dramatically lower than current levels, and when less attention was paid to operating efficiency and negative impacts of fishing on marine and atmospheric ecosystems. Current high energy prices and greater awareness of ecosystem impacts are realities and present major challenges for the viability of fisheries. This may be especially true in developing countries where access to and promotion of energy efficient technologies has been limited (FAO, 2007). Despite a growing number of initiatives and experimentation with alternative energy technologies such as wind assisted propulsion (kites and sails), compressed air engines, biofuels and others, there is presently no viable substitute to the use of fossil fuels for powering fishing vessels.

With fossil fuels remaining the dominant energy source for capture fisheries, pursuing energy efficiency may realize a multitude of benefits such as reduced operating costs and environmental impacts. However, the overall success of any transition will depend heavily on developing and applying suitable and acceptable measures to conventional fisheries and creating the appropriate incentive for change in the behavior of fishers such as through the development and implementation of a management system that is based on the ecosystem approach to fisheries (FAO, 2005; Fletcher et al., 2005; Bianchi and Skjoldal, 2008).

Modification of existing gears, development of low drag gears and adoption of alternative fuel-efficient gears all represent means to improve fuel efficiency. This paper deals with the development of "Low Impact and Fuel Efficient (LIFE)" fishing which refers to fishing gears and practices that ensure fish capture occurs using a low amount of fuel with low impact on the environment. It discusses some of the key capture technologies and identifies gaps, constraints and opportunities towards development of LIFE fishing. In addition, it explores transfer and adaptation of technologies from other fisheries that have demonstrated commercial potential for similar species. The primary focus is on commercial capture-fisheries although some environmental issues concerning small scale artisanal fisheries are discussed. The paper deals mainly with demersal fishing.

2. Environmental impacts of fishing operations

Fishing gears vary widely in their impacts on marine ecosystems (Jennings and Kaiser, 1998; Jennings et al., 2001; Bjordal, 2002; Tudela, 2004; Kaiser et al., 2006; Polet and Depestele, 2010) and without a specific context their ranking is extremely difficult (Morgan and Chuenpagdee, 2003; Jennings and Revill, 2007; Fuller et al., 2008; Gascoigne and Willsteed, 2009; Caddy and Seijo, 2011; Rochet et al., 2011). Impacts can be split into biological and physical impacts. Overall ecosystem impacts largely depend on the physical characteristics of the gear, the mechanics of its operation, where, when and how the gear is being used as well as the extent of its use. Gears that rank highly for one type of impact may have a lower rank for another (Gascoigne and Willsteed, 2009). For instance, dredge gears may generally have a high rank for bottom impacts (Løkkeborg, 2005) but have a low rank for bycatch of endangered, threatened and protected species (ETP species).

Physical damage to the marine environment may result from the nature of the capture technology or from the inappropriate use of an otherwise acceptable gear. For example, the exploitation of previously untrawled grounds by bottom trawls can result in a significant reduction in the abundance of sensitive benthic invertebrates (Kaiser et al., 2006; Hiddink et al., 2006; Pitcher et al., 2009). However, it should be noted that use of such gear on previously trawled ground does not necessarily equate to increased cumulative impacts. Only a small number of fishing methods, such as explosives and toxins, are recognized as inherently destructive irrespective of where they are used (McManus et al., 1997; Barber and Pratt, 1998; Garcia et al., 2003).

Some fishing activities (e.g. shrimp trawling) capture a significant quantity of species and sizes beyond those targeted leading to the incidental catch of a wide variety of fish and invertebrates including juveniles of ecologically important and/or economically valuable species. This component of the catch is frequently not retained and is disposed of overboard as discards, which are mostly dead or mortally injured. During 1992–2001, the average yearly level of discards in the world's marine fisheries was estimated to be 7.3 million tonnes (Kelleher, 2005). Since this time there have been substantial efforts to manage bycatch and reduce discarding (e.g. Broadhurst, 2000; Hall et al., 2000; Kennelly, 2007; Zhou, 2008; ICES, 2010; FAO, 2011). Excessive levels of bycatch of non-target species and undersized target species still, however, occurs for many fisheries (Lewison et al., 2004; Davies et al., 2009).

There is concern about impacts of unaccounted fishing mortalities including ghost fishing which results from abandoned or lost fishing gears (Matsuoka et al., 2005; Macfadyen et al., 2009) or the unseen mortality of fish that encounter fishing gear, escape but ultimately die (Chopin and Arimoto, 1995; Suuronen, 2005; Broadhurst et al., 2006). Fishing can also result in the incidental mortality of a variety of endangered, threatened, protected and charismatic non-target species such as seabirds, sea turtles and marine mammals. Finally, some fishing activities may cause damage to vulnerable marine ecosystems such as coldwater coral reefs which can take many decades or centuries to recover (e.g. Lewison et al., 2004).

Despite the variability and complexity of the issue, and the fact that incidental capture of non-target and charismatic species is a problem in several pot, trap and hook fisheries, the overall environmental impacts of these types of passive fishing gears are generally considered less severe in comparison to many types of demersal trawls, and in particular to dredges and beam trawls (Bjordal, 2002; Morgan and Chuenpagdee, 2003; Valdemarsen and Suuronen, 2003; Fuller et al., 2008; Polet and Depestele, 2010; Caddy and Seijo, 2011). Encircling gears, that are dragged a limited distance at slow speed, such as bottom seines, are generally considered less damaging than bottom trawls (Tulp et al., 2005; ICES, 2006). Well-managed purse seine fisheries generally have minor ecosystem impacts (Morgan and Chuenpagdee, 2003). In some purse seine fisheries the release of the catch or portions of the catch from seine (slipping) is a common method of regulating the size and quality of the catch. The mortality of pelagic species subjected to a release may be high especially when the crowding density during slipping is high (e.g. Huse and Vold, 2010). Gillnets can be an environmentally friendly option but may be problematic due to negative impacts on vulnerable species or ghost fishing by lost or abandoned gear (Rihan, 2010).

3. Fuel consumption and greenhouse gas emissions of fishing operations

Fuel costs for the fishing industry have risen substantially over the last forty years during which time there were three major spikes when oil prices rocketed. For instance, between 2003 and 2008 the price of crude oil rose from US $25 per barrel to US $135 per barrel. This rapid increase severely affected the profitability of the catching sector. Despite the decline of oil prices after the 2008 peak, the medium term forecasts for oil prices indicate a high likelihood for further and steady increases (International Energy Agency, 2011).

FAO and World Bank reported that the global fishing fleet consumes approximately 41 million tonnes of fuel per annum at a cost of $22.5 billion (World Bank and FAO, 2009). This amount of fuel generates approximately 130 million tonnes of CO_2 but there is a paucity of detailed data on Green House Gas (GHG) emissions from fishing vessels (e.g. Buhaug et al., 2009). While the inadequate techniques for analysis make it difficult to rank fishing gears and practices by their GHG emissions, relative fuel consumption across methods offers a reasonable surrogate for GHG emissions (except when the share of catch refrigeration is significant, see Winther et al., 2009). Those fisheries which are energy intensive will typically have higher GHG emissions.

Overall, approximately 620 L of fuel (527 kg) is used per tonne of landed fish (Tyedmers et al., 2005) but fuel consumption rate varies widely according to gear type and fishing practice (Thrane, 2004; Tyedmers et al., 2005; FAO, 2007; Schau et al., 2009; Winther et al., 2009). Operational techniques and the distances between fishing grounds and fishing ports, as well as vessel design and age will all affect the amount of fuel consumed. There are also substantial differences in fuel consumption between fisheries targeting groundfish or shellfish and those targeting pelagic fish or industrial fish (Schau et al., 2009).

Studies of fuel consumption patterns by gear types report that passive fishing gears such as pots, traps, long-lines and gillnets generally require lower amounts of fuel (approximately 0.1–0.4 L of fuel per kg of catch) than active fishing gears such as bottom trawls (from 0.5 up to 1.5 L/kg). Bottom seines rank between passive gear and bottom trawl in fuel consumption (Thrane, 2004; Winther et al., 2009; ICES, 2010). The variation in fuel consumption, however, can be large between seine net vessels due to different fishing effort and steaming times to fishing ground (Rúnarsson, 2008).

Active pelagic gears like midwater trawls and purse seines target fish that form dense schools and enable the catch of hundreds of tonnes of fish with one short tow or haul. Fuel consumption for these methods is generally low in relation to the quantity of catch. In particular, purse seining is one of the most fuel efficient techniques for catching fish (approximately 0.1 L of fuel per kg of catch) but the vessels using this gear often spend significantly more time and therefore fuel searching for schools than actually catching fish (Thrane, 2004; Schau et al., 2009; Winther et al., 2009).

Fishing with the help of powerful artificial lights is common practice in purse seining, squid jigging and stick-held-dip netting particularly in Asia. While the fishing operation itself is fuel efficient, the use of the lights can make it energy intensive. For example, the coastal Japanese jigging boats (less than 20 GR), that use up to 160 kW electric power for the lights, typically consume about 600 L of fuel per operation for lighting these lamps (Matsushita et al., 2010). To save energy, the use of low-energy Light Emitted Diodes (LEDs) has emerged as an alternative with fuel savings of 20–30% but fishing efficiency may also be reduced (Yamashita et al., 2012), and there remain concerns about the effect of light intensity on the environment (light pollution).

Rising fuel costs has promoted research and development on various energy saving technologies (Curtis et al., 2006; Winther et al., 2009; Abernethy et al., 2010; Heredia-Quevedo, 2010; E-Fishing, 2010) but fuel continues to be a major cost and the catching sector remains exposed to progressively increasing fuel prices. In developing countries, mechanization continues to increase and high fuel prices will impact such countries even more than developed countries. Increasing fuel prices often results in governments establishing fuel-subsidies to support the viability of fishing operations (Sumaila et al., 2008, 2010; World Bank and FAO, 2009) but such subsidies often work against the development of energy-efficient fishing operations.

It is noteworthy that life cycle assessments (LCA) show that significant energy consumption and greenhouse gas emissions are possible even after the catch is taken onboard and landed due to fish processing, cooling, packaging and transport (e.g. Thrane et al., 2009; Winther et al., 2009; Vázquez-Rowe et al., 2011). Minimizing impacts and energy consumption throughout the product chain may be another important element needed to reduce the environmental costs of fishing.

4. Low Impact and Fuel Efficient [LIFE] capture techniques

4.1. Potential approaches in LIFE fishing

Changes from current fishing methods or practices that use a high level of energy and cause high impacts on marine ecosystems, to methods with lower energy consumption and ecosystems impacts, offer opportunities for conserving fuel, preserving ecosystems and improving food security. Transitioning from one gear type to another, however, is seldom easy or practical. First, the size and design of existing fishing vessels and their machinery and equipment often limit the possibilities of changing the fishing method. Second, fishing gears, fishing vessels, operations, and practices have evolved over a considerable period of time, around specific fishing grounds and behavior of target fish species. Accordingly, the evolved fishing gear and practices are “tailor-made” to catch specific target species or species groups in a manner that is often perceived to be optimized to the best technical and economic

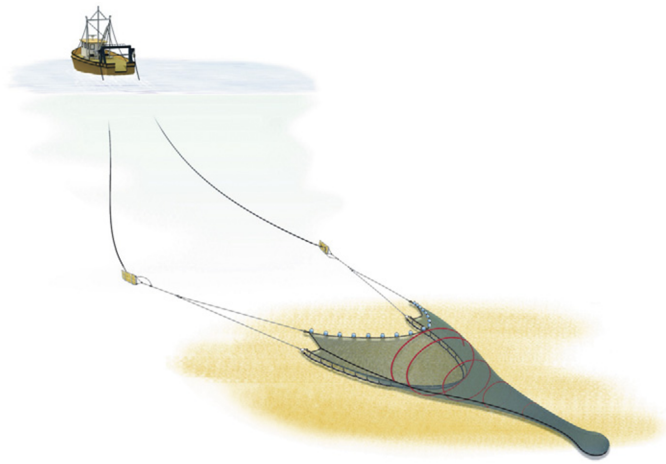

Fig. 1. A single-boat bottom trawl designed to catch species living on or near the bottom by towing it steadily along the seabed. The ground gear (or the footrope) of the trawl has contact with the bottom while fishing and is designed to withstand this interaction with minimum damage. The horizontal opening of the netmouth is maintained by otterboards. Floats and weights produce the vertical opening of the net.

Courtesy of FAO and SEAFDEC.

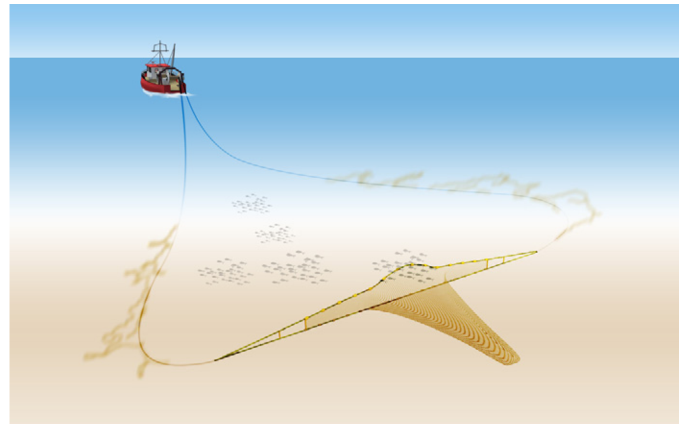

Fig. 2. A bottom seine has long towing ropes extending from the wings of the net that herd the fish into the path of the net. The boat hauls ropes simultaneously when steaming slowly forward. The hauling speed of the ropes is increased gradually towards the end of the operation.

Courtesy of FAO and SEAFDEC

scenarios that will be encountered during fishing. Furthermore, where fishing practices are rooted in tradition, there is a strong resistance to change.

Fuel consumption and ecosystem impacts can be reduced through changes in operational techniques and gear design without drastic changes in behavior (Valdemarsen and Suuronen, 2003; van Marlen, 2009; He and Winger, 2010; Rihan, 2010). This approach has in many cases shown promising results and is often preferred by the fishing industry. Transitioning to a completely new gear type and fishing practice is an alternative that has many more uncertainties and higher economic risks. However, when incremental improvements in existing technology do not allow low-impact and fuel-efficient fishing, alternative practices and/or gear may need to be considered.

4.2. Increasing the operational efficiency and reducing seabed impacts of demersal trawling

Trawls (Fig. 1) are flexible gear that can be used on many types of areas and grounds, in shallow and deep waters, and by small and large vessels for a wide range of target species. These characteristics have made trawling the preferred fishing method for many fishers. Currently, trawling may be the only effective solution for capturing certain species, for example certain "shrimp" species. However, bottom trawling has been identified as one of the most difficult methods to manage in terms of bycatch and habitat impact.

There are many techniques and operational adaptations available to reduce the drag and weight of the bottom trawl gear and thereby to reduce fuel consumption and seabed impacts (Table 1). Some of these techniques have been reported to reduce environmental impacts and gear drag without marked decrease of the catch of the target species (e.g. Glass et al., 1999; He, 2007; Valdemarsen et al., 2007; Queirolo et al., 2009; van Marlen, 2009). For instance in the bottom trawl fisheries in Mexico, Colombia and Chile, several modifications have been successfully tested in trawls to reduce bycatch and fuel consumption. A reduction of the gear drag between 20 and 35% and fuel saving between 23 and 43% have been reported in these tests (Zúñiga et al., 2006; Rico-Mejía and Rueda, 2007; Melo et al., 2008; Heredia-Quevedo, 2010).

More work is needed to improve the construction of different components of trawl gear to minimize friction on the bottom and to reduce overall gear drag. Technology should be further developed to automatically measure and adjust pressure of trawl doors and ground gear on the seabed. An example of this approach is a system developed in Spain to control the bottom fishing gear of the fleet operating close to a gas pipeline (ICES, 2010). In this case, the system monitors and records fishing gear parameters with the geographical position of each sensor (installed on the doors and the headrope center) relative to the pipeline. This allows vessels in the vicinity of the pipeline to raise their gear over it without damage to their gear or the pipeline. One example where seabed contact has been reduced while catching efficiency was maintained is the use of ballast elements or dropper chains to hold the footrope near, but not contacting, the bottom (He and Winger, 2010). In some fisheries moving from bottom trawling to semi-pelagic trawling can make trawling activities more sustainable and energy efficient (Jørgensen and Valdemarsen, 2010).

In beam trawls, progress has been made in recent years in developing alternative gear designs that reduce the amount of tickler chains, avoid excess weight in the beams, and use other stimuli (e.g. electric pulses) as an alternative to chains to scare the target fish off the bottom and into the net (Polet and Depestele, 2010). The use of acoustic, light, or any other additional stimuli to enhance encounters by target species within the catching sphere of trawl nets should be further explored.

The use of improved location and targeting of fish with the help of electronic seabed mapping tools and integrated GPS navigation systems, have resulted in avoidance of sensitive bottom habitats and minimize fishing effort and fuel consumption. Multibeam acoustics has been successfully applied to mapping scallop beds on the Browns Bank, Nova Scotia. By applying fine-scale acoustic mapping of beds, the Canadian scallop fishery on Browns Bank has been able to reduce fishing time and towing distance by 70% between 1998 and 1999 while still harvesting the same scallop quota (National Research Council, 2005).

4.3. Alternative fishing practices and gear types

4.3.1. Bottom seining

Bottom seining (Danish, Scottish and pair seining, Fig. 2) is generally considered to be a more environmentally friendly and fuel efficient fishing method than bottom trawling (Dickson, 1959; Einarsson, 2008; ICES, 2010). The gear is lighter in construction and the area swept is much smaller than in bottom trawling, and because there are no trawl doors or warps, there is less pressure

Table 1
Examples of potential energy saving techniques and operational adaptations to reduce fuel consumption and environmental impacts of demersal trawling.

Technique/measure	Effect	Constraints–barriers
Use of thinner and stronger twines, super fibres, knotless netting, square mesh netting, T90 net, less netting, larger mesh size	Reduces the amount, weight and surface area of netting and increases water flow through the net, thereby reducing the overall drag	High price and availability of materials; use of larger meshes can reduce the catch of marketable species and sizes; cost benefit analyses not carried out for most fisheries
Use of smaller and/or multiple nets for species that exhibit poor avoidance behavior to the presence of the fishing gear (e.g. shrimp, flatfish)	Reduces the overall netting surface area and thereby the weight and the drag without reduction in catch	Policy, complexity of rigging, resistance to change
Use of effective bycatch and benthos reduction devices (BRDs)	Allows the escape of unwanted species or sizes of fish and other unwanted objects thereby reducing the weight and overall drag	Variability in performance, lack of technical support to test and optimize BRDs, loss of revenues of target species and sizes, perceptions
Using four-panel design (instead of typical two-panel) in the belly, extension piece and codend, using square mesh netting in the belly	Ensures easier installation of BRDs and better geometry and stability for the back end of the trawl	Cost benefit analyses not carried out for most fisheries
Use of hydrodynamic trawl doors and use of optimal warp length (that corresponds to optimal door efficiency)	Less drag (traditional trawl doors contribute up to 25-35% of the overall gear drag), less weight, better fuel efficiency	Price, performance monitoring, control in different sea conditions and depths
Use of raised or flying trawl doors where the weight element of the door is separated from the spreading element (doors can be flown above the seabed to open the trawl)	Better spread, less drag and less pressure on the bottom (less seabed disturbances)	Price, performance monitoring, control in different sea conditions, depths, not suitable for all species
Better rigging of the gear, lighter ground-gear, shorter ground-gear, less discs and better rotation capacity, self-spreading ground gear, composite ropes, lengthened bridles, off-bottom bridles, lightweight warps, and proper matching of trawl net and trawl doors	Lighter and reduced contact points to seabed, less seabed pressure, smaller impact area, less drag	Performance monitoring
Use of hydrodynamic shape of floats, kites, beams, pulse trawls, SumWing-design	Reduced drag, reduced seabed contact	Performance monitoring, speed dependence
Converting from single boat trawling to pair trawling	Reduces fuel consumption, less seabed damages	Policy, human behavior
Improving real-time monitoring and control of gear with acoustic gear surveillance technology	Maintenance of optimal gear performance, reduces energy consumption and bycatch	Price, training
Installing real-time camera observation system for informing skipper of fish behavior and composition in the trawl	Helps to maintain optimal gear performance, reduces bycatch and collateral impacts. The next step may be an active mechanism to release unwanted catch	Price, training
Improving navigation and fish finding, and improving knowledge on fishing grounds (GPS, electronic charts, sea-bed mapping)	Maximizes catches and minimizes time, energy and collateral impacts	Price, training
Use of speed controls, reduction of towing speed	Reducing speed directly reduces the fuel consumption	Human behavior
Vessel and propulsion system optimization, preventive maintenance of vessel and engine, change in trip planning practices	Reduces fuel consumption	Price, human behavior

on the seabed. The light gear and low hauling speed means that fuel usage may be lower than for a comparable trawling operation. A seine is cheaper and less bulky than a trawl and can therefore be an effective technique for smaller and low horsepower vessels, depending on the target species. Nevertheless, there are several operational limitations in seine netting (Table 2).

Bottom seine nets are generally regarded as having low impact on benthos, although few specific studies have measured this impact (ICES, 2006). Tulp et al. (2005) derived fishing event mortality rates for four main fishing gear categories, including bottom seine. Gear average mortalities calculated across 12 benthic invertebrate phyla were 0.25 for beam trawl, 0.1 for two otter trawl fisheries (*Nephrops* and mixed roundfish) and only 0.05 for seine gears, showing seines to have the lowest mortality for towed gears. Two Canadian reviews recently concluded that the main impact of seining is bycatch of both undersized individuals of the target species and individuals of non-target species (Donaldson et al., 2010; Walsh and Winger, 2011). In terms of other environmental impacts, including bycatch of protected species such as marine mammals, pinnipeds and seabirds, there are no reported impacts other than a few benign interactions. In Australia, some interactions with seals are noted by Wayte et al. (2004) but with no resultant mortality. Donaldson et al. (2010) reported bycatches of winter skate (*Leucoraja ocellata*) by seiners in the Southern Gulf of St. Lawrence, a species that has been listed as endangered.

The high-quality of catch is recognized as an advantage of bottom seines. Fish are caught in the net during the very last

Table 2
Potential advantages and disadvantages of demersal gear explored in this study.

Gear	Advantages	Disadvantages	Priority actions
Trap-net and pound-net	• Low energy use • Selective for species and sizes (if properly designed) • Live capture (possibility) • Minimal habitat impact	• Not easily portable • Operation may be labor intensive • Maintenance labor-intensive • Expensive to construct • Operation limited to relatively shallow waters • Occasionally significant bycatches	• Development of designs and practices that prevent the entangling of non-fish species in the mooring ropes and nettings of the trap
Pot	• Low energy use • Flexible and transportable • Can be operated in rough bottoms • Selective for species and sizes • Live capture—good catch quality • Potential for low bycatch mortality • Minimal habitat impact • Predator safe • Availability of wide variety of suitable local (natural) materials • Cheap to construct	• Low capture efficiency for many finfish species • Ghost fishing of lost pot • Lost pots contribute to marine debris • Low catch rates	• Fish behavior studies to enhance ingress and reduce escape • Alternative attractants • Comparative fishing experiments • De-ghosting technologies • Human behavior–barriers to a change • Research and development work at infancy
Long-line	• Low energy use • Portable • Flexible and versatile • Species selective • Minimal habitat impact • Good catch quality • Cheap to manufacture	• Labor intensive and time consuming to operate • Incidental bycatch of non-target species • Snagging on benthic epifauna • Availability and price of bait • Low catch rate for many species	• Bait issue/bait availability • Alternative attractants
Gill-net	• Low energy use • Easily portable • Versatile and flexible • Good size selectivity (except trammel-nets) • Possible to target specific size range allowing effective exclusion of small and large fish. • Relatively cheap to manufacture	• Labor intensive • Most fish die during capture • Catch quality • Poor species selectivity • Capture of non-target species, often sea birds, turtles and other charismatic species • Ghost fishing of lost nets • Benthic impacts	• Development of practices and technologies that reduce bycatch
Bottom seine	• Relatively low energy use • Possible to operate with low horsepower vessels • Reduced bottom impacts compared to bottom trawling • Requires less space than bottom trawling (possible to operate in small patches of good ground) • Allows easy moving between fishing ground • Relatively low gear costs • Less gear damage and wear than in bottom trawl fishery • Easier to use and repair (than bottom trawl) • High fish quality • Great scope for modifications and improvements	• Not as flexible and effective as bottom trawling • Operation limited to relatively flat and clean grounds (warps snag easily on boulders) • Operation can also be restricted by depth, strong tides, bad weather and lack of daylight • Not effective for non-herded animals such as shrimp and nephrops • Operation requires good skills • Workload can be relatively high • Relatively poor selectivity for species and sizes • Potential sea bed impacts • A large seine can be expensive to manufacture	• Research and development work needed in improving the operation on rough grounds, in sea currents, and in deeper waters • Substantial energy saving possibility • Training is needed because the technology not well known
Beam trawl	• Effective • Relatively easy and practical to use	• Seabed impacts • High fuel consumption • Bycatch • Suitable only for relatively clean grounds • Expensive	see Table 1
Bottom trawl	• Effective • Versatile	• Seabed impacts • High fuel consumption • Bycatch • Expensive • Operation requires high skills and advanced equipments	see Table 1

periods of the capture process leading to higher catch quality relative to trawling where fish collect in the codend throughout hauls often lasting many hours. In Norway, bottom seining is the most widely used fishing method to collect fish for the capture-based aquaculture (Humborstad et al., 2009), and fishers obtain a markedly higher price of live-captured fish compared to normal fishing where fish are delivered dead (Dreyer et al., 2006).

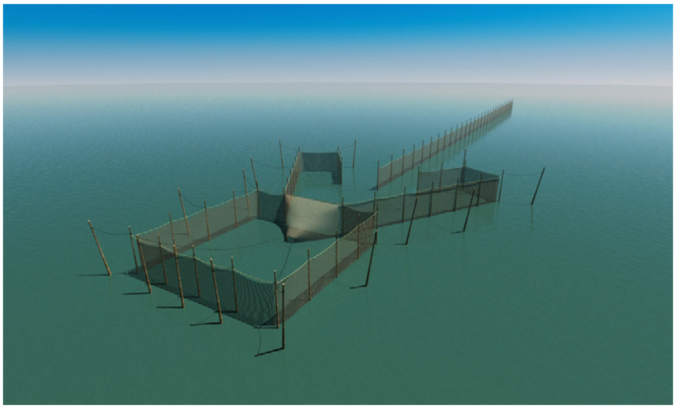

Fig. 3. A traditional stationary trap-net (pound-net) mounted on stakes in shallow water. Trap-nets often have a long leader net placed across the path of migrating fish to guide them towards the holding chamber from which escape is hampered by funnel devices or gorges.

Courtesy of FAO and SEAFDEC.

4.3.2. Trap-net fishing

Trap-nets (Fig. 3) are passive fishing gears that have evolved from simple barriers to modern-day netting enclosures with herding and retaining devices. They are usually set on traditional sites in the path of migrating fish in coastal waters. Leader-netting herds and guides fish into a holding chamber or pound where they are entrapped and retained. Designs are unique to particular locations (Slack-Smith, 2001; He and Inoue, 2010). Trap-net fisheries can be energy efficient, selective and habitat-friendly providing catches of high quality since the catch is usually alive when brought aboard the vessel. The benefits of live capture techniques provide the operator with a greater number of options – to sell immediately, to control supply to the market or to hold and grow/fatten – all of which can contribute to added value of the catch.

The pontoon trap (Fig. 4) is a new innovation and offers various advantages compared to traditional trap-nets such as easy to transport, handle and haul, and is adjustable in terms of size, target species and capture depth as well as being predator-safe (Suuronen et al., 2006; Hemmingsson et al., 2008; Lehtonen and Suuronen, 2010; Lundin et al., 2011). Potential new innovations may include large-scale ocean-based fish traps which may use chemical, electrical, light or acoustic attractants. A large stationary trap-net may attract marine life and function as an artificial reef. This characteristic has attracted research and development work particularly in Asia (Jeng, 2007). Incidental capture of non-target species is a problem in some trap-net fisheries, and development of designs and practices that prevent the entangling of non-fish species in the netting and mooring ropes of the trap are needed (Table 2).

Fig. 4. A pontoon trap offers various advantages compared to traditional trap-nets such as easy transportation and hauling. It is adjustable in terms of target species and capture depth. This pontoon trap has attached an additional smaller trap for live-capture of seal that attempt to enter the gear.

Courtesy of the Finnish Game and Fisheries Research Institute.

4.3.3. Pot fishing

A pot is a small transportable cage or basket with one or more entrances designed to allow the entry of fish, crustaceans or cephalopods, and prevent or retard their escape. Pots are usually set on the bottom, with or without bait, singly or in rows tethered to a single line, and connected by rope to a buoy on the surface. They can be hauled by hand or mechanized pot haulers.

Pots are extensively used in the capture of crustaceans such as lobster and crab (e.g. Krouse, 1989; Miller, 1990; Ahumada and Arana, 2009). The use of pots for capturing finfish has a long tradition in many parts of the world but has progressively declined since the 1960s at least partly due to the introduction of nylon gillnets and the expansion of demersal trawling (Thomsen et al., 2010). Pots typically have relatively low capture efficiency for finfish, especially when compared to gears such as trawls, seines and gillnets. However, pots are an economically viable fishing method for Pacific cod and sablefish in the Gulf of Alaska and the Bering Sea (Thomsen et al., 2010). They are also successfully used in fisheries targeting coral reef species inhabiting areas where the use of active gears is banned or not practical.

Pots, like trap-nets, possess several appealing characteristics compared to many other fishing gears: low energy use, minimal habitat impact, high quality, and live delivery (Slack-Smith, 2001; Thomsen et al., 2010; Table 2). Pots can be left in the water for a long time and the catch is still retained in good condition (O'Brien and Dennis, 2008). Some fisheries that specifically target the capture of live fish have developed pots as the principal capture method. Live-capture may bring a substantially higher price to the fisher. Where the quality of the catch is critical, pots may be the preferred capture method. While pot fishing vessels, in general, have low fuel use, some fisheries exhibit high fuel use. For instance in the lobster fisheries in the Gulf of Maine, one vessel may set over 800 pots per trip, and lift multiple pots per day. These operations require steaming at high speeds over long distances.

Because fish usually remain uninjured in the pot until it is hauled, unwanted bycatch organisms can be released with a high probability of survival, although factors such as air exposure, barotraumas, or thermal shock may jeopardize such potential benefits (Broadhurst et al., 2006). Bycatch from pots can be minimized by using appropriate baits, mesh sizes, materials and choosing the correct size, shape, location and design of entrance and escape openings (Boutson et al., 2009; Arana et al., 2011; Table 2). Nevertheless, the potential for reducing unwanted bycatch and incidental mortality in pot fisheries requires further investigation.

Pots may continue catching target and non-target species when lost (ghost-fishing) and contribute to marine debris and its associated effects (Al-Masroori et al., 2004; Matsuoka et al., 2005; ICES, 2009; Macfadyen et al., 2009). Design features such as biodegradable materials and galvanic timed releases may reduce ghost fishing while delayed surface marker buoys and location aids may promote the recovery of lost gear (Valdemarsen and Suuronen, 2003). Spatial and temporal separations from other fisheries can also reduce gear loss. Furthermore, pots can induce habitat damage on seabed and coral reefs (Valdemarsen and Suuronen, 2003), and have impacts on marine mammals due to entanglement on riser lines (Rihan, 2010).

Understanding fish behavior in relation to pots is essential to increase efficiency for those species that are currently not captured by pots in commercially viable quantities (Furevik and Løkkeborg,

Fig. 5. A Newfoundland collapsible cod pot is being hauled onboard. Courtesy of Philip Walsh, Fisheries and Marine Institute, Memorial University, Canada.

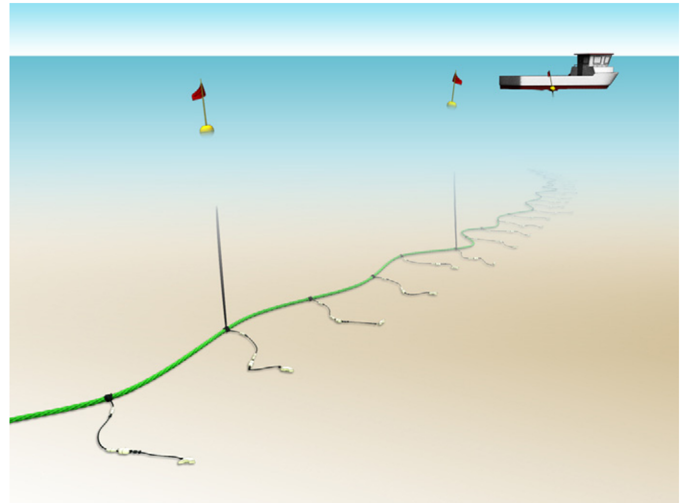

Fig. 6. A bottom-set long-line consists of a horizontal main line with snoods (gangions) and baited hooks attached at intervals. The gear is usually anchored at either end of the line with weights. The length of the longline can range from a few hundred meters to more than 50 km.

Courtesy of FAO and SEAFDEC.

1994). The release rate of odor (attractant) from a natural bait decreases rapidly over time (Løkkeborg, 1990). A system that prolongs the release of bait odor and in which the odor plume (dispersal) is controlled could increase pot efficiency. Research has shown that low catching efficiency of pots is often due to low ingress rate rather than low numbers of fish being attracted to the gear, and use of additional stimuli such as light and sound may trigger more fish to enter a pot (Thomsen et al., 2010). More work is needed to define optimal baiting strategy and the potential for using artificial baits.

Collapsible (foldable) pots made of polyethylene netting (Fig. 5) have recently been tested on the east coast of Canada with promising results for Atlantic cod (Safer, 2010; Sullivan and Walsh, 2010). Fish remained alive in the pots until they were hauled and fishers received significantly higher price of these fish compared to the gillnet-caught fish (Safer, 2010). A floating pot developed in Norway for cod provides another example of an innovative pot design that has shown significant potential (Furevik et al., 2008). Floating the pot off bottom allows the pot to turn with the current so the entrance always faces down current resulting in significantly higher catch rate of target cod. Floating the pot off bottom has proved to be an effective way to avoid non-target catch of crabs, and may also reduce the seabed impacts compared to a pot sitting on the bottom. The same type of floating pot has successfully been tested in Sweden as an alternative to the gillnet fishery for cod that faces problems with depredation by seals (Ovegård et al., 2011).

4.3.4. *Hook and lines*

Hook and lines (Fig. 6) refer to gears which fish, squid, or other species are attracted by natural or artificial bait, or lure placed on a hook, on which they are caught. Hook-and-line gear may be used with one hook or with large numbers of hooks, each fixed to the end of a line. Wide variations in hook and line configuration and their mode of operation have made them an effective gear type for a wide variety of species (George, 1993; Bjordal and Løkkeborg, 1996; Thomas et al., 2007; Løkkeborg et al., 2010). It is a versatile fishing method, employed by a wide range of vessels from artisanal boats to large mechanized long-liners with on-board processing and freezing plants. Hook and line fishing is generally considered an environmentally friendly but labor-intensive fishing method that catches fish of very high quality (Table 2). Fuel consumption in these fisheries is relatively low although it can be increased significantly depending on the distances vessels have to travel to fishing ground (e.g. coastal hook and line fisheries versus high-seas tuna long-lining). In addition, where natural bait is used, there may be a need for targeted fishing activity to obtain the bait and this will increase the total amount of fuel burned.

The capture principle of hook and line fishing is to attract fish to hooks using odor-releasing bait although the visual stimuli provided by the bait may also play a role. The characteristics of the bait are fundamentally important in the capture process; hooking probability is species specific, while larger baits tend to catch larger fish (Løkkeborg and Bjordal, 1992; Bjordal and Løkkeborg, 1996). The shape of the hook affects not only the hooking rates but also the types of fish caught. More research should be aimed at the development of alternative baits based on surplus products or waste materials (Løkkeborg, 1991; Erickson and Berkeley, 2008) since most baits used today are made from fish and other raw materials that might be better used for human consumption. Bait also has a high associated cost in most long-line fisheries, as these resources also are sold for consumption. Light sticks and small LED lights are often used in pelagic fisheries targeting swordfish (Hazin et al., 2005). A wider use of potential new attractants in long-line fisheries should be explored further.

Long-line fishing can cause the incidental mortality of seabirds, sea turtles and sharks, many of which are either protected or endangered (Montevecchi, 2001; Erickson and Berkeley, 2008; Løkkeborg, 2011). Because bycatch interactions may reduce gear efficiency (and profitability of fishing) due to the associated loss of baits, it is in the interest of fishermen to reduce such interactions. There are several mitigation measures capable of reducing the likelihood of incidental seabird and sea turtle bycatch (Gilman et al., 2005; FAO, 2009; Løkkeborg, 2011; Gilman, 2011). Long-lines set with a streamer line in order to deter seabirds from seizing the baited hooks gave 32% higher target catch rates than those set without this measure in a demersal long-line fishery (Løkkeborg, 2011). Hook designs such as the Circle-hook and “weak hook” have successfully been developed to help increase the survival rates of animals that are released from the hook but the effects are species specific (Yokota et al., 2006; NMFS, 2011). Erickson and Berkeley (2008) demonstrated that artificial baits can reduce bycatch on certain unwanted species such as sharks while maintaining catch rates of target species.

Bottom-set long-lines may snag and damage benthic epifauna and irregular objects on the bottom. This type of damage can be most pronounced during gear retrieval. However, long-line

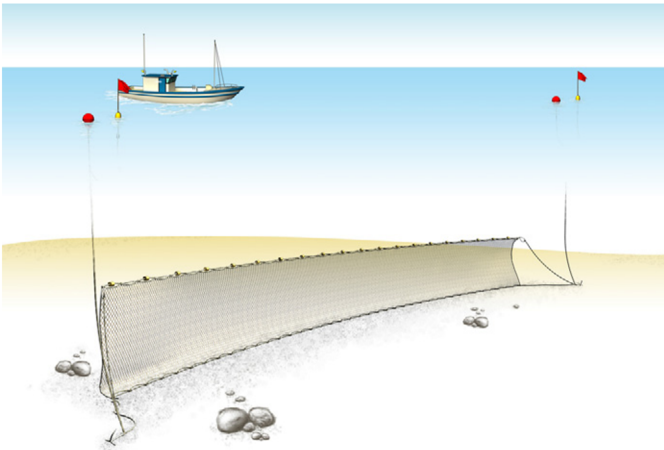

Fig. 7. A bottom set gillnet typically consists of a single wall of netting held vertically in the water by a floatline and weighted groundline (leadline), and kept stationary by anchors or weights.
Courtesy of FAO and SEAFDEC.

fisheries offer the potential to conduct fishing without severe habitat damage relative to many other methods. The potential for catching species that are not currently pursued with hook and line gear should be investigated.

4.3.5. Gill-netting

Bottom set gillnets (Fig. 7), encompassing gillnets, entangling nets and trammel nets, are widely used throughout the world. Improved materials and techniques have allowed the expansion of such gear to rougher grounds including wrecks and reefs and deeper waters (He and Pol, 2010). Gill-netting is a versatile, fuel-efficient and flexible fishing method but can also be labor intensive because the fishers must manually release or untangle the catch from the net. With the exception of trammel-nets, the size-selectivity for finfish is generally good but, depending on species assemblages in the area fished, species-selectivity may be poor (Valdemarsen and Suuronen, 2003).

Fish caught by gill-netting are often mortally injured during capture, accordingly catch is typically of lesser quality than with pots, traps and long-lines. However, when soak-times (i.e. the time the net is left in the water to fish) are short gillnets may provide catches of relatively high quality. In a comparative experiment conducted in Canada, the mortality for gillnet-caught Atlantic cod was low (<5%) at 6 h soak time but raised to about 30% with 12 h soak time and continued to increase with longer soak times (O'Brien and Dennis, 2008). Pots and long-lines showed significantly higher survival and fish quality. The practice of leaving nets at sea with long soak times often leads to high discarding of dead and partly decomposed catch. This is a problem for instance in many NE Atlantic gillnet fisheries (Hareide et al., 2005).

Any direct benthic impacts from gillnet fishing operations is likely to occur only during retrieval of the gear, during which the nets and leadlines are more likely to snag bottom structures. In particular, reef-forming organisms and other sessile epibenthic organisms frequently become entangled in gillnets and are damaged when the nets are hauled. Likewise, the capture of seabirds, sea turtles and marine mammals by gillnets has received increased attention (Davoren, 2007; Gilman et al., 2010; Rihan, 2010). These problems can be reduced by various gear modifications but these may reduce the catching efficiency of nets for certain target species (Valdemarsen and Suuronen, 2003; Løkkeborg, 2011). Moreover, efficient measures to reduce seabird bycatch in gillnet have not yet been identified (Løkkeborg, 2011).

There is concern about impacts of ghost fishing by lost and abandoned gillnets which may continue to fish for several weeks, months or even years, depending on their construction, the depth, and prevailing environmental conditions (Humborstad et al., 2003; Hareide et al., 2005; Brown and Macfadyen, 2007). This problem can be partially addressed by the use of biodegradable materials or other means to disable unattended gillnets (Matsushita et al., 2008). However, commercially viable solutions are few if any. Better results might be obtained by increasing efforts to avoid loss of gillnets, or by facilitating the quick recovery of lost nets. In some areas, gillnet fishing grounds are periodically "swept" for lost nets. Lost gillnets are common in areas where bottom trawling activity is high, since the trawl gear displaces or cuts the nets, or their buoy lines. Abandoned gillnets have been identified as a particular problem in deeper waters and when long fleets of gillnets are deployed (Hareide et al., 2005; Brown and Macfadyen, 2007; Graham et al., 2010). Many of these problems can be mitigated by better cooperation between fisher groups through the development of codes of conduct. Gillnet fishing requires a careful selection of the fishing ground.

5. Barriers to the transition to Low-Impact and Fuel-Efficient fisheries

Through technological improvements and behavioral change, capture fisheries can decrease the damage to aquatic ecosystems, reduce emissions and lower fuel costs without excessive impacts on fishing efficiency. Each fishing gear and practice described here has advantages and disadvantages (Table 2), and the suitability of each gear largely depends on the conditions and species to be targeted. Despite this, there are barriers to the transition to low-impact and less fuel-intensive practices and gears (Glass et al., 2007; Jennings and Revill, 2007; Gascoigne and Willsteed, 2009). These include:

- lack of familiarity with cost-effective and practical alternatives;
- availability of technologies;
- incompatibility of vessels with alternative gear;
- risk of losing marketable catch;
- additional work;
- concerns with safety at sea by using unfamiliar gears or strategies;
- high investment costs;
- lack of capital or restricted access to capital;
- ineffective technology infrastructure support; and
- inflexible fisheries management systems.

Rigid regulatory regimes can create problems that fishers must solve and this may effectively deny fishers the flexibility required to innovate and adopt new technologies. Furthermore, the absence of uptake by all fishers may put an individual fisher at a commercial disadvantage. From an individual fisher's point of view the fundamental question is: what are the economic benefits in switching to new gears and practices. Fishers will not willingly adopt techniques that they fear will increase costs and/or workload and reduce earnings. Fishing effectiveness and practicality of new designs are important. An inefficient gear will not be used.

The change to a new fishing gear or practice may not necessarily involve significant changes in the nature of the fishery. The basic gear type, target species and area of operation may remain the same. In some cases, however, it may be necessary to reduce or completely eliminate some gear groups or fleets in order to promote new ones. For instance, in many existing fisheries a sustainable exploitation of finfish stocks by non-trawl gears will only be possible after a reduction in fishing effort and spatial restrictions on bottom trawling. Fisheries management systems should encourage low impact and fuel efficient fisheries, and should give fishers a space in which to operate as efficiently as possible. One possibility is to allocate to LIFE-fishing extra quota or preferential access to specific fishing areas. Reducing the 'race to fish' by imposing individual quotas can facilitate the adoption of LIFE fishing practices in some fisheries.

Understanding the "human behavior barriers" that have to be overcome and what the catalytic drivers might be that could change these behaviors is critically important (Branch et al., 2006; Hall et al., 2007; Gjertsen et al., 2010). Christy (2000) argued that in many small-scale fisheries, a decentralized community-based management would most effectively permit fishers to adopt those measures and practices, most suitable for their particular situation and the most sustainable option in the long run. He also argued that a shift to more stationary fishing gears would improve the ability of the communities to establish effective fisheries management systems. Gutiérrez et al. (2011) demonstrated the critical importance of prominent community leaders and robust social capital, combined with clear incentives through catch shares, in promoting successful fisheries and management of aquatic resources. They identified strong leadership as the most important attribute contributing to success in fisheries co-management. Interestingly, the research showed that less important conditions included enforcement mechanisms, long-term management policies and life history of the resources. It is also obvious that where fish are more abundant, the relative competitiveness of passive fishing gears improves. Restoration of depleted fish stocks is fundamentally important to the success of LIFE fishing.

6. Conclusions

With continued exposure to rising fuel prices, the fishing industry will continue to suffer a loss in profitability. It is apparent that if resource abundance and fish prices remain static, some conventional bottom trawl, beam trawl and dredge fisheries may become uneconomic while passive gear fisheries or seine net fisheries should be less affected by these pressures. Since capture production from demersal trawl fishing currently forms a significant part of the world catch for direct human use, this scenario could have a major affect on global fish supply and food security.

The fishing sector should strive to lower its fuel consumption, reduce its carbon footprint, and decrease ecosystem impacts. To achieve significant and permanent reductions, governments will need to strengthen their fisheries sector energy policy and create an enabling environment in which fishing sector can rapidly and comprehensively adopt LIFE fishing technologies and practices. The development and adoption of LIFE fishing techniques offer scope for maintaining long term profitability and sustainability.

Excessive use of any gear type, even low-impact gear, may cause overexploitation and ecosystem impacts if total fishing effort is too high. Therefore, without being part of an effective fisheries management system, an improvement in fuel efficiency will not necessarily lead to a sustained reduction in the total fuel consumption because higher returns may attract new entrants into the fishery. The adoption of LIFE fishing techniques should therefore be seen as one of the strategies that can be used to improve the outcomes for a fishery that is operating within an EAF based management system.

Global research and development priorities should be established with work undertaken to support development and uptake of LIFE fishing. These include (1) promoting and funding studies of cost-effective gear designs and fishing operations, including the establishment of technology incubators and other public–private sector initiatives to commercialize economically viable, practical and safe alternatives to conventional fishing methods, (2) analysis and review of best practice operations across fisheries, (3) improvement of technical ability among fishers, (4) establishment of appropriate incentives, and (5) execution of robust but flexible fishery management policies that support the transition to alternative technologies. Close cooperation between the fishing industry, scientists, managers and other stakeholders will be necessary to enable the development and introduction of LIFE fishing technologies.

Given that fishing is a complex system, changing one variable can have a ripple effect on other variables and the affects may not change in a linear manner. Therefore, changing one variable may not necessarily achieve the desired or expected outcome. As we move to address the numerous environmental and commercial problems facing fisheries, we need to take a comprehensive and holistic approach and not independently focus on a single facet of the many drivers that affect fishery performance. Clearly, the optimal solutions will vary among fisheries.

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