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Quantifying fishing effort: a synthesis of current methods and their applications

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Abstract

The need to accurately quantify fishing effort has increased in recent years as fisheries have expanded around the world and many fish stocks and non-target species are threatened with collapse. Quantification methods vary greatly among fisheries, and to date there has not been a comprehensive review of these methods. Here we review existing approaches to quantify fishing effort in small-scale, recreational, industrial, and illegal, unreported and unregulated (IUU) fisheries. We present the strengths and limitations of existing methods, identifying the most robust methods and the critical knowledge gaps that must be addressed to improve our ability to quantify and map fishing effort. Although identifying the 'best' method ultimately depends on the intended application of the data, in general, quantification methods that are based on information on gear use and spatial distribution offer the best approaches to representing fishing effort on a broad scale. Integrating fisher's knowledge and involving fishers in data collection and management decisions may be the most effective way to improve data quality and accessibility.

Keywords Bycatch, effective effort, fishing capacity, fishing effort quantification, nominal effort

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Introduction

Fishery activities around the globe have been increasing in recent decades as human populations grow and the availability of arable land declines (Valdimarsson and James 2001). This increase in fishing pressure has raised concerns about the sustainable removal of both target (Worm *et al.* 2006) and non-target catch (Kelleher 2005), and the ecosystem effects from widespread fishing activities (Caddy 1999; Pauly *et al.* 2005). Current and accurate information on fisheries catch and effort is a necessary component to facilitate sustainable fisheries management, to reduce the occurrence of bycatch and discards, to track fishing capacity and to monitor illegal fishing.

The most commonly reported measure of fisheries production is the amount of catch (Maunder and Punt 2004). This is in part due to relative ease of data collection; catch data can be collected at ports or landing sites. While catch data provides important information on the number of individuals harvested, it does not provide information on the expended effort, including details on gear, capital and labour used to harvest stocks (Yew and Heaps 1996). The amount and types of resources devoted to fishing is directly related to the harvesting capacity of the fleet (Kirkley *et al.* 2001), as well as the take of non-target species (Caillouet *et al.* 1996). Effort information is needed to interpret changes in the amount of catch, and to regulate fishing efficiency to maximize profit and minimize overfishing (Branch *et al.* 2006). Metrics of fishing effort also can be used to monitor changes in market trends, the impacts of new fishing practices and gear, to delineate and enforce marine protected areas and to track changes in stock abundance (Gallaway *et al.* 2003b). Because the effects of a fishery are determined in large part by both the intensity of fishing effort and the habitat where the effort occurs (Bellman *et al.* 2005), quantifying and monitoring changes in fishing effort is imperative for effective fisheries management.

Measurements of fishing effort: definitions and applications

There are two general categories of fishing effort: nominal and effective fishing effort. Nominal fishing effort describes the resources allocated to fishing, such as time (days or hours fished), capital (number of vessel days, length or horsepower of vessel), labour (number of person hours or number of crew) or gear (mesh size or number of hooks; Pascoe and Robinson 1996; Del Valle *et al.* 2003; Ruttan 2003). Nominal fishing effort can also be thought of as a measure of fishing power, i.e. the capacity of a fishery to produce a potential yield level. Effective fishing effort is a standardized measure of effort, such as the rate of fish capture, or instantaneous rate of fishing (Padilla and Trinidad 1995). The calculation of a catch rate, or catch per unit effort (CPUE), requires both catch or landings data and some metric of nominal effort, such as net length and soak time (Gillis and Peterman 1998). Unlike nominal fishing effort, effective fishing effort is a means to account for variability in the efficiency of fish capture, such as differences in skipper skill or technological differences among vessels or fleets.

Trends in effort have been an important means of estimating trends in stock abundance when independent abundance data are not available. As CPUE decreases, it may reflect a decrease in stock abundance. However, the assumption that there is a linear relationship between CPUE and stock abundance has come under much scrutiny (Harley *et al.* 2001; Medina and Soto 2003; Ruttan 2003; Branch *et al.* 2006). CPUE values are therefore typically standardized to control for environmental, seasonal, habitat and other extrinsic factors (Hinton and Maunder 2004). Although caution needs to be used when interpreting CPUE as an indicator of stock trends, it is still a useful index of abundance for stock trends over large ocean regions (Gaertner and Dreyfus-Leon 2004). In order to mitigate some of the factors that may negatively impact the comparability of CPUE among years and areas, standardization of the data are necessary (Padilla and Trinidad 1995; Jones *et al.* 1998; van Oostenbrugge *et al.* 2002; Battaile and Quinn 2004; Bishop 2006). Standardization removes trends in variables describing vessel characteristics, fishing season and areas (Jones *et al.* 1998; Branch *et al.* 2006). Standardization has been used to combine data from different fisheries, such as artisanal and recreational (Jones *et al.* 1998).

The amount of fishing effort or gear deployed can also be a means to estimate income of fishermen and profitability of the fishery (Rahikainen and Kuikka 2002). Fisheries managers working to maximize sustainable profits use measurements of effort to limit fishing activity to the level of maximum economic yield (Puga *et al.* 2005). Metrics such as fuel or labour costs may be used to measure fishing profitability, but are not as informative as combined metrics that standardize effort, e.g. person-days or costs per fishing hour. The distribution of fishing effort may be informative in designating the spatial extent of marine parks or reserves (Lynch 2006), which are becoming a more common tool to manage fish stocks (Monaco *et al.* 2007). Due to sensitivities of catch distribution information, effort measures may be the best available approach to mapping relative abundance of target species, and how they relate to different habitats. Effort information can be a way to estimate catch of non-commercial or non-target species (Dauk and Schwarz 2001). The measurement of fishing effort can be used to calculate a probability of catching sympatric non-target species (Fonteneau and Richard 2003; Gallaway *et al.* 2003a; Agnew and Kirkwood 2005) and to identify areas where deployed gear overlaps with known distribution of long-lived species such as birds, marine mammals and sea turtles (Caillouet *et al.* 1996; Lewison and Crowder 2003; Lewison *et al.* 2004).

Because fishing gear and practices, regulations, target species and their behaviour vary greatly both temporally and spatially, quantifying or comparing average or total effort across seasons, areas or fishing fleets is challenging. As direct measures of fishing effort are rarely reported, managers must rely on indirect quantification methods. However, little attention has been paid to which methods or approaches are most effective for different fisheries. The aim of this paper is to provide a comprehensive review of the existing methods used to quantify fishing effort across a range of fishery types. We review quantification methods across four broad classes of fisheries; namely, small-scale, recreational, commercial and illegal, unregulated and unreported (IUU). Despite the limitations with these methods, they provide some of the only means of characterizing fishing effort. This review points to the most appropriate and transparent models for particular fisheries and focuses attention on data collection and analyses needed to provide more comprehensive information on fishing activities.

Existing methods to describe fishing effort

Small-scale fisheries

Small-scale, or artisanal fishing, is typically defined as fisheries utilizing low technology gears and vessels to target a variety of species for subsistence and local markets (Staples *et al.* 2004; Tzanatos *et al.* 2006). Small scale does not necessarily mean small impact. In many countries, these fisheries contribute to the majority of the catch, and can have significant impacts on local ecosystems. For example, over 5000 vessels were known to operate in the artisanal fleet off the coast of Galicia, Spain in 2004 (Otero *et al.* 2005). At a larger scale, nearly half a million small, undecked vessels (<24 gross registered tonnes) were reported to operate in Indonesia and Malaysia in 1998 (FAO 2006). The primary challenge to quantifying effort in small-scale fisheries is a deficit of data due to lack of funds, oversight or infrastructure (Mohammed 2003).

To overcome the lack of data, many researchers use fisher interview data to quantify effort and gather information on length of fishing season, catch per fishing trip and number of trips and vessels (Gómez-Muñoz 1990; Hutchings and Ferguson 2000; Gladstone 2002; Okada *et al.* 2005; Otero *et al.* 2005). One approach is the Gómez-Muñoz model which has been developed and adapted to model fishing effort based on interview data collected from fisheries in Baja California, Spain and Scotland (Gómez-Muñoz 1990; Simón *et al.* 1996; Otero *et al.* 2005; Young *et al.* 2006). In the development of this method, a short survey of fishermen and staff registering catches at landing sites in Baja California provided information on length of fishing season, maximum and minimum catch per fishing unit per trip and number of trips and vessels participating in the fishery. In order to quantify total nominal effort, measured as the total number of fishing trips, the mean number of trips per month of one fishing fleet was multiplied by the number of fishing fleets and the length of the fishing season (Gómez-Muñoz 1990). Simón *et al.* (1996) used the Gómez-Muñoz model and found that catch and effort rates could be extrapolated from sampled ports to similar, non-sampled ports in Galicia, Spain. Although this approach relied on the ability to accurately assess similarity among ports, it generated catch and effort estimates where limited resources prevent extensive data gathering.

Another approach has been to create 'virtual fleets' in model simulations (Otero *et al.* 2005). By inputting an assumed amount of fishing effort per gear and target type derived from interview data, these simulated fleets can be used to generate effort estimates in multi-species and multi-gear fisheries. To test the reliability of this method, Otero *et al.* compared their simulation-based estimates to official fisheries data collected from a small number of ports and found a strong correlation between the model and the official data (Otero *et al.* 2005). Fishing effort estimates for small-scale fisheries may also be generated from statistical relationships between habitat types and fishing intensity. For example, information obtained from fisher interviews revealed significant correlations between habitat zones and CPUE, as well as gear and vessel types used (Okada *et al.* 2005). This approach may be particularly helpful in areas where habitat data are easier to obtain than fisheries information.

Each of these methods used interview data from fishers to generate some type of approximation of fishing effort (Table 1). The benefits of these approaches are that they can be completed relatively quickly, and in some cases can yield high resolution temporal and spatial information about fishing practices. These data can also be extrapolated to unsampled areas, depending on the similarity among fishing areas and the representativeness of the sampling design. However, there are limitations. Reliable interview information requires access and trust with local fisher communities. Obtaining information from interviews relies on fisher's accuracy, a high degree of cooperation from participants, consistency in interpretation of questions, and may require a large interview sample size to accurately represent the fishery (Hutchings and Ferguson 2000; Rocha *et al.* 2004; Otero *et al.* 2005). Interview data may also include considerable error. Despite these limitations, these methods represent the best approaches available for data deficient areas.

Recreational fisheries

The smaller scale and decentralized distribution of recreational fisheries yield few incentives for collection of detailed effort data, despite the fact that recreational fishing is expanding in many countries (McPhee *et al.* 2002). Private recreational sports fishermen typically do not release proprietary records of where they fished or how much time and resources were spent fishing. Another challenge to quantifying effort in recreational fisheries is the spatial and temporal variability of the fisheries, and the wide range of gear and practices employed. Spatially, recreational fishers are not typically aggregated at commercial ports, but rather are spread across a coastline. Temporally, fishing activities may reflect seasonal distribution of targeted catch. This variability will have a strong influence on the data collected, i.e. information collected from a specific period may not be representative of average fishing effort. For example, information on number of boats or hours fished during a holiday weekend could not be accurately extrapolated across the week or month. In addition, information on one person's fishing activity may not be representative of recreational fishers as a whole. This challenge is relevant to all fishery types, but particularly so in recreational fisheries as there is no common goal of income generation shared across all participants.

To account for the spatial and temporal variability, effort in the recreational marine fisheries is estimated primarily by surveys and interviews, license numbers or the number of registered boats in a particular area (Table 1). Surveys may include boat or boat trailer counts, dockside interviews, aerial or vessel-based surveys, and mail or phone questionnaires (Osborn *et al.* 1996; Hoenig *et al.* 1997; Van Voorhees *et al.* 2000; Sharp *et al.* 2005). The surveys typically acquire information such as number of days fishing, amount of catch and number of fishers. To avoid the overestimation of total effort by individuals reporting a high number of fishing trips, the number of fishing trips may be limited to the value of the 95th percentile of a 5-year frequency distribution (Osborn *et al.* 1996). To reduce high variability in effort calculations, Hoenig *et al.* (1997) recommended using a time threshold to only include fishers who had exceeded a fixed trip duration.

Lynch (2006) took a more direct approach to measuring recreational fishing by counting all recreational fishers from a survey vessel, recording geographic coordinates of each fisher, number of people fishing and an assigned fishing behaviour. This high resolution approach to estimating fishing effort was then used to estimate a density of fishers in relation to known habitat types in a particular fishing area (Lynch 2006). Although this type of approach offers a means to estimate fishing effort at a fairly high spatial resolution, the results may only be representative of fishing effort in the surveyed area. Random surveys extrapolated to unsampled areas can be used to characterize effort over a wide geographic range and temporal scale, but will probably underestimate true effort depending on the representativeness of the sampling design of the surveys (Van Voorhees *et al.* 2000). Depending on the application of the effort data, this may not be as important as the consistency of the measures across

Table 1 Summary of quantification approaches for small-scale, recreational, industrial, and illegal, unregulated and unreported (IUU) fisheries.

	Challenges	Methods	Data types	Pros	Cons
Small scale	Data deficiencies; broad geographic distribution of fisheries; variable gear and target species	Gómez-Muñoz model; extrapolation to other ports based on similar characteristics; estimating virtual fleet in mixed gear fishery; habitat correlations with gear and vessel type; model per-capita consumption	Interview, market data, official catch statistics, human census	Information gathered quickly, high spatial and temporal resolution, can be extrapolated to unsampled locations	Unpredictable access to local communities; reliance on memory, cooperation and trust; requires consistent interpretation of questions; may need large sample size to be representative
Recreational	Typically untracked by fisheries managers; wide distribution of fishers; inconsistent effort across time, space and individual; mixed gear within vessels	Surveys (boat/trailer counts, phone, mail); instantaneous count of fishers present; roving survey	Interview; survey; licenses	Detailed data from interviews; large extent of sampling because of boat dispersion; spatial information	Limited spatial scale for portside interviews; high variability in fishing efficiency and effort
Industrial	Data highly variable among and between fisheries; rapid technological change	Bioeconomic models; spatial models; data proxies for gears or fleets	Logbook and observer data; government statistics; market data; financial statements; processing output; habitat measures (e.g. bathymetry)	Consistent information; different scales of analysis; ability to extrapolate to data deficient areas	Unable to account for rapid technological changes
Illegal, unreported and unregulated	Scarcity of data; strong disincentives to report	Aerial and boat-based surveys; comparisons of official statistics with market and processing plant production; models predicting fishermen behaviour; modeling rate of capture by enforcement patrols	Sighting records from merchant vessels, cruise ships, research, fishing and patrol vessels; data from registered vessels as proxy	Direct observations provide fine spatial and temporal resolution	Effort in illegal fisheries may be highly inaccurate (e.g. vessels do not abide by effort restrictions, area or time regulations, or bycatch reduction protocols); vessels actively evade detection

time, i.e. under or over estimation of effort expended may not be as important as the ability to assess effort trends over time.

Mail and phone questionnaires enable data collection from a higher number and more widely distributed sample of fishermen than could be obtained from dockside interviews. However, several biases exist with these methods including uncertainties associated with non-respondents, inaccurate memory of respondents, potential for exaggeration or minimization of catch and effort, and the representative nature of the sample (Sharp *et al.* 2005). Some of these issues can be addressed analytically. Biases from questionnaires associated with non-respondents, which would arise if respondents are significantly different than non-respondents, can be minimized by using response propensity stratification to adjust survey results to remove non-response bias (Fisher 1996; Haziza and Beaumont 2007). Despite this, quantification of effort in recreational fisheries is vulnerable to either over- or under-estimation, both of which are attributed to incomplete coverage of fisher activities.

Industrial fisheries

Industrial fisheries are large-scale commercial operations commonly involving at-sea processing, enabling fishing activities to continue without the need to offload landings at port. Data from industrial fisheries varies greatly from region to region, as well as fishery to fishery. Data availability also varies over time due to changing regulations, funding and reporting incentive, making it difficult to identify spatial and temporal trends. Catch data are often available in industrial fisheries as landings go to market. Effort data are not as readily available, but necessary for calculating effective effort indices such as CPUE. In the most data, rich scenarios, dedicated observers record information such as gear types, catch locations, species composition, including non-target species, details on fishing vessels, crew, skipper experience, search times, gear set or soak times, as well as date and volume of catch. Ideally, fishery independent survey data are also available to compare with commercial catch and effort data, although in most cases, fisheries-independent datasets are rare or are patchily distributed.

In data-limited regions, effective and nominal fishing effort must be inferred indirectly. Bioeconomic models have been utilized in recent years as one indirect approach to estimate fishing power or capacity (Kirkley *et al.* 2001; Chae and Pascoe 2005). Number of fishing days from a sample of vessels representing one gear type, or engine power information from a subset of vessels representing the majority of catches, have been used to represent the average effort expenditures of the entire fishing fleet in Korean waters (Chae and Pascoe 2005). Other studies have also used other proxies, such as number and size of nets, or presences of electronic gear, such as echo sounders, to represent effort across a fleet and for specific areas (e.g. Padilla and Trinidad 1995; Fonteneau and Richard 2003). These extrapolations assume similarity across gears and time, which may substantially impact the interpretation of effort estimates.

Some of the tools developed to study data-poor situations in small-scale fisheries can also be applied to industrial fisheries, particularly for non-target species or mixed stock fisheries. Specifically, interview data have been used exclusively or to supplement official statistics in data-poor regions (Cheung and Sadovy 2004; Rocha *et al.* 2004). Rocha *et al.* (2004) found that the results from the Gómez-Muñoz model were as good an estimator of catch and effort as the official statistics in the Northeast Atlantic, as there was not a significant difference between the estimates derived from the interview data and estimates derived from logbooks and market data. The results from a study by Cheung and Sadovy (2004) near Hong Kong also support the credibility of using data derived from interviews and other sources to quantify effort.

Although data-poor fisheries clearly present challenges to estimating effort, large volumes of data can also present complications to estimating fishing effort in industrial fisheries if those data are not homogenous. With large amounts of data, there is a need to stratify or categorize the data by space, time and attributes of the fishery. This addresses the assumptions of constant catchability and closed populations in fish stocks (Battaile and Quinn 2004). Categorizing fisheries based on gear, target species area and season also facilitates an understanding of spatial and temporal distribution patterns of effort (Tzanatos *et al.* 2006). Research in the North Sea and North Atlantic provides two examples of data categorization in order to estimate effort specific to gear or vessel classes (Watson *et al.* 2000; Marchal *et al.* 2002). In the North Sea, trawl fleets have been categorized by a combination of gear and horsepower, or by CPUE. CPUE in this case was estimated by taking the average weight (kg) per one hour of trawling (Marchal *et al.* 2002). In the North Atlantic, a 'taxonomic' approach to characterizing the fishery was used that was based on gear type, location, tonnage class of vessels and major target species, where multiple criteria were used to distinguish dissimilar fisheries (Watson *et al.* 2000).

Most studies that incorporate a spatial dimension tend to focus on where fish are caught, but rarely analyse how gear is distributed. In some cases, it has been found that maps of fishing effort better represent resource distribution than catch rates (e.g. Swain and Wade 2003). If spatially explicit data exist, it is possible to create maps to represent spatial variability in fishing effort (Riolo 2006). This can be particularly informative in assessing the intensity of fishing impacts on certain habitats, or where overlap of distribution with vulnerable non-target species is known to occur (Bellman *et al.* 2005). Quantifying effort spatially can also be a way to extrapolate effort to areas without data (Marchal *et al.* 2002; Petitgas *et al.* 2003; Swain and Wade 2003; Bellman *et al.* 2005). When effort can be associated with habitat type, there is the potential to assign effort to areas based on assumptions of suitability of fishing and likelihood of target species being present in each habitat area. For example, deciphering spatial patterns in fishing effort has been used to associate stock removal with environmental variables such as sediment type (Marrs *et al.* 2002), which can then be used to extrapolate effort to similar areas that lack detailed spatial effort information.

Electronic logbook data derived from automatic vessel monitoring systems which download satellite-derived geographic coordinates at a pre-set time interval have the capacity to record detailed information on locations of hauls, distance from port and movement patterns of vessels while searching for fish patches and while actively fishing (Marrs *et al.* 2002; Gallaway *et al.* 2003b). These data provide much more accurate accounts of spatial distribution and intensity of effort than do more conventional data forms, such as port-side interviews, because information is recorded in real time and is not subject to human interpretation or manipulation when recorded (Gallaway *et al.* 2003a,b; Cole *et al.* 2006). The difference in effort calculated from on-board observer data and from programmed electronic logbooks has been found to be statistically insignificant (Cole *et al.* 2006). Electronic logbooks offer the potential for recording information 24 h a day, without the costs associated with human labour. However, there is substantial resistance among fishers to a record of exact fishing locations and actions of fishing vessels and that resistance is one of the largest challenges to implementing automatic data logging systems fleet wide.

Due to the breadth of information from industrial fisheries, several approaches have been employed to quantify effort in these fisheries. Many of these approaches involve addressing information gaps through interviews, theoretical and spatial modeling, and market data (Table 1). Perhaps the largest challenge to estimating effort through time in industrial fisheries is the rapid technological changes that occur relative to other types of fisheries. While some attempts have been made to classify data according to level of technological development (see Cheung and Sadovy 2004), no method has been developed that can accurately account for the changes in the types and configuration of gears, vessels, and methods for increased efficiency in finding fish. Large amounts of data also require the technology and infrastructure to manage large databases. The costs associated with obtaining, maintaining and operating sufficient computing resources and hiring the technological expertise to manage large databases may be cost prohibitive for some agencies or governments.

Illegal, unregulated and unreported (IUU) fisheries

Quantifying catch and effort in illegal, unreported and unregulated (IUU) fishing activities is extremely challenging due to scarcity of data and difficulty in monitoring such activity (Le Gallic and Cox 2006; Riddle 2006). These fisheries include pirate fishing, catch of species and biomass above established quotas or with banned gear types, and unmonitored fisheries. Catch is therefore rarely, if ever, known in IUU fisheries, and typically is inferred by assuming a given CPUE from other fisheries. Some of the approaches taken to quantify effort of IUU fishing include monitoring trade or landings with fishmeal factory outputs, comparing the number of observed fishing vessels with the number of official licenses or permits, and quantifying anecdotal information with stock assessments (Pitcher *et al.* 2002; Agnew and Kirkwood 2005; Riddle 2006). Interview data can also be a useful means to quantify illegal, or unreported catch and effort across fisheries (Castillo and Mendo 1987).

Ainsworth and Pitcher (2005) combined several data sources to estimate ranges of IUU fishing effort in British Columbia and compared the estimate to observed discarding and illegal fishing activity. Their study is a good example of how qualitative data can be converted to quantitative values, although there is probably substantial error in the estimates. This method relies on having some observations of discarding or illegal activity and having information on legal catches, which may itself be based on indirect data. Using observed illegal activity is a more direct method of quantifying IUU effort, but can only provide a minimum of IUU fishing effort. Agnew and Kirkwood (2005) used IUU vessel sightings from patrol cruises and catch data from licensed vessels to calculate IUU effort in Antarctic waters. Ball (2005) extended the Agnew and Kirkwood method and developed a model that allowed for the estimation of nominal IUU fishing effort even when no IUU activity was reported. Unlike the Agnew and Kirkwood model that essentially assumed an equal probability of an illegal fishing vessel to be detected or not detected, Ball's model incorporated the probability of illegal vessels actively evading detection (Ball 2005).

Methods to quantify the rate of illegal harvest in terrestrial systems also may have useful application to understanding fishing effort. The rate of capture of poachers per enforcement patrol index was estimated to then calculate total illegal take of a known number of African buffalo in Serengeti National Park (Hilborn *et al.* 2006). A similar approach could be applied to fisheries if there was information on the amount of illegal activity observed by enforcement patrols as a function of distance from a known location. This spatial information can be included as a decay function and can estimate spatial distribution of effort (Gallaway *et al.* 2003b). For fisheries, the decay function would represent a decreasing likelihood of encountering fishers with increasing distance from port or a processing ship as a means to estimate distribution of fishing intensity (Sampson 1992; Branch *et al.* 2006). This function can also incorporate fuel capacity, fish hold capacity, vessel length, engine horsepower, and hull construction as variables that affect a vessel's geographic range. A decay function might also be appropriate when habitat variables, i.e. depth or slope, are known.

Estimating effort in IUU fisheries involves many of the same challenges inherent to small-scale fisheries (Table 1). In the case of illegal fisheries, however, there is even less incentive to report fishing activities. Direct visual observations of IUU fishing from patrols or other sources may allow for fine temporal and spatial scale effort estimation. Models to estimate unseen activity (e.g. Ball 2005; Hilborn *et al.* 2006) are particularly helpful in filling information gaps, but may rely on assumptions regarding the population size of targeted stock, the distribution of target species and patrol boats.

Summary

Progress in and limitations of fishing effort quantification

The most robust estimates of actual fishing effort integrate technological advances within and among fleets and distribution of effort at fine temporal and spatial scales. The use of on-board electronic logbooks (Marrs *et al.* 2002; Gallaway *et al.* 2003a,b; Cole *et al.* 2006) to analyse fine scale relationships between distribution of effort and environmental variables along with the use of multiple effort metrics (Hanchet *et al.* 2005) offer the most comprehensive estimates because they track actual fishing activity in time and space. These methods have produced effort maps that are likely to represent gear and time distribution more accurately than do official landings and fishing effort estimates. While spatial data may not be necessary for estimating stock size or fishing capacity, it is becoming more important when investigating relationships between fish distribution and protected areas, overlap with threatened species or efficiency of a fishery. Effort estimates that are stratified to reflect vessel classes and gear characteristics, such as soak time or number of hooks, are more applicable to estimating catch and monitoring stock trends. Due to the wide range of vessel and gear types, finding a common metric is difficult and all metrics will have limitations. Some recent research has used engine horsepower to effectively map fishing activity (Watson *et al.* 2000, 2006; Marchal *et al.* 2002), although this characterization is likely to be influenced by fluctuating fuel costs and engine efficiency.

Electronic logbooks are relatively inexpensive (<US $500) and offer a means to obtain detailed spatially explicit effort data 24 h a day that is not subject to human error or bias (Cole *et al.* 2006). However, there is substantial resistance to this technology from fishers. Confidentiality agreements among fishers and fishing management agencies may address some concerns. If electronic vessel

monitoring system data or detailed gear information are not available, a combination of direct observations (Agnew and Kirkwood 2005; Lynch 2006), and indirect sampling, such as financial statements (Chae and Pascoe 2005) offers the ability to obtain detailed data that can be extrapolated over wider geographic and time scales. Approaches that combine interview data and official statistics also offer a way to estimate effort on a larger scale than would otherwise be possible with one type of source data. In addition, piecing together information from logbooks, processing plants, interviews, financial statements and stock assessments not only increases the volume of data, but provides a means to compare estimates from these different information sources. Studies that find similarity in the estimates produced by different data sources (Cheung and Sadovy 2004; Rocha *et al.* 2004) can be more confident in the precision of their models.

Less accurate methods of estimating fishing effort are those that rely solely on the most indirect information to represent fishing rates or capacity. Boat trailer counts (Osborn *et al.* 1996; Van Voorhees *et al.* 2000) and fish meal factory outputs (Pitcher *et al.* 2002) are two examples of very indirect approaches to estimating effort. Mail (Sharp *et al.* 2005) or phone questionnaires (Osborn *et al.* 1996; Van Voorhees *et al.* 2000) that rely on accurate memory from a sample of fishermen that may not be representative of the fishery are less precise in design than methods that obtain information more directly and do not rely on memory recall, e.g. real-time logbook data.

Improving effort estimates

A lack of specific, accessible and reliable direct data from fisheries is a common challenge among all fishery types. To address this challenge, research resources need to be directed to obtaining data that includes details on gear, time spent fishing and searching, catch rates and fine spatial and temporal information across the entire fishery. Although how these data will be applied affects the levels of accuracy, consistency, spatial and temporal detail needed, there remain common measurements across fisheries that are useful to all management applications. This is particularly true as fisheries management moves toward long-term sustainability of a resource vs. maximizing short-term exploitation. Beyond the data gaps, existing data are often inaccessible to scientists or management agencies (Garces *et al.* 2006). Incentives to increase data availability could include funding national agencies to create electronic formats from data in logbooks, internal documents and reports. Developing collaborations between national and international fisheries organizations would promote data sharing.

In light of the information available, extrapolations from sampled areas to non-sampled areas (Simón *et al.* 1996; Marchal *et al.* 2002; Fonteneau and Richard 2003; Petitgas *et al.* 2003) are essential. This approach relies heavily on having an appropriate sample design. The study by Simón *et al.* (1996) is a good example of how a study design that yields representative data can effectively integrate information from sampled fishing areas to fishing areas with very limited data. However, even with a strong sample design, many difficult-to-quantify variables may confound effort estimates. The amount of information shared among skippers, skipper skill, vessel competition for physical access or information, repetitive fishing in the same area, and technological advances influence the efficiency of fishing effort (Hilborn 1985; Gaertner and Dreyfus-Leon 2004; Bez *et al.* 2006; Bishop 2006; Branch *et al.* 2006). Using multiple units of effort can be a means to minimize biases of effort measurements. For example, regulation changes, number of crew, amount of gear in the water, length of trip or time spent actively catching fish, can all confound interpretation of the unit 'trip' (Hanchet *et al.* 2005). In many cases, one unit of effort could remain relatively constant over time, like number of nets, or number of days fished, while the size of nets and total engine power of the fishing vessels increase, thereby substantially increasing fishing capacity (Rahikainen and Kuikka 2002; Chae and Pascoe 2005).

Conclusions

Accurate estimates of fishing effort are essential for accurate stock assessment, tracking of market trends, estimating profitability of a fishery, designation of marine protected areas and estimation of total catch (including discards and bycatch), all critical components of promoting sustainable fisheries. For fisheries where landings are unreported, e.g. IUU, small scale or recreational fisheries where landings are not reported, nominal effort metrics are one of the only means of monitoring the fishery. As a measure of how much gear is deployed for a given fishery, effort can be a vector for estimating the probability of catching non-target species occupying the same time and space. The measurement of fishing effort may be particularly critical for identifying areas where fishing gear overlaps with known distribution of long-lived species such as birds, marine mammals and sea turtles.

An increase in the quality and quantity of effort metrices is the first step to making effort quantification more accurate. Regardless of data quality, the use of multiple metrics better represents fishing activity than the use of any single metric. Multiple metrics combined with spatial approximations of fishing distribution, e.g. decay functions, may improve estimations using available data. As the need to promote and maintain sustainable fisheries intensifies, the importance of accurate fishing effort estimation methods will continue to be a management priority. Estimation methods that include spatially explicit information on gear use offer the best approaches to accurately representing fishing effort, and innovation and development in spatial analysis will advance effort quantification in all fisheries. Methods that integrate fisher knowledge and involve fishers in data collection and management decisions may be the most effective way to improve data quality and accessibility.

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