Food and Agriculture Organization
of the United Nations

A Review of Literature Related to Master Sampling Frames for Fisheries and Aquaculture Surveys

Publication prepared in the framework of the
Global Strategy to improve Agricultural and Rural Statistics

February 2017

A Review of Literature Related to Master Sampling Frames for Fisheries and Aquaculture Surveys

Technical Report 1- Prepared for the Global Strategy research project on Master Sampling Frames for Fisheries and Aquaculture

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Acknowledgements

This technical report was prepared as part of the Global Strategy to Improve Agricultural and Rural Statistics. The line of research focused on the Master Sampling Frame for Fisheries and Aquaculture Statistics concept. The document was written by Emily Berg and Mark Kaiser of Iowa State University under the supervision of Dramane Bako, International Consultant Statistician, and Flavio Bolliger, Research Coordinator of the Global Strategy. The authors are grateful for the comments and inputs provided by Jacques Delincé, Senior Consultant in Agricultural Statistics and Remote Sensing, and Tiago Almudi, Agriculture Research Analyst, at the Brazilian Institute of Geography and Statistics.

Acronyms and Abbreviations

CPUE	Catch Per Unit Effort
CWP	Coordinating Working Party on Fishery Statistics (FAO)
FAO	Food and Agriculture Organization of the United Nations
ICES	International Council for the Exploration of the Sea
MRAG	Marine Resources Advisory Group
NASS	National Agricultural Statistics Service (USA)
NMFS	National Marine Fisheries Service (USA)
NOAA	National Oceanic and Atmospheric Administration (USA)
SIAP	Statistical Institute for Asia and the Pacific

Executive Summary

The fishery and aquaculture sectors make vital contributions to national food supplies and economies: fish are viewed as a sustainable food source, and small-scale fisheries alone employ an estimated 109 million people. To be effective, policies and management approaches must respect the ways in which fisheries and aquaculture interact with society as a whole and reflect the attitudes and perceptions of the individuals involved. Large-scale data collection must therefore address various dimensions of the target populations. The role of a master sampling frame is to provide a framework for surveys of the different dimensions of the fisheries and aquaculture sectors.

A first step in developing a data-collection plan is to define the objectives. A major set of objectives in surveys of fisheries and aquaculture relates to estimating catches. Examples of variables related to catches include total weight of fish harvested and total effort. In capture fisheries, estimation of bycatch and discards is important in evaluating the health of the surrounding ecosystem. Parameters relevant to the social dimensions of a fishery include the number of individuals involved, their sex, ages, incomes and levels of education. Biological and environmental variables are often collected through dedicated studies rather than government-sponsored surveys, but lists and sampling plans maintained primarily for production or socio-economic studies may also have value for biological and environmental research. In formulating the objectives, it is essential to define the population elements and the units of measurement: fishing effort, for example, may be measured in terms of time units, number of boat trips or number of boats. Conversion factors may be needed to standardize measurement units in different administrative lists.

The sampling frame is a representation of the target population from which a sample can be selected. The frame for a particular survey will depend on the objectives and structure of the target population, and it may be constructed from direct enumeration of operations: a census describing the structure of the sector is an example. Spatial-temporal sampling frames cross-classify a geographic area with a set of time points. Administrative records such as fishermen's licences or registers of aquaculture facilities can form the basis of a sampling frame or serve to enhance a sampling frame with additional information. A list of households, possibly from an agricultural or demographic survey or census, can also be used as a sampling frame. Aquaculture surveys have traditionally been based on lists obtained from earlier surveys of agriculture, but the possibility of direct sampling from lists of aquaculture facilities or areas where aquaculture activities occur deserve greater attention. Lists of households have also been used as frames for surveys of fisheries, particularly when socio-economic characteristics are of interest.

In probability sampling, a subset of elements is selected from the frame in such a way that every element has a known non-zero probability of inclusion. Probability sampling makes it possible to construct inferences for population parameters with quantifiable measures of uncertainty. Concepts in sample design that are important in surveys of fisheries and aquaculture include multi-stage sampling, unequal selection probabilities and stratification. Multi-stage sampling is particularly useful when the ultimate population elements cannot be directly sampled from the frame: an example is the selection of landing sites from a spatial-temporal frame as the primary sampling unit, and selecting fishing trips associated with particular landing sites as the secondary sampling units. Multi-stage samples are often used in surveys of aquaculture when an agricultural survey provides the basis for the sampling frame: in such cases agricultural households are selected in the first stage, and individuals involved in aquaculture are selected in the second stage. Unequal selection probabilities may be used, for example to select large aquaculture operations or regions with high fishing effort with relatively high probability. Selection of units with probability directly related to size can lead to more efficient estimators of totals for variables correlated with size. Stratification is valuable when the groups defining the strata explain variability in the variables of interest. Examples of stratification variables for aquaculture facilities may include permanency, density or size; strata for surveys of fisheries may be time devoted to fishing, dominant gear category or geographic region.

Two categories of contact methods are "on-site" and "off-site". The former refer to data-collection procedures in which an individual is contacted at the location where fishing or aquaculture takes place; in the latter, data are collected indirectly through household surveys or administrative lists.

Off-site data-collection methods are widely adopted because they are often less expensive than on-site methods. The frame for a household survey may be derived from an agriculture or population census, or from an administrative list of licences. Most aquaculture surveys are household surveys that use a previous agriculture survey or census as the sampling frame. In surveys of fisheries, use of a demographic survey rather than agricultural survey is advisable because it will maximize coverage. Household surveys can be an efficient means of collecting demographic data, but measurement error from recall bias is often a concern, particularly for variables related to production. Information from administrative records such as fishing logbooks can be informative with regard to change over time, but often produce biased estimators of level for a single time point caused by intentional misreporting.

On-site methods are often used when accurate estimators of variables related to production are needed; contacting anglers at a fishing access point, for example, is recommended when an accurate estimator of catch is a high priority. Aerial surveys can provide efficient estimators of effort for large fishery areas; placing observers on fishing vessels is an approach used in capture fisheries when bycatch or illegal fishing is a concern. On-site data collection is more common in surveys of fisheries than in surveys of aquaculture, but investigation of on-site data-collection methods for aquaculture surveys can be useful for future investigation.

Different contact methods introduce different sources of measurement and selection error. Collection of several measurements of related variables provides information about potential for systematic bias. Surveys that use different contact methods for different variables can help leverage the relative strengths of different approaches.

Estimation procedures should reflect the way samples are selected. Among standard estimation procedures appropriate for complex designs, the use of non-linear estimators and models are important for surveys of fisheries and aquaculture. A major non-linear estimator is the ratio: it is used, for example, to estimate catch per unit effort and to classify variables by domain – species and gear type are examples. Non-linear estimators are also used to combine information from different components of a multi-mode survey: an example is obtaining an estimate of total catch by combining an estimate of catch per unit effort from a survey in which recreational anglers are contacted directly at the fishing site with an estimate of total effort from an aerial survey. Models can help to address objectives that are not easily combined in a design-based framework. Applications of models to surveys of fisheries include assessment of non-sampling errors, determination of sample size and small-area estimation.

1

Overview

This report reviews the literature related to the monitoring of characteristics of fisheries and anglers. We begin with an overview of why monitoring several dimensions of a fishery is important for the development of effective management plans (de Graaf *et al*., 2015), and consider aspects that might have particular relevance for developing and emerging economies, where small-scale fisheries are important and present unique challenges (Jacquet and Pauly, 2008).

1.1. Sampling for management: the value of an integrated approach

Management plans for specific fisheries and policies for the fisheries sector often aim to improve food security by encouraging sustainable practices (de Graaf *et al*., 2015; Stamopoulos, 2002). In developing fishery-management plans, it is advisable to consider the implications of the fisheries sector in a the national economy, the surrounding ecosystem and the food supply (de Graaf *et al*., 2015). "Sustainable resource use, increased fish production, and earnings of foreign currency..." are examples of prominent issues in fisheries policies (de Graaf, 2011). To ensure that the environment can provide a sustainable supply of fish, many management plans seek to mitigate ecological stresses such as over-fishing and bycatch. Degradation of marine ecosystems has immediate consequences for people who depend on fishing for their livelihoods (Chuenpagdee *et al*., 2006). And if management programmes do not adapt to the culture of a fishing community, compliance may become a problem.

Programmes that monitor several dimensions of the fisheries sector provide the information needed for a data-driven approach to developing and evaluating fisheries management plans. Before proceeding, we clarify our use of the term "monitoring" in this context. Many sources use it to mean the regular and usually automated collection of data for a functional purpose, possibly related to the administration of a government programme; such systems lead to a particular kind of administrative data, which in turn arises from the natural data collection process. We refer to continuous automated collection of data for a functional purpose as "routine data collection", and use the term "monitoring" to describe a statistical approach to collecting data and estimating defined population parameters for a specified geographical area and time period. Examples of "monitoring" programmes in this sense are surveys and censuses conducted over time.

Recent work on the monitoring of fisheries stresses the importance of what we will call an "integrated approach" – collecting data related to several aspects of the fisheries sector: "In practice, fisheries assessments should always combine biological, economic, sociocultural, and compliance indicators to guide management decisions…" (de Graaf *et al.*, 2015). Environmental data provide information about fishing-related stresses on an ecosystem such as over-fishing and bycatch. Socio-cultural and economic data are often needed to assess compliance, understand factors that encourage or discourage participation in the fisheries sector and describe the social and economic implications of fisheries. Joint analyses of characteristics related to different aspects of the fisheries sector can reveal more than analyses of single dimension. Food-balance sheets, often used for analyses of food security, contain information about catches, catch distribution by species, imports, exports and human populations: "Time series of fishing effort, catches and prices are often used in socio-economic studies..." (Stamopoulous, 2002). Zollett *et al.* (2015) suggest that dimensions related to "…science, industry, and enforcement…" should be considered when identifying the goals of a monitoring programme.

A focus on "…economic and socio-cultural data collection…" is increasingly seen as "…necessary to answer many management questions that biological data alone cannot address". Developing "…appropriate monitoring techniques and coverage levels…" depends on "stakeholder input" and "fishery attitudes" as well as scientific goals. Social issues are particularly relevant in many developing countries, where small-scale fisheries are important to the food supply and also "…underpin the social fabric of many communities..." (de Graaf *et al*, 2011). Case studies are reviewed in Section 6.

1.2. Monitoring fisheries in developing countries: small-scale fisheries and associated challenges

In developing countries, small-scale fisheries contribute substantially to employment and production in the sector. An estimated 119 million people depend directly on fisheries for their livelihoods, of whom 96 percent live in developing countries and of whom 109 million are employed in the small-scale sector (de Graaf *et al.*, 2011). Small-scale fisheries contribute to 45 percent of global fish production – 48 million mt; and developing countries account for

85 percent of production from small-scale fisheries – 41 million mt (de Graaf *et al.*, 2011).

Nonetheless, the World Bank BigNumbers project revealed under-reporting of catches and employment in the sector (de Graaf *et al.*, 2011), and annual national statistics for landings reported to the Food and Agriculture Organization of the United Nations (FAO) may not always include the catches of small-scale fisheries (Chuenpagdee *et al.*, 2006). Research on small-scale fisheries has hitherto focused on social and anthropological characteristics (Chuenpagdee *et al.*, 2006), but information on catches and value is needed because of their importance in food supplies and livelihoods (de Graaf, 2011).

Classifying a fishery as small-scale or large-scale is challenging because of the variations in the size and nature of national fisheries (Carvalho *et al.*, 2011; Chuenpagdee *et al.*, 2006). Criteria used to define small-scale fisheries include boat size, gear type, gross registered tonnage, engine size and sometimes the distance from shore or the depth where fishing takes place (Chuenpagdee *et al.*, 2006). Small-scale fisheries are often defined as those operating in boats of 15 m or less, or that do not use boats (Jacquet and Pauly, 2008). Small-scale fisheries may provide subsistence livelihoods, but many are commercial-scale operations (Chuenpagdee *et al.*, 2006). The variety of definitions led Pauly and Charles (2015) to recommend that FAO Member States adopt their own definitions and disaggregate statistics between the small-scale and industrial-scale sectors. Garcia *et al.* (2008) adopt the approach of Johnson (2006) and defined fisheries in terms of "…social organization of production and operations in time and space." The term "artisanal" refers to socio-economic characteristics, whereas the term "small-scale" describes a fleet in terms of gear type and vessel size (Garcia *et al.*, 2008; Johnson, 2006).

Data collection for small-scale fisheries is challenging. Fishing communities in developing countries are often remote, separated from political structures and without landing facilities, and are less likely to participate in subsidy programmes than industrial fisheries (Chuenpagdee *et al.*, 2006). Under-coverage of small-scale fisheries in terms of catch estimates has been attributed to their "…dispersed nature, weak institutional capacity and traditional methods … that make routine data collection cumbersome" (de Graaf *et al.*, 2011). In the South Pacific, for example, catch, effort and information about gear types are collected for large-scale fisheries, but "…almost no information is collected for small-scale fisheries..." (de Graaf *et al.*, 2011). Garcia *et al.* (2008) reiterates the importance of filling the gap in data collection for small-scale fisheries.

Another challenge in surveys of small-scale fisheries in developing countries is the cost of censuses of all fishing entities – often called "frame surveys" and discussed in Section 3. Comprehensive enumeration can provide the basis for a sampling frame for fisheries surveys, but the cost is often too high and information about the sector may hence be incomplete or outdated (de Graaf *et al*., 2011).

1.3. Importance of a reliable sampling frame

On the basis of a review of fisheries data from 17 developing and 11 developed countries, de Graaf *et al*. (2011) asserts that the "main priority" in developing monitoring programmes for small-scale fisheries is to develop a sampling frame: "Innovative sampling strategies are required. The main priority is to determine the best sample frame for small-scale fisheries." In view of the data-collection challenges discussed in Section 1.2, de Graaf (2011) observes that sampling frames that could be used for small-scale fisheries in developing countries are "…likely to be found outside that sector…" and recommended adding fishery-related questions to population or agricultural censuses (see Section 3).

1.4. The concept of a master sampling frame

The aim of this part of Global Strategy research is to provide guidelines for developing a master sampling frame for the fishery and aquaculture sectors. Martinez (2013) and Tuner (2003) discuss the concept, but we adopt the definition of Carfagna (2013):

"A master sampling frame is a sampling frame that provides the basis for all data collections through sample surveys and censuses in a certain sector, allowing to select samples for several different surveys or different rounds of the same survey, as opposed to building an ad-hoc sampling frame for each survey. The aims of the development of a master sampling frame are: avoiding duplication of efforts, reducing statistics discrepancies, connecting various aspects of the sector, allowing the analysis of the sampling units from the different viewpoints, and having a better understanding of the sector."

In short, a master sampling frame is a structure or collection of structures that covers target populations of interest and includes procedures for using the structures. A structure may be a "list frame" such as a catalogue of addresses or vessel licenses, or an "area frame" – a spatio-temporal description of a target population such as the two-way classification defined by geographic locations and time points. Our guidelines will focus on evaluating structures in terms of their applicability for monitoring fisheries in developing countries.

1.5. Combining several sources of data

An integrated approach will combine several data sources, and will be important in compiling lists to use as frames and constructing estimators based on the selected samples. The frames will include geographic layers and lists from the public and private sectors, and, as population-level data sources will be able to provide auxiliary information at the estimation stage. Using several data sources can also improve the coherence of estimates from different samples. Berg and Li (2015) and their references discuss the role of multiple data sources in frame construction and estimation for surveys in general.

1.6. Outline of the literature review

First we review the literature related to monitoring several dimensions of characteristics associated with fisheries and anglers. Sections 2–5 review general concepts associated with variables of interest, types of frames, contact methods and sample survey methods. Section 6 reviews specific applications in developing countries. The primary resources were review articles on issues arising in developing countries: de Graaf *et al*. (2015 and 2011) and Stamopolous (2002) are examples. Because small-scale fisheries are known to have characteristics in common with recreational fishing in developed countries (Volstad *et al*., 2014), we drew on the literature on surveys of recreational anglers in developed countries: Pollock *et al*. (1994) is an example. Section 7 summarizes the foregoing review of fishery statistics, Section 8 discusses aquaculture, and Section 9 is a brief synthesis of the paper.

2

Variables

As noted in Global Strategy (2015) "…the development of a master sampling frame begins by defining the data items to be measured." De Graaf *et al*. (2015) review variables relevant to fisheries in connection with monitoring programmes for West Africa: the variables were classified according to the information required – socio-economic data, fishing effort, production, abundance and compliance – and their relation to policy objectives such as job creation, food security and sustainable management of marine environments. Stamopoulous (2002) provides a similar classification of data items relative to the objectives of monitoring programmes.

Chuenpagdee *et al*. (2006) and de Graaf *et al*. (2011) review the nature of fisheries data collected in many countries. Chuenpagdee *et al*. (2006) use FAO country fishery profiles[1] and other sources to compile a database with information on 140 maritime countries: it included catches by small-scale fisheries, number of vessels used, target species and gear type. In view of their importance in small-scale fisheries, Chuenpagdee *et al*. (2006) include data related to women and children. In de Graaf *et al*. (2011), fuel efficiency and the contribution of the fishery sector to gross domestic product and employment emerged as important variables. Specific variables related to employment included the numbers of fishers, post-harvest jobs and women employed.

Given the large number of possible data items to be collected, it is tempting – but dangerous – to create extensive questionnaires and data-collection protocols (de Graaf *et al*., 2011). To avoid excessive burdens on respondents and other difficulties, de Graaf *et al*. (2015) recommend that variables be selected that are "directly related to objectives", with a distinction between "need-to-know and nice-to-know information." One way to rank variables is on the basis of the number of quantitative indicators that use a particular variable: catch per unit effort, for example, is a common indicator of ecosystem health in that a fall in catch per unit effort over time can result from a decrease in stock; it requires two variables – catch and effort. In a review of several quantitative indicators, de Graaf *et al*. (2015) found that "…catch, effort, and value are vital to a wide

[1] See: http://www.fao.org/fishery/countryprofiles/search/en

variety of indicators or may themselves be used as indicators.” In Sections 2.1—2.3 we classify variables in four categories: i) catch-related variables; ii) biological data; iii) environmental data; and iv) socio-economic variables. Measurement issues in catch-related variables and socio-economic variables are discussed in Sections 2.1.1 and 2.1.3.

2.1. Catch-related variables: landings and discards

Catch-related variables include harvest or kept catch, discards, bycatch and effort. De Graaf *et al*. (2015) advise that catches should be broken down into categories such as species or gear type, that the disposal of catches and trans-shipping at sea from fishing boats to transport vessels should be taken into account and that geographic and temporal reference points associated with catches should be recorded.

The term "effort" relates to the amount of fishing activity. It is an indicator for fish stocks, and is used in setting fishing controls. De Graaf *et al*. (2015) state: “Recording fishing effort requires careful thought on how effort will be used and how it may be collected practically.” Effort should be related to gear type, and measures of effort may include time spent fishing, number of fishing trips, the time trapped fish remain in the water, time spent trawling or number of boats.

Catch and effort have implications for economic and environmental indicators. An important derivative of catch and effort is "catch per unit effort" (CPUE). Declines in CPUE over time can indicate degeneration of the health of the ecosystem. Breaking down CPUE by gear type or target species is also informative.

Bycatch and discards also have environmental implications. Observer programmes for industrial fisheries, particularly in developed countries, often aim to provide data related to the health of marine ecosystems (Zollett *et al*., 2015; Brooke, 2012), so the variables to be considered include bycatch, discards, catches, effort and CPUE. Information about gear types is important because certain types are likely to damage habitats or result in bycatch of non-target species: ground trawling, for example, can destroy sea-bottom habitats (Jaquet and Pauly, 2008), and bycatch of dolphins from purse seines targeting tuna led to the development of the National Oceanic and Atmospheric Administration (NOAA) observer programme (Brooke, 2012). The International Council for the Exploration of the Sea (ICES) discussed the issue of estimating the survival rates of discarded fish and reviewed the related literature in ICES (2013a).

2.1.1. Issues affecting the measurement of catch and effort

Three measures of catch are weight, volume and number of fish. Conversion factors from processing units or local units such as baskets, cartons and ground weight to standard units are important if data are collected from processors. If there is a reliable length/weight relationship, information about fish length can inform assessments of total catch.

Effort can be measured in terms of time spent fishing, number of trips or number of boats. The choice of measure often depends on gear type (see Figure 1). Decoupling the time spent fishing from time engaged in fishing-related activities such as travel to fishing grounds or time searching for fish can be difficult, but the objective must be to obtain a consistent and interpretable index of effort.

Figure 1. Measures of effort by gear type (de Graaf *et al*., 2015)

Gear type	Variables
All gear	Time sailing; time fishing; number of labour by type; types of gear; electronics; other capital inputs
Trawl and dredge	Date, times, speed, positions (latitude/longitude, location ID, grid ID, depth) for gear "set", "on bottom", "at school", "closed", "off bottom", "haul start", "on surface"
Purse seine	Date, times, positions (latitude/longitude, location ID, grid ID) of start set, end set, pursed, pumped/brailed, on board
Longline	Number of hooks set; date, times, positions of start set, end set, start haul, finish haul
Trap	Number of traps set; date, times, positions of start set, end set, start haul, finish haul
Vertical nets	Number and length of strings set; date, times, positions of start set, end set, start haul, finish haul
Pole and line and jiggers	Number and type of poles; number and type of jigging machines; date, start time, end time, position (latitude, longitude, depth) of operation
Beach seine	Length of net; date, start time, end time

2.2. Biological and environmental variables

Biological and environmental variables may be obtained through scientific research other than the surveys of interest here. In countries that monitor commercial fisheries, biological information is often collected as part of intercept sampling at landings sites and by observers on fishing trips or other research cruises. Countries that base the regulation of fisheries on catch quotas, area restrictions and length restrictions generally rely on stock assessment modelling – also known as modelling of population dynamics – to estimate and forecast stocks over time and under various systems of regulation. Because these are extensive topics in their own right, we do not cover the collection of biological information here. But because basic biological and environmental data are needed to assess the state of any fishery we review the types of variables considered useful.

Tracking trends in the size and composition of stocks requires data in the form of biological indicators. Catch and CPUE are sometimes taken as indictors of stock size, and although they can indicate changes in stock health over long periods they exhibit substantial variability over short periods: interpreting them in terms of stock size must hence be done with caution. The variables of length, weight, sex and age are used to estimate the age, sex and size of fish populations, and, along with external information on fecundity by age, are essential inputs to fish stock assessment models. Understanding changes in the frequencies of length and weight in a population can be used in conjunction with trends in CPUE to gain a basic understanding of the structure and health of a population. Surveys seeking such information to augment or complement production surveys are possible in the case of direct-contact sampling, but if production surveys use indirect contact methods additional enquiries will be needed.

Fishing can affect the environment and is in turn affected by environmental conditions. Oceanographic and meteorological variables can provide information about the extent and conditions of a habitat and levels of pollution. Oceanographic variables include water temperature, the direction and speed of currents, salinity and concentrations of nitrates, oxygen and other water-quality indicators. These variables can be collected on fishing trips if observers are employed, otherwise sampling strategies other than fish-production surveys are needed. Meteorological variables include rainfall, air temperature, wind speed and direction, ice formation and pressure gradients: these can be obtained from weather and climate models or observations from balloons and satellites. It is becoming increasingly important to understand the spatial and temporal scales at which such information can be combined with fisheries estimates.

2.3. Socio-economic data

Socio-economic variables describe the anglers, dealers and processors involved in the fisheries sector. These data are related to economics, demographics and culture: examples of economic data include incomes, prices paid and prices received; other variables of interest with regard to anglers include levels of education, age, sex, ethnicity and numbers of adults and children in households.

The social and economic aspects of fishing communities have hitherto received less attention than the characteristics of fisheries in terms of catches, the environment and fish species (Himes-Cornell *et al.*, 2016; Jepson and Colburn, 2013). Research in the early 1990s indicated that fishery scientists knew little about the attitudes of anglers or the extent to which they valued fishing (Miranda and Frese, 1991). In the context of small-scale fisheries in developing countries, research into the social aspects of fishing communities was primarily anthropological (Chuenpagdee *et al*., 2007).

Managers and scientists have recently begun to recognize the value of understanding the related socio-economics of industrial and small-scale fisheries, for example in developing management plans (Matlock *et al*., 1991; Voiland and Duttweiler, 1984), assessing the effects of regulations, increasing compliance and anticipating reactions to new policies (Pollock *et al*., 1994; Himes-Cornell, 2016).

The re-authorization of the Magnuson-Stevens Fishery Conservation and Management Act in 1996 stimulated research into the socio-economic dimensions fisheries in the Unites States (Jepson and Colburn, 2013). This included: i) the decision by the United States National Marine Fisheries Service "…to develop quantitative indexes related to community well-being…" (Himes-Cornell, 2016); ii) the use of census and fisheries data by the NOAA to assemble profiles of fishing communities in designated fisheries regions; and iii) the recognition that "…when NOAA's National Marine Fisheries Service (NMFS) plans to implement fishery management plans, it is necessary to conduct (among other analyses) a social impact assessment…" (Smith *et al*., 2011).

Pollock et al. (1994) separate economic concepts of interest in analyses of fisheries into two categories: effects and value. Data related to expenditure were the most relevant for measuring effects: in the context of surveys of recreational anglers, they recommended using the concept of "the maximum price one would be willing to pay" as a measure of value, and distance travelled to the fishing location as a proxy.

Quantitative studies of the socio-economic characteristics of a fishery can involve the development of quantitative indicators to measure conceptual attributes such as well-being (Pollnac et al., 2006) vulnerability (Himes-Cornell et al., 2016) and resilience (Jepson and Colburn, 2013). Methods such as factor analysis and principal component analysis are used to identify groups of specific variables that contribute to quantitative indexes measuring these concepts.

Specific variables used for socio-economic studies describe fisheries and the individuals involved. The variables used in Smith *et al*. (2011) and Himes-Cornell *et al*. (2016) are listed below; Pollnac *et al*. (2006), Marine Resources Advisory Group (MRAG) Americas and Jepson (2008) and Marshall and Marshall (2007) provide further detail. In particular, Pollnac *et al*. (2006) provide a table that links constructs such as safety, job satisfaction, mobility and mental or physical health to specific variables. The appendix of MRAG Americas and Jepson (2008) lists census variables used to form demographic profiles of fishing communities. The variables listed below may be measured at the individual level or aggregated to the level of a community. Marshall and Marshall (2007) is unique in that their analysis unit was an individual instead of a community: in practice it is important to associate each variable with a precise reference period.

Fishery variables used for socio-economic studies

- Landed value by species
- Value of vessels by type/size
- Number of vessels by type/size
- Place where fish are unloaded, and method
- Fishing supplies bought and location of purchases
- Changes in fishing practices over time

Social variables used for socio-economic studies

- Household income
- Level of education
- Employed/unemployed/not working
- Men/women
- Ethnicity
- Involvement in tourism
- Availability of work outside the fisheries sector

2.3.1. Measurement issues in socio-economic studies

Accurate definition of items of interest, reference points and units is important in all aspects of statistics-based monitoring; Pollock *et al*., 1994 note that they are particularly nuanced in socio-economic studies. We consider issues related to defining the units of analysis, spatial sizes of communities and fishing trips that arise in socio-economic studies of fisheries.

In socio-economic studies, the unit of analysis may be an individual (Marshall and Marshall, 2007) or a community (Himes-Cornell et al., 2016). In formulating guidelines for collecting data on fisheries through household surveys, Global Strategy (2016) makes a distinction between household-level items and community-level items: the decision to examine individual-level characteristics or community-level characteristics often depends on available resources and the scientific objectives, and community-level studies are sometimes favoured because published community-level data are available.

In community-level analyses, the definition of the area occupied by a "fishing community" (Himes-Cornell et al., 2016) is not always straightforward and has been a frequent topic of research (MRAG Americas and Jepson, 2008). One reason for the difficulty is that fishing often affects an area larger than the immediate surroundings of the fishing site. Shopping in a location between a residential area and a fishing site illustrates the potential regional-level economic effects of fishing.

The definition of a "fishing trip" in socio-economic studies may differ from the definition of a trip used to measure variables such as catch and effort. In measuring variables related to production, a trip often refers to a single period of time in which an angler is actually fishing, so it could refer to several boat trips in a single day. For the purposes of socio-economic analysis, such separate outings by boat would constitute a single "fishing trip" (Pollock et al., 1994)

3
Frames for Fishery Surveys

Probability sampling begins with the construction of a sampling frame, which is the list of units from which the sample is selected. As advised in Global Strategy (2015), construction of the sampling frame requires consideration of the target population and the population elements; it also discussed in detail the concepts related to population elements and target populations. We provide an overview in relation to fisheries surveys.

The "population elements" are the units in the population whose characteristics are of interest. Anglers and fishing trips are examples of population elements. The relevant unit, which depends on the variables of interest, will guide the selection of a sampling frame.

The "target population" is the totality of population elements of interest. An ideal sampling frame completely covers the target population and contains no ineligible elements. In practice, under-coverage of the sampling frame and the inclusion of ineligible elements – over-coverage – are common. Volstad *et al.* (2014) give examples of the use of weighting adjustments account for under-coverage in a survey of small-scale fisheries in Mozambique.

It is often important to make a distinction between the sampling unit and the population element (Lohr, 2010, pg. 3). The sampling unit is the element selected from the sampling frame. Surveys of fisheries often involve several stages of selection with different sampling units at each stage: in a survey of recreational anglers, for example, the primary sampling unit may be combination of landing site and time-unit, the secondary sampling unit may be a boat trip and the "angler trip" in the boat may be selected at the third stage of sampling (Breidt *et al.*, undated).

Sampling frames are often classified into two categories: list frames and area frames. A list frame is an enumeration of sampling units, often derived from administrative data; sources of list frames for fisheries surveys may be lists of telephone numbers, processors or vessel licenses. Area frames are geographic representations that cover a target population; an area frame for a fisheries survey may be a representation of an area where fishing occurs.

List frames often have rich auxiliary information that the designer can exploit to improve the efficiency of the estimators. List frames can be expensive to maintain, and they may fail to cover the target population if they are based on out-of-date information. Area frames, on the other hand, typically cover the entire population, though in certain cases they may be inefficient because ineligible units and limited supporting information may be included. In other situations, area frames allow the use of geographic information such as distances, temperature maps and water depths as auxiliary variables. Volstad *et al*. (2014) and Breidt *et al*. (undated) use area frames in their sampling plans for small-scale fisheries and recreational anglers.

More than one list may be needed to cover the target population completely. List frames may be composed of administrative lists such as vessel licenses, information from government subsidy programmes and telephone numbers. Linking such records is often the main challenge when combining several lists to form a unified frame with better coverage than an individual list. Multiple-frame surveys offer a different way to utilize more than one frame to cover the population of interest in that samples are selected from separate frames, and estimators account for the probability of selecting an element in more than one sample. A common approach to multiple-frame surveys is to select one sample from a list frame and one sample from an area frame. A multiple-frame survey of this kind has been used to measure the under-coverage of a list frame for a survey of recreational anglers (Breidt *et al*., undated). Global Strategy (2015) discusses estimation for multiple-frame surveys.

Many types of sampling frames are used for fisheries surveys: the choice depends on the variables of interest and the population elements. Practical issues such as the available resources and the quality and reliability of administrative data will also guide the choice of sampling frame, which is also affected by the decision to use indirect or direct sampling. In direct sampling (Section 4.1), data collection takes place at the fishing site. In indirect sampling, information about anglers is obtained from household surveys or indirectly from logbooks, diaries and administrative sources.

Resources for constructing fishery sampling frames are discussed below. Discussion of the concept of a fishery census is followed by a listing of the characteristics of the fishery sector, consideration of resources for developing list frames and the structure of spatio-temporal sampling frames for fisheries surveys. The material below is largely from Pollock *et al*. (1994), de Graaf *et al*. (2015) and Stamopolous (2002).

3.1. Fisheries sector censuses

One way of constructing a fisheries sampling frame is to conduct a census that collects basic information about the entire sector. In the literature this process is referred to as a "frame survey", which is a census that describes the basic structure of the fishery-production sector and related activities (de Graaf *et al*., 2015), but we avoid the term because it not used in other official statistics to describe a census, and it is easily confused with the standard notion of a statistical survey sample. Nonetheless, the concept of a complete enumeration describing the fishery sector is important: Stamopolous (2002) describes the process as "...a census-based approach in which data is collected on all fishing vessels and gear (at all homeports/fishing sites), which could be potentially operating within the estimation context."

Variables gathered in a fishery census may include the size of landing sites, times of the day and year when fishing occurs, gear types, employment, access to markets and demographic characteristics (Stamopoulous, 2002). The results may indicate a need to exclude disused home ports or to reflect changes to classifications of boats and gear. Complete enumerations of fishing activities through censuses may be legally required, possibly for regulatory purposes. Stamopoulous (2002) discusses the use of fishery census results as frames for subsequent surveys of fishing effort or catch.

In developing countries, financial resources for regular fishery censuses are often unavailable and information is hence out-of-date (de Graaf et al., 2011). The role of such censuses in developing countries and the difficulties associated with them are discussed in de Graaf et al. (2011):

"Structural information on the number, characteristics, and spatial, distribution of vessels, gears, fishers, landing sites, and fishing communities is traditionally obtained through a frame survey, which is essentially a fishery census…These should be updated regularly, but this does not happen often because of their high cost. For example, the last marine frame survey in Bangladesh was carried out in 1984/1985, and in Nigeria, the 1976 survey was only updated in 2006. In Benin, frame surveys are only done if donor funds are available, and in Guinea, the first inland survey was made in 2010. This explains why outdated and unreliable structural information was indicated as a major bottleneck for the assessment of small-scale fisheries in Central America and West Africa."

3.2. Administrative data related to registration in fishery-related programmes

Records of participation in government programmes or membership of private organizations can also contribute to list frames. Examples include "...lists of anglers who have purchased fishing licenses, stamps, or permits…lists of registered boat owners, lists of angling clubs, and lists of angling club members..." (Pollock *et al*., 1994). Such lists may contain auxiliary information such as gear type or demographic characteristics such as age or place of residence; but they may be incomplete, for example because of non-compliance with administrative regulations or "age exemptions" (Pollock *et al*., 1994)." With regard to industrial fisheries, administrative sources include mandatory lists of reported landings, electronic logbooks, vessel monitoring systems and boat inspection reports. Lists for the purpose of collecting information on value may come from the point of initial sale and trade data.

De Graaf *et al*. (2011) suggest that administrative data may be useful in constructing sampling frames for fishery surveys in developing countries:

"In many countries, the fishery regulations allow for or oblige small-scale fishing vessels to be registered, and boat-owners must have an official license to fish. Full registration, combined with the licensing and numbering of vessels, could provide basic structural data on small-scale fisheries, so could replace frame surveys. In China, this system is in place for professional small-scale inland fisheries, but unfortunately it has not been implemented in most other countries."

3.3. Lists of households, telephone numbers and addresses

Lists normally used for surveys of people – addresses or telephone numbers, for example – may also be used in surveys related to fisheries. Pollock *et al*. (1994) provided examples of the use of such lists in surveys of recreational anglers. De Graaf *et al*. (2011), recognizing the challenges associated with frame surveys in developing countries, propose the use of frames of households derived from population or agricultural censuses for surveys of small-scale fisheries in such countries:

"The case studies examined in the BigNumbers project showed massive underreporting of subsistence fisheries, whose contribution to food security and poverty alleviation in developing countries is not sufficiently recognized…the main bottleneck is the sample frame, and the lack of information on how many people/households are engaged in subsistence fisheries. Structural information on subsistence fisheries cannot be obtained through frame surveys or registration. The only way to obtain a good sample frame is to make use of external resources, e.g. by including fishery questions in more general activities such as a population or agricultural census. In Vanuatu, for example, three fishery-related questions have been incorporated in the census questionnaire: i) household uses a private canoe/boat; ii) household uses a shared/community canoe/boat; and iii) household fishes for subsistence and/or commercial purposes. Therefore, subsistence [fishing] and commercial fishing households have been identified, and their boats enumerated and located. This type of information demonstrates how cost-effective sample-based household surveys can be constructed."

Use of a demographic survey instead of agricultural survey or census is recommended with a view to reducing the possibility of omitting individuals involved in fishing from the sampling frame.

3.4. Spatio-temporal area frames

On-site surveys of anglers often rely on frames with spatial or temporal dimensions. The spatial dimension is a partition of a region, a body of water or several bodies of water into sections from which samples are drawn. A geographic representation of access points or landing sites may also constitute the spatial dimension of an area frame. If all landing sites are not known, roving or aerial surveys will ensure complete coverage. In defining the temporal dimension of a frame, a period such as a fishing season or a year is divided into units such as days, working days, hours or weekends from which a sample is selected. (Pollock *et al*., 1994)

A common type of frame for fisheries surveys combines spatial and temporal dimensions (Pollock *et al*., 1994). These are termed "area x time frames", and consist of the two-dimensional array of geographic locations and time units. The area x times approach can prevent problems of under-coverage that arise in list frames derived from administrative sources. Volstad *et al*. (2014) use an area x time frame to survey small-scale coastal fisheries in Mozambique.

4

Contact Methods

The choice of sampling frame is related to the contact method, through which collectors of data reach the population element. Pollock *et al*. (1994) review contact methods for surveys of recreational anglers and provided guidelines on choosing them. Zollett *et al*. (2015) discuss the relative merits of dockside monitors and on-board observers for surveys of large-scale industrial fisheries.

Following Pollock *et al*. (1994), we categorize contact methods for fishery surveys into on-site methods and off-site methods. In on-site methods, discussed in Section 4.1, the data are collected at the location where fishing occurs. Off-site methods, reviewed in Section 4.2, include telephone surveys, mail surveys and data collected from logbooks. The choice of contact method depends on the objectives of the survey: Section 4.3 considers the strengths and weaknesses of different contact methods. Complemented survey designs, discussed in Section 4.4, use several contact methods with a view to leveraging the strengths of different approaches. Sections 4.1–4.4 summarizes Part III of Pollock *et al*. (1994), which addressed issues in recreational fisheries. Discussions of commercial fisheries, primarily from Zollett *et al*. (2015) and de Graaf *et al*. (2014) are cited where relevant. As noted in the introduction of Zollett *et al*. (2015), the concepts and guidelines developed in the context of a recreational or commercial fishery apply generally.

4.1. On-site contact methods – direct surveys

The term "on-site" refers to a survey in which a data collector reaches an angler at the location where fishing occurs. On-site contact methods are best when the primary objective of a survey is to obtain accurate information about fishing effort, catch, discards, bycatch and harvested fish species (Pollock *et al*., 1994). The frame for an on-site survey is typically a spatio-temporal sampling frame of the type discussed in Section 3.4. Specific on-site contact methods are access point surveys, roving creel surveys and aerial surveys, for each of which we provide a definition, a list of the primary parameters that the survey measures, data-collection approaches, distinguishing characteristics and consideration of applicability to capture fisheries. The following is a summary of Pollock *et al*. (1994).

4.1.1. Access point surveys

- Definition. In an access point survey, an angler is intercepted at a landing site immediately after completion of a fishing trip.
- Variables. The primary variables collected are harvest and effort; discards, which are needed for total catch, can also be obtained. Some economic data or information about anglers' attitudes can be obtained as a secondary objective. Initial sale price can also be collected (de Graaf *et al*., 2015).
- Optimal conditions. Access point surveys are suited to situations in which the anglers in the target population use public docks or piers. Designing the survey requires an enumeration of access points for known bodies of water that are of interest.
- Data collection. Data collectors, often called creel clerks**,** typically count anglers as they record their harvest. Effort is obtained by asking anglers to report the number of hours spent fishing or the start time of the fishing trip; otherwise the number of cars in the parking lot or exiting from it can be counted. Catch can be obtained by interviews or direct measurement. Discards are obtained by interviewing anglers, but may be subject to intentional misreporting or some recall bias. A clerk may also ask about economic or social issues during the interviews, and may collect basic contact information for use in a future survey (see Section 4.4).
- Distinguishing characteristics. All anglers are selected with equal probability, regardless of the length of any trip. Recall bias is usually minimal because the interview takes place immediately after the fishing trip. The accuracy of measurements of catch or of catch by species is often better in access point surveys than in other contact methods, especially if creel clerks are well trained.
- Applicability to capture fisheries. Zollett *et al*. (2015) discuss the use of dockside monitors, which is a form of access point survey, for commercial fisheries, and encourage dockside monitoring programmes in situations where "accurately reported landing data" are a priority.

4.1.2. Roving creel surveys

- Definition. Creel clerks contact anglers during a fishing trip by boat or on foot.
- Variables. Catch rate is the primary variable; effort, which is required for total catch, is also obtained. As with access point surveys, some socio-economic data can be obtained during interviews, but a more common approach is to collect contact information for use in a follow-up survey.

- Optimum conditions. These surveys are recommended if fishing is dispersed or if the number of access points is too large for an access point survey.
- Data collection. Catch rate is obtained by asking anglers for start times and measuring total catch at the time of the interview. Effort, which is required to expand the catch rate to a measure of total catch, is collected separately because interviews take place before fishing is complete. Access point surveys or counts of anglers may be used in conjunction with a roving survey to measure effort.
- Distinguishing characteristics. Anglers on long fishing trips are more likely to be selected. An assumption of a constant catch rate over the time of fishing underlies many estimators. Robson (1961), Hoenig *et al*. (1997 and 1997) discuss estimation procedures; Brouwer *et al*. (1997) apply the method to a survey of recreational anglers in South Africa.
- Applicability to capture fisheries. The method was developed primarily for recreational fisheries in North America, which resemble small-scale fishing by individuals in many parts of the world, with output sold in markets, bartered or consumed directly. Roving surveys have potential for application to fisheries that involve individuals and small boats, particularly for inland waters or small bays.

4.1.3. Aerial surveys

- Definition. An aircraft flies over randomly selected segments of a fishing area; observers make instantaneous counts of anglers or boats.
- Variables. Effort is the only variable collected.
- Optimal conditions. Collection of data for large numbers of anglers over large areas.
- Data collection. Counts of anglers or boats obtained visually.
- Distinguishing characteristics. These surveys can provide an independent measure of effort that is not subject to recall bias. They can be useful for identifying and measuring fishing intensity in terms of time or area, and can provide information for constructing sampling frames or sample designs for subsequent surveys. Visibility bias can cause measurement error when estimates are constructed.
- Applicability to capture fisheries. Aerial surveys are applicable primarily in coastal marine environments where vegetation does not obstruct visual identification of boats and anglers, though cloudy conditions may limit observation. Situations in which a fishery is distributed around an archipelago call for aerial surveys to eliminate travel and access

difficulties for on-site observation. Visibility bias can be a source of measurement error.

4.1.4. At-sea or on-board observation

- Definition. Observations by trained personnel on fishing vessels.
- Variables. The observers have usually collected data on bycatch and discards in commercial marine fisheries (Zollett *et al*., 2015; Brooke, 2012). Total catch and effort variables can sometimes be recorded by on-board observers, who may also collect biological data; these are generally considered secondary to discard variables.
- Optimal conditions. An official permit allowing fishing vessels to carry observers is the best option. Vessel captains or operators have been known to manipulate schedules and times of departure with a view to avoiding observers. Observer programmes require that departure locations are few and clearly understood. Travel requirements will affect the numbers of observers available at the right places and times for a representative sample of trips for observation.
- Data collection. Observers record the number or weight of discards and kept bycatch; measurement varies depending on gear and often on the target species. For measurement of fish on deck as a result of a trawl, sub-sampling in baskets may be used, but observers recording discards from long-line operations will count individual fish because they are rarely brought on deck. Large observer programmes such as those of the National Marine Fisheries Service of the United States involve extensive training for observers. Guidelines for training observers in West African fisheries are provided in Dietrich (2011).
- Distinguishing characteristics. A major feature is immediate collection of data during fishing. Using observers requires consideration of liability, insurance and safety considerations to ensure that the process does not interfere with normal fishing. The social interaction between fishers and observers creates opportunities for conflict or bribery, which have been known to occur in some fisheries (Western and Central Pacific Fisheries Commission, 2014).
- Applicability to capture fisheries. At-sea monitoring is recommended when self-reporting of bycatch or discards needs to be verified or cannot be trusted. Zollett *et al*. (2015) recommend at-sea monitoring in fisheries that involve at-sea processing, high-impact gear, interactions with endangered species, significant discards and vulnerable stocks, or that are "data-poor".

4.2. Off-site surveys – indirect surveys

In off-site surveys data collection does not take place at the location of the fishing trip: it may be collected from anglers at their homes or from logbooks or administrative sources. This section considers data collection through household surveys and from administrative sources. Frames for off-site surveys are often list frames of the kind discussed in Sections 3.2–3.3.

4.2.1. Household surveys

These include surveys by mail and by telephone, and individual interviews: socio-economic data and information about anglers' attitudes are the primary variables collected. Household surveys may be used in cases where fishing licenses are not required, as in the French sea bass recreational fishery (Rocklin et al., 2014). Data on catch and effort obtained through household surveys are often unreliable because recall bias may be considerable; under-reporting is known to occur in telephone surveys because respondents may not recall recent fishing trips (Andrews et al., 2014). Pollock et al. (2014) discuss the issue of non-response in household surveys and cite evidence of higher response rates among more active anglers. E-mail has been investigated as an alternative to the telephone in surveys of recreational anglers (Zarauz et al., 2015; Henderson, 2014).

Data from population censuses and surveys can provide information on the socio-economic attributes of anglers and fishing communities. Information from the United States decennial population census in 2000 was used to characterize commercial and recreational fishing communities along the northeast coastline of the United States: the variables obtained from census data included the number of people who were self-employed, median household and per capita income and the number of people engaged in fishing-related activities (Smith et al., 2011). Himes-Cornell et al. (2015) describe the result of the first wave of a longitudinal survey to evaluate the impacts of a bycatch management programme in ground-fishing communities in Alaska.

4.2.2. Self-reporting through administrative sources

Logbooks, diaries and catch cards are examples of administrative sources that contain information on catch, effort and possibly socio-economic characteristics. We follow Pollock *et al*. (1994) and classify these as off-site contact methods, because the issues associated with possible reporting bias are similar to those that arise in the context of household surveys. Use of such sources is attractive because data collection is inexpensive. Intentional misreporting such as prestige bias resulting from intentional over-reporting, and under-coverage in voluntary reporting programmes, can lead to systemic bias, particular in estimators of level of catch for a particular point in time. Nonetheless, continuous monitoring of administrative sources can reveal time-related trends. Registration systems can provide reliable information for "...relatively static variables, such as vessel length or engine size..." (de Graaf *et al*., 2015). Self-reported data from processors can provide reliable information about prices and sales (de Graaf *et al*., 2015). Collecting sales information from fish processors is analogous to collecting price data for agricultural products from the first buyer, as in the United States National Agricultural Statistics Service (NASS) prices programme (NASS, 2011). Export data can provide price information from at-sea transactions (de Graaf *et al*., 2015).

4.3. Choosing the contact method on the basis of objectives and selection and measurement errors

The objectives of a monitoring programme will guide the choice of contact method. On-site methods are preferred when bycatch, discards, harvest and effort are the primary variables of interest. Household surveys are best suited to characterizing populations of anglers in terms of socio-economic characteristics.

Each of the three on-site methods – access point surveys, roving surveys and aerial surveys – is suited to different objectives. Access point surveys and dockside monitoring programmes are recommended when exact landing data are required, because a trained data collector can measure landed catch accurately. In access point surveys, information about effort, bycatch and discards are obtained from interviews with anglers, and may be subject to modest recall bias or intentional misreporting, if accurate information on bycatch or discards is a priority, roving surveys are recommended. Roving surveys are useful for situations where self-reporting may be unreliable, for example where illegal catch or bycatch is a concern, or if discarding is illegal as in Icelandic ground-fisheries (Zollett *et al*. 2011). Aerial surveys are an efficient way to collect data on effort from fisheries that cover a broad area.

The contact methods discussed above have various strengths and weaknesses in terms of selection and measurement errors. Selection errors are mechanisms that cause a sampled population to differ from the target population (Lohr, 2010). Measurement errors are mechanisms that cause collected data to differ from target variables of interest (Lohr, 2010). Bias in selection and measurement occurs when these sources of error lead to systematic differences between estimators and corresponding population targets. Pollock *et al*. (2014) state that on-site data collection typically minimizes selection and measurement errors, particularly for catch and effort, but that it is more expensive than off-site methods.

Examples of mechanisms leading to selection bias include under-coverage of a sampling frame and non-response. Data-collection methods based on self-reporting from sources such as logbooks, diaries and catch cards are subject to selection bias if reporting is voluntary and the properties of fishing operations that provide self-reported data are different from the properties of fishing operations that do not. Non-response can lead to selection bias in household surveys. Response rates in mail surveys are reported, for example in Himes-Cornell *et al*. (2015), to have positive correlations with commitment to fishing (Pollock *et al*., 2014). Off-site surveys in which the frame is obtained from lists of fishing licences can cause selection bias as a result of under-coverage (Andrews *et al*., 2014). Aerial surveys can also suffer from selection bias when bad weather leads to non-random selection of flight days. As noted in Section 4.1.2, some roving surveys select anglers with probability proportional to the length of fishing trips. If catch rates are related to the length of fishing trips, any failure to account for the relationship between selection probability and fishing trip length can lead to biased estimators for catch rates (Hoenig *et al*., 1997). An example of an application where inaccessibility of landing sites leads to selection bias in an access point survey is quoted by Volstad *et al*. (2014) to show how to account for the potential bias in the estimator.

Examples of mechanisms that lead to measurement bias include recall bias, prestige bias and intentional mis-reporting. Recall bias occurs when an angler is asked to recall the properties of a fishing trip but cannot accurately remember the information requested; it is known to be a problem in measuring catch in household surveys of recreational anglers. Prestige bias occurs when an angler inflates the number or size of fish caught; the off-site data-collection methods discussed in Section 4.2 are negatively affected by such bias (Pollock et al., 1994). Access point surveys often yield unbiased measurements of catch because trained data collectors, who have no incentive to over-report, measure catches. Information about effort derived from interviews at access points is less likely to be subject to recall bias than data obtained off-site. Intentional mis-reporting of bycatch and discards may occur in off-site or access point surveys, particularly if illegal fishing is involved (Zollett *et al*., 2015). If accurate measures of bycatch or discards are a priority, at-sea roving surveys are usually recommended.

4.3.1. Studies of non-sampling errors in surveys of recreational fisheries

The issue of bias resulting from selection and measurement errors is a theme in many surveys of recreational anglers. We highlight a few studies here that cover developed countries; applications in emerging and developing countries are reviewed in Section 6.

We first provide examples of sub-national programmes that obtained estimates on a small scale. The use of weighting and imputation to adjust for potential non-response bias is exemplified in a survey of Texas fishing licence holders (Fisher, 2011) and in a cost-and-earnings survey of the Alaskan charter boat sector (Lew *et al*., 2015). Estimates of recreational catch and effort for the Western Australian rock lobster fishery from a telephone survey, a telephone diary and a mail survey are compared in Baharthah (2007). The results of the telephone and mail surveys showed that estimates of catch and effort obtained through these approaches were substantially higher than the corresponding estimates based on the telephone diary, a finding consistent with previous fisheries surveys (Pollock *et al*., 1994) showing that telephone and mail surveys resulted in avidity bias in catch and effort because active anglers were more likely to provide a response.

National-scale survey programmes for estimating parameters of recreational fisheries also address the issue of non-sampling errors in their quality assessments. ICES (2013a) proposes a quality-assessment tool that included questions to use when evaluating survey programmes for recreational fisheries, and reviewed the status of recreational fishing surveys for cod, eel, salmon and shark in Belgium, Denmark, Estonia, Finland, Germany, Latvia, Lithuania, the Netherlands, Norway, Poland, Sweden and the United Kingdom. ICES (2015) applied the 2013 quality-assessment tool to evaluate the recreational fishery survey programmes of Denmark, the Netherlands and Sweden. Zarauz *et al*. (2015) carried out surveys by e-mail, telephone and mail to estimate recreational catches of European sea bass in the Basque Country. The mail survey had complete coverage but only a 7 percent response rate; the telephone survey had a response rate of 77 percent, but excluded 81 percent of the target population. The e-mail survey was the least expensive option, but it had the lowest coverage at 15 percent and a response rate of only 10 percent. Hartill *et al*. (2016b) compares recreational harvest estimates from an aerial survey with corresponding estimates from an off-site panel survey: although there was evidence of "...under-reporting of zero-catch trips..." in the panel survey, they found that the estimates derived from the two methods were "remarkably similar." Andrews *et al*. (2014) finds evidence of selection bias resulting from the under-coverage of a licence-based list frame survey of recreational anglers in the United States, and discussed measurement issues in a telephone survey.

4.3.2. Studies of non-sampling errors in surveys of capture fisheries

As discussed in Section 4.1.5, non-sampling errors also affect estimates of bycatch and discards from on-board observer programmes. In the context of estimating bycatches of small dolphins off north-western Spain, Lopez *et al*. (2003) discuss sources of error in observer trips, a carcass-recovery scheme and interviews with fishermen. They hypothesized that observer trips and interviews underestimated bycatch because the sample of fishermen was self-selecting, and noted that compliance was a problem for observer trips because "...neither national nor European legislation places any requirement on fishermen to cooperate with on-board observation schemes..." (Lopez *et al*., 2003). Because face-to-face interviews were conducted, they conjectured that under-reporting in their survey might have been less of a problem than under-reporting in mail surveys of the same topic, and suggested that a management framework such as the Marine Mammal Protection Act in the United States might encourage fishermen to cooperate.

4.4. Complemented survey designs

Fishery surveys use complemented survey designs that utilize multiple-contact methods (Stamopolous, 2002) because they can balance the strengths and weaknesses of different data collection procedures. An aerial survey, for example, may provide information on effort to estimate total catch, whereas a landing site survey might measure catch rate. Electronic monitoring of logbook data in the British Columbia groundfish sector is an example of a complemented survey design (Zollett *et al*., 2015).

Pollock *et al*. (1994) advocate complemented survey designs to collect economic or demographic data from anglers initially contacted at access points. Contact information was obtained during the on-site survey, and anglers were subsequently contacted for additional information about social and economic characteristics such as attitudes and expenditures.

One type of complemented survey is the aerial-access design, which may be based on maximum-count or random-count. Pollock *et al*. (1994) discuss random-count designs in which random times during the day were selected. Hartill *et al*. (2011) use a maximum-count aerial-access design because it required only one flight each day. Volstad *et al*. (2006) compare maximum-count and random-count designs.

Volstad *et al*. (2006) and Hartill *et al*. (2011) argue that the aerial-access design is a cost-effective way of collecting data on-site. Hartill *et al*. (2011), who describes aerial-access surveys of recreational anglers in the Delaware river in 2002, finds that the sample size for an access survey would have had to be seven times larger to achieve the same level of precision; they also describe an aerial-access survey of the harvest from New Zealand's largest recreational fishery. They prefer on-site data collection to off-site methods because it reduces the potential for recall bias.

4.5. Using several indirect data sources for socio- economic studies

Combinations of several indirect data sources are becoming more prevalent in socio-economic studies of fishing communities. Himes-Cornell *et al*. (2016) use interview data obtained from a non-probability sample to validate socio-economic indicators based on administrative data sources. Jacob *et al*. (2010) use a similar approach with qualitative instead of quantitative interview data. Smith *et al*. (2011) classify fishing communities using census data on demographic characteristics and administrative data on commercial fisheries data from the United States National Marine Fisheries Service database. MRAG Americas and Jepson (2010) use data from permits in conjunction with census data, focusing partly on the ratio of number of permits to population in selected communities.

4.6. Data storage and management

A consistent archiving system will provide precise data-collection protocols and hence improve the quality of the final statistical product. MRAG Americas examined the feasibility of developing a generic fisheries information management system database for small-scale commercial and subsistence fisheries; this was supported by pilots in Bangladesh (MRAG Ltd, 1999a) and in the Turks and Caicos Islands (MRAG Ltd, 1999b). The database included catch-related data on harvest and effort, biological data on species type and size, and socio-economic characteristics such as cost and earnings. They emphasized the need for well maintained identifying variables to give consistency over time and to link data on production and biology.

4.7. Electronic monitoring in on-site data collection:

cameras and apps

Electronic monitoring is being used more and more for on-site data collection, as discussed in Section 4.1; video cameras may be placed at the dock or on boats. Electronic monitoring was advocated by Dinsdale *et al*. (2013) to minimize the costs and complexities associated with on-board observers. Zollett *et al*. (2015) discuss electronic monitoring in the British Columbia groundfish sector, which is used to "...defray costs and eliminate the need for an at-sea monitor on every vessel." Hartill *et al*. (2016a) describe the use of imagery from video cameras overlooking the boat ramp in combination with a creel survey to monitor boat ramps continuously on the north-eastern coast of New Zealand's North Island. Challenges and recommendations associated with the use of iPhones and tablets to gather data on recreational catch and effort through apps[2] are discussed in Venturelli *et al*. (2016). The cost of on-board observers in Scotland was compared with the cost of remote electronic monitors by Dinsdale *et al*. (2013), who pointed out that the electronic monitors have high set-up costs in the first year but cost less per haul than observers, who can nonetheless collect information on age, sex and maturity. Osmond *et al*. (2016) describe a pilot project in the Gulf of California, Mexico and Indonesia for developing cost-effective electronic monitoring systems for small-scale fisheries.

[2] See, for example: http://angleraction.org/angleraction/login/auth

5

Sample Design and Estimation

Once a set of objectives, an enumeration of the target population and a data-collection system have been established, the next steps are sample design and estimation. Many of the principles of sample design and estimation apply to surveys of fisheries: Pollock *et al.* (1994) discuss the concepts in the context of surveys of recreational anglers.

Our discussion of sample design and estimation issues relevant to surveys of fisheries is not a tutorial in probability sampling, but it does assume an understanding of the concept of probability sampling. Other readers should refer to Global Strategy (2015), Lohr (2010) or Pollock *et al.* (1994) before proceeding.

5.1. Sample design issues in fishery surveys

The first step is to introduce notation. We use i to denote the ultimate population element, where $i = 1, \dots, N$, and N is the total number of population elements. The finite population or universe is denoted by U, where $U = \{i = 1, \dots, N\}$. The specific meaning of i depends on the context. Examples of population elements include a "time x location" intersection, a boat trip or an angler. The characteristic y_i is associated with each element. The characteristics of interest with regard to the elements in the population are linked to the objectives of the survey: in a landing site survey to estimate total harvest or kept catch in terms of fish weight, for example, y_i may be the total weight of fish caught by boat trip i. In a mail survey to estimate anglers' income from fishing, on the other hand, y_i may be the income from fishing of angler i. A parameter of interest in fishery surveys is a function of $\{y_i : i = 1, .., N\}$. An example of a parameter is total catch in the population. In the notation from the first example above, total catch can be expressed as $T_y = \sum_{i=1}^{N} y_i$, where y_i is the catch of boat trip i. Similarly, an expression for the parameter "average income per angler" is $\bar{Y}_N = N^{-1} \sum_{i=1}^{N} y_i$, where y_i is the income of angler i.

A probability sample is a subset of the N elements of the finite population such that every element has a known non-zero probability of inclusion. The probability of selecting element i is denoted by π_i, and the probability of selecting both elements i and j is π_{ij}. The sample inclusion indicator I_i is equal to 1 if element i is sampled, and 0 otherwise. The selected sample $A = \{i = 1, .., N: I_i = 1\}$, and the sample size $n = \sum_{i=1}^{N} I_i$.

In a simple random sample of size n selected without replacement, every subset of size n of the N elements in the population has the same probability of being selected. The probability of selecting element i is $\pi_i = n/N$, and the probability of selecting two different elements i and j is

$$\pi_{ij} = n(n-1)/[N(N-1)].$$

Operational and statistical considerations may motivate a more complex design than a simple random sample: estimates may be required, for example, for geographic or temporal domains of interest. Estimators with smaller variances than estimators derived from a simple random sample may be obtained by incorporating auxiliary information into the design. The ultimate population elements may not be directly accessible and may need to be reached by first selecting a group of population elements, called a "cluster". If the population contains a very large unit such as a waterbody with high fishing traffic, then the sampler may wish to select this large unit with certainty or with high probability. These concepts are related to the issues of stratification, clustering and unequal selection probabilities discussed below. Sampling textbooks such as Lohr (2010) cover these concepts in detail; we consider examples and issues related to fisheries surveys.

5.1.1. Stratification

In stratification the finite population elements are divided into H mutually exclusive and exhaustive sets called "strata". A separate sample is then selected from each of the H strata. The strata membership for the elements in the population must be known at the design stage, before data are collected.

Stratification is common in surveys for operational and statistical reasons. If estimates for groups known at the design stage are of interest, the designer may align the strata with the groups of interest. If the strata define homogeneous groups with respect to the characteristic of interest – the variance of y_i within each stratum is smaller than the variance of y_i in the overall population –

estimators based on a stratified sample can have smaller variances than estimators based on a simple random sample of the same size.

Stratification is appealing for two reasons: i) it can make a sample more representative than a simple random sample in terms of classification variables that are known in advance and are of interest; and ii) it can lead to more efficient estimators of overall population means and totals than estimators obtained from a simple random sample.

Several examples of strata are used in fisheries surveys. Geographic strata, for example may be defined by administrative regions or waterbodies; temporal strata include time of day, day of the week, month of the year or season. Defining two temporal strata based on "weekdays" or "weekends" is common in recreational fisheries surveys; definition based on "day" or "night" may be advisable, however, when night fishing is prevalent. If dominant gear categories are known in advance, strata may be aligned with gear classifications.

5.1.2. Cluster samples and multi-stage samples

In many situations there is no list of ultimate population elements, or the ultimate sampling units cannot be selected directly. Cluster samples and multi-stage samples resolve this problem by clustering the ultimate population elements into groups that can be sampled. We call a group that contains several ultimate sampling units a "cluster" or "primary sampling unit" and the ultimate population element within the primary sampling unit the "secondary sampling unit". In cluster sampling, the first step is to select a representative set of primary sampling units, from each of which a subset of secondary sampling units is chosen. This procedure extends directly to three or more levels.

The distinction between a cluster sample and a multi-stage sample is important. In a cluster sample, all secondary sampling units in the primary sampling unit are selected: the cluster total is hence known after data have been collected. The principles that apply to element sample designs – that is, designs where the ultimate sampling unit is sampled directly – apply to cluster samples. For a multi-stage sample, a subset of the secondary sampling units in a primary sampling unit is selected: the cluster total is hence not known after data collection and must be estimated from the sampled secondary sampling units. This introduces a second level of variability in the estimators from multi-stage samples that does not exist in cluster samples. Lohr (2010) discusses estimation and variance estimation for cluster samples and two-stage samples.

A clustered population is similar in structure to a stratified population in that the clusters – the primary sampling units – partition the ultimate population elements into mutually exclusive and exhaustive sets; otherwise, clustering and stratification are different. The main difference is that clustering tends to reduce the efficiency of the estimators, whereas stratification generally improves it. Clustering is often necessary, for example because a list of ultimate population units does not exist, whereas stratification is often a matter of choice, for example to improve the efficiency of the estimator. Characteristics of elements in the same cluster are often more similar than characteristics of interest in two different clusters. This type of group homogeneity improves the efficiency of estimators from stratified samples, but it generally increases the variances of estimators from multi-stage samples. In a stratified sample, a subset of elements is observed from all strata, whereas in a cluster sample only a subset of clusters is observed.

Cluster samples and multi-stage samples are often needed in fisheries surveys because lists of ultimate population elements do not exist. If, for example, a boat trip is the ultimate population element on which the characteristic is observed a list of boat trips is unlikely to exist, and the sampler might construct a frame in which primary sampling units are intersections of time periods and landing sites and select a sample of "time x landing site" primary sampling units. From each sampled "time x landing site" intersection, the sampler would observe boat trips – all of them in the case of a cluster sample, a subset of them in the case of a multi-stage sample. If angler characteristics are of interest, a third level of sampling will involve selecting a sample of anglers from each sampled boat trip. Surveys to measure demographic characteristics of anglers may also employ multi-stage designs: a sampler may, for example, select villages as primary sampling units, households as secondary sampling units and anglers in households as tertiary sampling units.

5.1.3. Unequal probabilities of selection

Unequal probabilities of selection occur when $\pi_i \neq \pi_j$ for at least two elements $i \neq j$. Unequal probabilities of selection can arise in stratified, cluster sample and multi-stage designs. If an auxiliary variable – x_i – is known for each element in the population, it can be used to define the probabilities of selection. Stratification is an example of using auxiliary information in a design where the auxiliary variable is the indicator of stratum membership.

A common type of unequal probability sample is a probability proportional to size sample, when the auxiliary variable is a measure of the size of the sampling unit. The selection probability in such a case is

$$\pi_i = \frac{n\, x_i}{\sum_{i=1}^{N} x_i}$$

where n is the target sample size and x_i is the auxiliary size measure. Modifications are often needed to ensure that selection probabilities are between 0 and 1. If the auxiliary size measure x_i is correlated with the characteristic of interest y_i, estimators of population totals based on the probability proportional to size sample are often more efficient than corresponding estimators based on a simple random sample of the same number of elements. Note that the efficiency gain does not necessarily transfer parameters other than the total. In a cluster sample the auxiliary size measure x_i may be related to the number of secondary sampling units in a primary sampling unit. Selecting larger clusters with higher probability can lead to more efficient estimators of population totals.

We provide three examples of "effort" as a size measure in unequal probability samples. First, suppose that primary sampling units are intersections of bodies of water and hours in a day; suppose also that a proxy of total fishing effort is available from a previous census for each intersection of waterbody and time period: a probability proportional to size sample of intersections of waterbodies and time periods may hence be selected, where the size variable is the proxy for total fishing effort. Second, in the case of selecting a particular time period from a workday for an access point survey of fishing effort (Hoenig *et al.*, 1993) a time interval may be selected from a collection of time intervals with probability proportional to an estimate of total effort within the time interval. Third, roving creel surveys are automatically probability proportional to size samples, where the size measure is the length of the fishing trip.

In the next section we explain how to account for unequal selection probabilities in estimation.

5.2. Estimation

A fundamental estimator for probability samples is the Horvitz-Thompson (HT) estimator. The HT estimator of a population total from an element sample design is

$$\hat{T}_{y,HT} = \sum_{i=1}^{n} \pi_i^{-1} y_i$$

The HT estimator is design unbiased for the population total, and the design-variance of $\hat{T}_{y,HT}$ is

$$V(\hat{T}_{y,HT}) = \sum_{j=1}^{N} \sum_{i=1}^{N} (\pi_{ij} - \pi_i \pi_j) \pi_i^{-1} y_i \pi_j^{-1} y_j$$

An estimator of the variance of the HT estimator is

$$\hat{V}(\hat{T}_{y,HT}) = \sum_{j=1}^{n} \sum_{i=1}^{n} \pi_{ij}^{-1} (\pi_{ij} - \pi_i \pi_j) \pi_i^{-1} y_i \pi_j^{-1} y_j$$

Note that estimation of the variance of the HT estimator requires knowledge of the joint inclusion probabilities for π_{ij} for sampled elements. Modifications to the variance estimator $\hat{V}(\hat{T}_{y,HT})$ exist to avoid negative variance estimates.

The HT estimator is a building block for many other estimators in survey sampling. We discuss estimation issues below that are relevant to surveys of fisheries; for a thorough treatment the reader is referred to Lohr (2010).

5.2.1. Non-linear transformations of linear estimators: ratios and products

Many estimators are non-linear transformations of multiple HT estimators. In the context of fishing surveys, consider as an example CPUE: the population parameter of catch per unit effort can be expressed as the ratio of total catch to total effort. Let $T_{y,1}$ denote total catch in the population and let $T_{y,2}$ denote total effort: catch per unit effort in the population can hence be expressed as

$$\theta = \frac{T_{y,1}}{T_{y,2}}$$

Let $\hat{T}_{y,1}$ denote the HT estimator of total catch and $\hat{T}_{y,2}$ the HT estimator of effort. An estimator of θ is hence $\hat{\theta} = \hat{T}_{y,2}^{-1} \hat{T}_{y,1}$. The estimator $\hat{\theta}$ is an example of a "ratio estimator," which is a ratio of two HT estimators.

In this section we consider estimation and variance estimation for non-linear estimators such as the ratio estimator. We first discuss estimation and variance estimation for non-linear functions of HT estimators in general, and then provide examples of non-linear estimators that arise in surveys of fisheries.

Let the parameter of interest be defined by $\theta = g(T_{y,1}, \dots, T_{y,K})$, where $T_{y,1}, \dots, T_{y,K}$ are population totals for K characteristics of interest, $g()$ is a smooth function from $R^K \to R$, and R is the real line. We consider an estimator of θ defined by

$$\hat{\theta} = g\left(\hat{T}_{y,1}, \dots, \hat{T}_{y,K}\right)$$

where $\hat{T}_{y,k}$ is the HT estimator of $T_{y,k}$.

We first consider variance estimation for a case in which the estimators are obtained from the same survey. By the "delta method" or a first-order Taylor expansion, the variance of $\hat{\theta}$ is approximately equal to the variance of the linear estimator defined by

$\hat{T}_d = \sum_{i=1}^{n} \pi_i^{-1} d_i$ where

$$d_i = \sum\nolimits_{k=1}^{K} \frac{\partial g}{\partial T_k} \left(y_{ik} - \frac{\pi_i}{n} T_k \right)$$

and $\partial g / \partial T_k$ is the partial derivative of $g()$ with respect to T_k. An estimator of the variance of $\hat{\theta}$ is therefore an estimator of the variance of $\hat{T}_d$ given by

$$\hat{V}\left(\hat{\theta}\right) = \sum\nolimits_{j=1}^{n} \sum\nolimits_{i=1}^{n} \pi_{ij}^{-1} (\pi_{ij} - \pi_i \pi_j) \pi_i^{-1} \hat{d}_i \pi_j^{-1} \hat{d}_j$$

where $\hat{d}_i$ an estimator of d_i obtained by replacing unknown population totals with estimators.

A special case of an estimator $\hat{\theta}$ is the ratio estimator $\hat{\theta} = \hat{T}_{y,2}^{-1} \hat{T}_{y,1}$. For the ratio estimator the linearized variable d_i is given by $d_i = N T_{y,2}^{-1} (y_{i1} - \theta y_{i2})$ and $= T_{y,2}^{-1} T_{y,1}$. From the form of d_i we see that the variance of the ratio estimator is relatively small if $y_{i1} \approx \theta y_{i2}$. The bias of the ratio estimator can be significant, particularly for small sample sizes or situations in which y_{i1} and y_{i2} are not highly correlated. Tin (1965) discussed methods to reduce the bias of the ratio estimator.

A useful application of a ratio estimator is in estimating domain means. A domain in this context refers to a classification variable such that the category to which an individual belongs is unknown until the data are collected. In a domain mean, the numerator is the total of the characteristic of interest for a particular category and the denominator is the total number of elements in the category. In estimating domain means, the totals in the numerator and denominator are replaced by the corresponding HT estimators. Examples of domains of interest for fisheries statistics include species, gear category and disposition of catch.

To reinforce this concept we revisit the example of estimating catch per unit effort, which can be expressed as a ratio of total catch to total effort. In this case $\hat{\theta} = \hat{T}_{y,2}^{-1}\hat{T}_{y,1}$ where $\hat{T}_{y,2}^{-1}$ is the HT estimator of total effort and $\hat{T}_{y,1}$ is the HT estimator of total catch. The variance of $\hat{\theta}$ can hence be calculated as $\hat{V}(\hat{\theta}) = \sum_{j=1}^{n}\sum_{i=1}^{n}\pi_{ij}^{-1}(\pi_{ij} - \pi_i\pi_j)\pi_i^{-1}\hat{d}_i\pi_j^{-1}\hat{d}_j$, where $\hat{d}_i = N\hat{T}_{y,2}^{-1}(y_{i1} - \hat{\theta}y_{i2})$.

The variance estimator is different for a situation in which the estimators are obtained from different surveys. Assume the surveys are independent: an estimator of the variance of $\hat{\theta}$ is therefore defined by

$$\hat{V}(\hat{\theta}) = \sum_{k=1}^{K}\left(\frac{\partial\hat{g}}{\partial T_k}\right)^2 \hat{V}(\hat{T}_{y,k})$$

where $\partial\hat{g}/\partial T_k$ is an estimator of $\partial g/\partial T_k$ and $\hat{V}(\hat{T}_{y,k})$ is an estimator of the variance of $\hat{T}_{y,k}$.

To illustrate this, consider estimation of total catch from a complemented survey design in which catch per unit effort is obtained from roving creel survey and total effort is obtained from an aerial survey. Assume the estimators the two surveys are independent. The parameter θ total catch can hence be written as $\theta = T_{y,1}T_{y,2}$ where $T_{y,1}$ is total catch and $T_{y,2}$ is effort. An estimator of θ is given by $\hat{\theta} = \hat{T}_{y,1}\hat{T}_{y,2}$, and by the delta method an estimator of the variance of $\hat{\theta}$ is

$$\hat{V}(\hat{\theta}) = T_{y,1}^2 \hat{V}(\hat{T}_{y,2}) + T_{y,2}^2 \hat{V}(\hat{T}_{y,1})$$

5.2.2. Use of auxiliary information in design-based estimators

An application of nonlinear estimation involves incorporating auxiliary information into the estimator. An auxiliary variable in this context refers to a variable such that the population total is known. Let T_x denote the known population total of the auxiliary variable x_i and assume that x_i is observed at the element level for sampled units. Incorporating auxiliary information in estimation can lead to estimators with smaller variances than HT estimators.

An important way of incorporating auxiliary information into an estimator is through a ratio estimator. A ratio estimator of the population total T_y is

$$\hat{T}_{y,R} = T_x \frac{\hat{T}_{y,HT}}{\hat{T}_{x,HT}}$$

where $\hat{T}_{x,HT}$ is the HT estimator of T_x. The variance of $\hat{T}_{y,R}$ is

$$\hat{V}(\hat{T}_{y,R}) = N^2 \sum_{j=1}^{n} \sum_{i=1}^{n} \pi_{ij}^{-1}(\pi_{ij} - \pi_i \pi_j)\pi_i^{-1}\hat{d}_i \pi_j^{-1}\hat{d}_j$$

where $\hat{d}_i = (y_i - \hat{T}_{x,HT}^{-1}\hat{T}_{y,HT}x_i)$. From the definition of $\hat{d}_i$ we see that the ratio estimator $\hat{T}_{y,R}$ is typically more efficient than the HT estimator $\hat{T}_{y,HT}$ if the relationship between y_i and x_i in the population is approximately a straight line through the origin.

To illustrate the ratio estimator, suppose that the objective is to estimate total bycatch of turtles in a segment of a fishery over a particular time period. The parameter of interest – T_y – is the total number of turtles caught. Suppose the total weight of shrimp harvested – T_x – is known from administrative data and that the total weight of shrimp for trip i is also collected in the survey for each sampled trip. The population total N in this context is the total number of trips. The HT estimator of bycatch is

$$\hat{T}_{y,HT} = \sum_{i=1}^{n} \pi_i^{-1} y_i$$

where y_i is the total number of turtles caught on trip i. The ratio estimator of T_y improves on the HT estimator by incorporating the known total weight of shrimp harvested. The ratio estimator of total bycatch of turtles is defined by

$$\hat{T}_{y,R} = T_x \frac{\hat{T}_{y,HT}}{\hat{T}_{x,HT}}$$

If shrimp harvest and turtle bycatch are approximately proportional, then we expect the variance of $\hat{T}_{y,R}$ to be smaller than the variance of $\hat{T}_{y,HT}$.

A generalization of the ratio estimator is the regression estimator, which provides a mechanism for incorporating more than one auxiliary variable and general weighting scheme (see Lohr, 2010 and Sarndal *et al*., 1992).

5.2.3. Use of model-based estimators

The discussion of estimation procedures in Sections 5.2.1 and 5.2.2 focuses on design-based inferences, in which variability arises from the hypothetical process of drawing several samples from a fixed population. The estimators discussed above are approximately design-unbiased, which means that the average of the estimator over several samples is approximately equal to the population parameter. The variance estimators above estimate the variance of the sampling distribution obtained from drawing repeated samples from the same N elements.

In a model-based approach, estimators are derived in a specified probability model; frequentist and Bayesian methods can be used for inference. Analysts may choose to use a model-based procedure for several reasons:

- Interpretability of parameters. In the design-based approach the parameter is a function of a fixed finite population, and the concepts of "unbiased" and "variability" are relative to a particular sample design. In applications the quantity of interest from a subject-matter perspective often has a more general interpretation that transcends a particular finite population. In such cases, postulating a probability model can facilitate parameter definitions that fit more naturally with subject-matter objectives. In a model-based approach the concepts "unbiased" and "variability" refer to the specified probability model and the data-collection procedure.
- Small area estimation. Small area estimation refers to a class of problems in which estimates are of interest for many domains and design-based

estimators are judged unreliable for the domains of interest. Problems with design-based estimators in this context often arise because sample sizes at the domain level are small. Specifying small area models makes it possible to incorporate auxiliary information and to pool information from several areas to estimate the parameter for a particular domain of interest.

- Accounting for measurement or selection errors. Non-sampling errors such as non-response and recall bias are discussed in Section 4.3. Given appropriate data external to the basic survey framework, it is sometimes possible to adjust for bias arising from non-sampling errors. These adjustments rely explicitly or implicitly on models that relate biased measurements to the target of interest.

Examples of model-based estimation procedures in fisheries surveys are found in Breidt *et al*. (undated), Volstad *et al*. (2014), Hoenig *et al*. (1997) and Lopez *et al*. (2003).

5.3. Sample size determination and allocation

In the above discussion the target sample size is assumed to be given. In practice the first step in designing the survey is to determine a sample size. A related issue for stratified samples is how to allocate the total sample size across strata. Valliant *et al*. (2013) discussed sample size determination and allocation with a view to practical applications.

Determining an appropriate sample size often requires a balance between practical issues and scientific objectives. Ideally, the desired precision of the estimators should guide the sample size, but in practice the cost of data collection and available budget have to be taken into account.

The variance of an estimator is a function of sample size, which can be based on the precision of estimators of parameters of interest. Measures of precision that may be used in determining a sample size include the coefficients of variation, standard error and confidence interval width. Using the coefficient of variation is useful when the variance increases with the size of the parameter, as is often the case in estimations of totals. Because the selected sample size is the minimum number of units required to achieve a desired level of precision, an anticipated value is required for the variability of the characteristics of interest in the population. If the coefficient of variation is the measure of precision of interest, an anticipated value for the mean or total is also needed: the anticipated values can be obtained from administrative data with variables related to the variables of interest or from previous surveys or censuses.

Bayley and Petrere (1989) evaluate the sample sizes needed to obtain to obtain a 95 percent confidence interval width that is less than 10 percent of the mean. They consider on-site surveys of canoe landings and household surveys (see Figure 2) and conclude that household surveys provided a cost-effective alternative to on-site surveys, noting that non-sampling errors should be borne in mind.

Figure 2. Sampling errors of canoe landings and house surveys of per capita consumption (Bayley and Petrere, 1989)

Method	Sample size	CV	Samples needed for 95 % confidence range within ±10 % of the mean	Source
Canoe landings from large rivers, Peruvian Amazon	30	187 %	1 340	Bayley (1981c)[a]
Canoe landings from intermediate rivers, Peruvian Amazon	30	268 %	2 760	Bayley (1981c)[a]
House survey in R. Palcazu Indian community, Peruvian Amazon	8	33 %	42	IMARPE (1972)[b]
House survey in a riverine communities on R. Paraguay	20	60 %	140	Bayley (1985)[c]
House survey in two lakeside communities L. Gatún, Panamá	22	99 %	380	Bayley (1986)[c]
House survey in two lakeside community, L. Madden, Panamá	11	50 %	96	Bayley (1986)[c]

[a] Statistical unit of catch per day based on the product of catch per unit effort, number of canoes, and proportion of time canoes were fishing; variance of and correlation between the first two components only were available; data supplied by FAO project PER/76/022 used in Chapman's (1981) catch assessment survey.

[b] The 8 samples were taken during different weeks in the year; these were the mean of 5 families surveyed each time.

[c] Randomly selected householders were asked to estimate the whole weight of fish typically consumed (purchased and/or captured from the river or lake concerned) and the number and age distribution of occupants; the statistical unit of whole fresh weight/average person/day calculated as in Bayley (1986).

In surveys of large-scale fishing operations sample size is determined in terms of the "coverage rate", which depends on the objectives and the available funding. With regard to the determination of coverage rate, Zollett *et al.* (2015) recommend: "Consider monitoring coverage levels for fisheries on a case-by-case basis. Consider a formal threat assessment and/or a cost– benefit analysis to determine the levels of monitoring that are needed to achieve the goals and objectives. Consider the needs of industry when setting coverage levels and develop incentives for fishermen to adopt higher levels of observer coverage." NMFS (2004) recommend target coefficients of variation for estimating bycatch. The coverage rate required to achieve reasonable levels of precision for bycatch estimates is typically higher for rare species (Smith *et al.*, 2011). Coverage rates for regulatory and compliance purposes are often high, and may be 100 percent (Smith *et al.*, 2011).

Lopez *et al.* (2003) consider the problem of determining the number of observer trips needed to estimate cetacean bycatch rates off north-western Spain. Using previous survey data and carcass-recovery schemes they estimated that the maximum bycatch rate that would maintain a sustainable cetacean population was 1.4 bycatch events per 1,000 trips. On the assumption that the bycatch events followed a Poisson distribution they estimated that 2,000 observer trips would be required to provide 95 percent confidence that the bycatch rate did not exceed the 1.4 bycatch events per 1,000 trips.

For stratified sample designs the specified sample size must be allocated to the strata. The allocation rule will depend on the objectives of the survey: if estimates for separate strata are needed, equal allocation – the same sample sizes in all strata – is recommended; if estimates for totals aggregated across all strata are of primary interest, the preference is for Neyman allocation (Valliant *et al*., 2013). Applications usually have several objectives, and analysts cannot always anticipate them all before the sample is selected. Compromise allocations such as power allocations (Bankier, 1988) allow flexibility in accommodating several objectives.

6

Overviews of Projects Relevant to Small-Scale Fisheries and Developing Countries

In this section we review some projects related to estimation in the fisheries sectors of developing countries.

Fisheries can be classified into four groups: i) large-scale commercial; ii) small-scale commercial; iii) subsistence; and iv) recreational (Zeller and Pauly, 2016). Large-scale commercial fishing is characterized by gear types that require large motor vessels that may cross national borders. Small-scale commercial fishing is characterized by gear types such as hand-lines and gillnets, and fishing areas within national borders. The term “artisanal” can describe the combination of small-scale commercial and subsistence fisheries: “small-scale” describes the technical aspects of a fishery, whereas “artisanal” suggests “...a simple, individual (self-employed) or family type of enterprise" (Garcia *et al*., 2008). The term “artisanal” makes no reference to size, but it is typically associated with small-scale operations. We exclude recreational fishing from this section because it is likely to be less important for the developing countries of interest in this project.

The applications discussed below focus on the first three categories. Section 6.1 provides examples of ways in which the concepts discussed in Sections 2–5 are applied to studies of small-scale fisheries in Europe. Section 6.2 reviews applications targeting small-scale commercial and subsistence fisheries in developing countries. Section 6.3 considers projects that address large-scale fisheries.

6.1. Assessments of small-scale fisheries in Europe

Guyader *et al*. (2013) analyse small-scale fisheries in the European Union, defined as those using vessels of less than 12 m, which account for 84 percent of the fishing fleets in the European Union; they employ 100,000 people and are important at the local level in socio-economic terms. Guyader *et al*. (2013) establish a set of technical, biological, socio-economic and institutional variables and indicators to characterize and compare small-scale fisheries. The characteristics examined included the number of vessels and their average length, engine power, tonnage and crew size. Gears were classified as "passive" or "mobile"; fishing resources were classified as "sedentary" or "mobile". Effort was measured in terms of number of days at sea per year; measures of value and expenditure included the prices of first sales and fuel costs. Levels of competition with small-scale, large-scale and recreational fisheries were evaluated. An index – 3 = high, 0 = none – was used to measure participation in management decisions at the local, regional and national levels.

Demanèche *et al*. (2013) estimate catch and effort in small-scale fisheries in French Guiana, Guadeloupe, Martinique, Mayotte and Réunion in an on-site survey of fishing trips and a telephone survey. The fishing trips were selected with an unequal probability multi-stage sample where “harbours x days” were selected in the first stage, fishing trips were sampled in the second stage and large fleets were selected with higher probability. The telephone survey collected data on weekly activity and last fishing trip.

Maynou *et al*. (2013) concentrate on the socio-economic characteristics of small-scale fisheries in the Balearic Islands. Data were collected through interviews with captains of artisanal vessels in major fishing harbours. The primary parameters related to costs, revenues and profitability.

6.2. Projects targeting small-scale commercial and subsistence fisheries in developing countries

Volstad *et al*. (2014) describe the methods and results of a probability-based survey to estimate catch and effort in small-scale fisheries in Mozambique. The contact method was an access point survey. The frame was defined by the two-dimensional array consisting of landing sites and days. The landing sites were stratified by size based on the number of registered fishing units. Days were also stratified into months. A multi-stage sample was used. The primary sampling unit was an intersection of a fishing location and a day, and for each selected primary sampling unit a census of the number of active and passive fishing units by gear type was conducted. A random sample of at least two passive units was selected from each primary sampling unit. For each sampled catch, total weight by species and number of fish was recorded. Size composition was obtained for a "limited number of species." Socio-economic and meteorological data were collected. The sample design and estimation procedures were applications of the procedures discussed in Section 5. Because some landing sites in the frame were inaccessible, there was potential for selection bias, but by using auxiliary information for all landing sites, the investigators adjusted weighting to account for the possibility of bias resulting from under-coverage.

Moore *et al*. (2010) report on a pilot project to evaluate the use of interview surveys to measure fishing effort and bycatch, interviewing 6,100 fisherman in seven developing countries. For most of the countries, the frame consisted of the national coastline. The "number of boats" was judged the most appropriate and practical measure of effort. The investigators cited collaboration with social scientists and use of standard survey practices as areas for improvement.

Salas *et al*. (2007) study small-scale coastal fisheries in Latin America and the Caribbean, identifying unifying characteristics of the fisheries and challenges in developing monitoring and management plans; the information was obtained from discussions at the first CoastFish conference and a literature review. The identifying characteristics of the fisheries include use of different types of gear, targeting several species, low capital, high labour, remote landing sites, large numbers of migrant and seasonal workers and lack of fishermen's power. Research had hitherto focused on biological and environmental aspects of the fisheries rather than the socio-economic attributes of the fishermen. Challenges in conducting fisheries assessments included unreliable data, changes in data collection and management programmes, technical and financial limitations and the abundant and highly dispersed nature of small pelagic fish populations. Figure 2 shows the variables collected.

Figure 3: Items covered in fisheries assessments in countries studied in Salas *et al*. (2007)

Summary of some fisheries assessment tools in use in Latin America and the Caribbean as reported by CoastFish participants and from bibliographic information

Tool	Argentina	Barbados	Mexico	Cuba	Venezuela	Colombia	Costa Rica	Brazil	Uruguay	Dominican Republic	Puerto Rico	Ecuador	Nicaragua
Data													
Catch statistics	x	x	x	x	x	x	x	x	x	x	x	x	x
Fishing effort statistics	x	x	x	x	x	x	x	x			x	x	
Size frequency	x		x	x	x	x	x	x		x	x	x	x
Spatial data			x	x	x				x				
Gears			x	x	x	x							
Biological surveys	x		x	x		x	x		x		x	x	
Observer program	x		x										
Sampling at landing	x		x	x	x							x	x
Number of fishers	x		x	x	x	x				x			
Number of permits	x		x	x				x					
Bio-ecological													
Growth	x	x	x	x	x	x	x	x	x	x	x	x	x
Mortality	x	x	x	x	x	x	x	x	x		x	x	x
Recruitment		x	x	x	x	x	x	x	x	x	x		
Larval studies			x	x						x			
Feeding	x		x	x									
Reproduction	x		x	x	x	x	x			x		x	
Trophic models			x			x							
Life history	x			x			x						
Spatial analysis			x	x		x			x	x			
Selectivity			x	x		x	x						
Production models			x	x		x	x				x		
Virtual population analysis	x	x	x	x	x		x	x				x	
GLM			x								x		
Time series				x			x				x		
Yield per recruit	x		x	x	x	x					x		
Stock assessment		x	x	x							x	x	
Oceanography	x		x	x		x				x			
Environmental issues	x		x	x	x								
Parasitology	x		x	x									
Fleet/fishing effort analysis			x	x		x			x				
CPUE trend analysis	x	x	x	x	x		x				x		
Fishing effort standarditation	x		x	x	x						x		
Socio-cultural													
Fishers perception		x	x					x	x				x
Participatory research		x	x	x									x
Institutional arrangements		x	x					x					
Social profile of fishers	x		x										
Migration		x	x										
Traditional knowledge		x						x					
Economic													
Cost/benefit analysis		x	x	x	x					x		x	
Ocuppational structure	x	x	x	x	x	x					x		
Economic assessment	x		x	x	x	x							
Uncertainty				x									
Bioeconomic models		x	x	x	x			x	x				
Market	x		x	x								x	

Kronen *et al*. (2010) consider the socio-economic characteristics of small-scale commercial and subsistence fisheries in Pacific Island countries, examining relationships between socio-economic conditions and the extent to which finfish and invertebrates were exploited. The socio-economic variables were considered at the household, community and national levels, with data collected through a household survey of 63 rural coastal communities in 17 Pacific Island coastal countries and territories. The socio-economic variables considered included household ability to meet living costs, availability of income opportunities and education levels; variables related to fishing included CPUE and catch, broken down by fishery type – subsistence or commercial – and species.

Morzaria-Luna *et al*. (2010) assess the vulnerability of artisanal fisheries in Mexico to climate change. Vulnerability was disaggregated into sensitivity, exposure and adaptive capacity; variables describing the fisheries and the people involved were used to quantify these components. The fisheries variables included type of target species, numbers of fishers, registered boats and fishing permits, and information about fishing infrastructure. The social variables include sex, years of schooling, number of rooms in house, religion and receipt of federal subsidies and health benefits.

Pollock *et al*. (1994) describe a socio-economic household survey by Malvuesto and Meredith (1989) in the Niger river fishery in Niger from April 1984 to December 1985, using a two-stage cluster sample design. The structure of the fishery was such that each household was associated with a landing, and no household was associated with more than one landing. In the first stage, landings were selected from a list of all landing sites; in the second, three households associated with a landing site were selected from each sampled landing site. The variables collected included "...monetary return from the sale of fish, capital investment in fishing, and expenditures for food in weekly markets".

Rendon *et al*. (2013) describe monitoring by on-board observers of bycatch of sea turtles in artisanal fisheries in nine eastern Pacific countries from Mexico to Peru. One objective of the observer programme – "...the largest regional artisanal fisheries conservation programme in Latin America..." – was to monitor the effectiveness of circle hooks on fishing lines in reducing turtle bycatch. The observers were trained to collect data and handle marine sea turtles. Information about vessel characteristics, gear types, identification of caught species and contact with non-target species were recorded in standard forms.

Brogan (2016) discusses monitoring of artisanal tuna fisheries in the western and central Pacific, the value of which was thought to equal the value of industrial tuna catches. The need for quantitative data to support this hypothesis led to the implementation of the monitoring programme in seven countries using log-sheet data and on-site data collected at a random sample of boat landings and beach sites. The use of smartphone and tablets to collect information eliminated the need for data entry and paper records.

6.3. Projects encompassing large-scale fisheries in developing countries

Bayley and Petrere (1989) consider the assessment and management of Amazon fisheries, advocating the collection of data on fish consumption through household surveys, which they argue could predict yields when access point surveys were too costly. They observe that "...interviewing fishermen at the multitude of separate landing points and making total boat counts with any useful level of accuracy is beyond the resources of the countries concerned [Brazil, Colombia and Peru]. Conversely, well-designed household surveys can estimate yields from dispersed fisheries as well as additional information such as effort by gear and man-hours, species composition, and proportion of consumption caught or purchased." They describe attributes of major commercial fisheries such as total catch and effort using government data that had been checked for discrepancies.

The request by the Republic of Georgia for technical assistance from FAO to develop management plans for the fishery and aquaculture sectors led to documents by Khavtasi *et al*. (2010), van Anrooy *et al*. (2006) and Ulman and Divovich (2015) describing the structure of the sectors, primary gear types, primary target species and changes in data-collection approaches in recreational, commercial and subsistence fishing in Georgia's extensive marine and inland water resources. Challenges in collecting nationally consistent data included changes in management structures when Georgia left the Soviet Union and illegal fishing facilitated by Abkhazia. Ulman and Divovich (2015) use models to reconstruct a time series of estimates of landed catch, bycatch and discards over periods before and after Georgia declared independence.

The scientific committee of the Indian Ocean Tuna Commission collects annual reports on tuna fishing and related monitoring and reporting in a standard format in Indonesia (Irianto, 2015), Mozambique (de Sousa, 2012) and Sri Lanka (Hewapathirana *et al*., 2015). These investigators describe the structure of fishing fleets, focusing on longline tuna fishing, provide estimates of catches, bycatch and effort, and explain the use of logbooks, vessel monitoring systems, on-board observers and dockside sampling schemes to collect data.

Irianto *et al*. (2015) was the 2015 edition of Indonesia's annual report to the scientific committee. Indonesian anglers target large pelagic fish such as tuna using long-lines, purse seine nets and hand-lines. Data were collected from logbooks, vessel monitoring, on-board observers and port sampling. The logbook data were mandatory, but the authors noted issues associated with validity and a consequent need for verification; each vessel was required to have a vessel monitoring system before leaving port. Irianto *et al*. (2015) set out the spatial and temporal distribution of observed hooks and commented that the observed sets never extended south of 20ºS. Monthly coverage rates for the port sampling system ranged from 45 percent to 72 percent.

7

Summary of the Review of Fisheries

This literature review is the first step in the development of guidelines for constructing a master sampling frame for the fisheries sector: it covers variables relevant to studies of fisheries, resources for constructing sampling frames, strengths and weaknesses of contact methods and aspects of sample design and estimation that are important in surveys of fisheries. The applications reviewed in Section 6.2 and 6.3 show how these general ideas apply in surveys of fisheries in developing countries. The following reviews three issues arising from our literature review.

The first issue is constructing estimates when data are few or absent. Zeller and Pauly (2016), Ulman and Divovich (2015) and ICES (2015) attempt to reconstruct coherent time series when data collection is inconsistent over time. ICES (2015) discusses the creation of estimates for countries in Europe that hold no data by extrapolating estimates from countries where data are collected. These methods relied on implicit or explicit models with strong assumptions about relationships between parameters for which data were directly measured and parameters for which no data were available.

The second issue concerns non-sampling errors such as selection errors and measurement errors. Examples of selection errors are under-coverage and non-response; under-coverage may occur if, for example, some fishing sites are difficult to reach (Volstad *et al*., 2014). Non-response is documented in household surveys of anglers (Pollock et al., 1994). Common instances of measurement error are recall bias in off-site surveys and intentional misreporting. One approach to reducing non-sampling errors is to use a complemented survey design in which different survey modes are used to collect information on different parameters. Collection of the same item using multiple survey modes, as in Hartill *et al*. (2016b), provides information on the nature of non-sampling errors. There is an extensive literature on non-sampling errors in surveys of recreational anglers (Pollock *et al*., 1994). The issue of under-coverage in a survey to estimate catch and effort in Mozambique is discussed in Vostad *et al*. (2014). To our knowledge measurement errors have not been investigated in the context of a survey of fisheries in a developing country.

The third issue is that complexities can arise when anglers from one country fish in the exclusive economic zone of another country. This is related to the problems of documenting at-sea transactions between different countries. ICES (2015) recommends collaboration between Denmark and the Netherlands to address this issue, and de Graaf *et al*. (2015) suggest handling fishery statistics from a regional rather than a national perspective. Brooke (2012) discusses procedures for monitoring international vessels in United States waters.

8 Aquaculture

Aquaculture is the fastest growing animal food producing sector. It accounted for 52.5 million mt of production in 2008, compared with 32.4 million mt in 2000 (FAO, 2011) and is generally viewed as a positive factor in addressing food insecurity, promoting economic development and reducing poverty (Simard, 2008).

A major goal is to develop aquaculture in a context of sustainable growth and healthy ecosystems (FAO, 2009a and 2010). Sustainable development of aquaculture systems involves issues such as direct effects on environments from nutrient enrichment and changes in community ethnic structures, depletion of natural fish stocks to provide fishmeal and other inputs for aquaculture, and risks to the genetic structure of natural fish populations caused by organisms that have escaped from aquaculture facilities (Fernandes *et al*., 2001; McNeely and Schutyser, 2003; Metian *et al*., 2014). Aquaculture is sometimes conducted in what is called an integrated system (FAO, 2009b; Jana, 1998) in which aquaculture operations are combined with other agricultural systems – fish and rice paddies in Southeast Asia and wastewater-fed aquaculture in Calcutta are examples. It has clear connections with social sectors such as employment, national economies, food security and nutrition, environmental quality, capture fisheries and urban planning.

The literature gives little attention to the collection of data on aquaculture. In 2005, FAO produced a set of recommendations on information in aquaculture, but they were largely concerned with country-level reporting of statistics rather than sampling designs targeting aquaculture. A generally agreed requirement is the addition of aquaculture-specific questions to established agricultural surveys, or possibly the development of a complete sampling frame for aquaculture facilities, which are assumed to be amenable to the frame-survey approach. Information about aquaculture is either assumed to be accurate and collected through agricultural surveys or with a sample of a complete frame of aquaculture facilities: there has been little suggestion that aquaculture may present sampling challenges that require designs other than those that have been successful in sampling livestock and crops. There are various web-pages of material on the topic, notably slides from training courses conducted by the Statistical Institute for Asia and the Pacific (SIAP, 2014; Tsuji, 2015).

8.1. Variables in aquaculture surveys

The most basic variable for surveys of aquaculture facilities is production, which is often defined as weight or volume of produced organisms such as fish or shrimp. Many surveys of aquaculture are modelled on surveys of agricultural sectors such as livestock, in which operators are questioned about a range of economic factors such as cost of inputs, land areas used, processing costs and sale prices. Questions on additional production-related variables such as growth rates, stock densities, survival and health problems are sometimes included in aquaculture surveys.

The species or groups of species being produced are important and are typically recorded as variables of interest rather than as stratification variables. The types of organism nurtured in aquaculture are to some extent related to the type of operation: prawns, for example, require ponds flooded with sea water, and marine finfish are often produced in sea cages or pens. Freshwater fish may be raised in inland ponds, often in cages, or in enclosed tanks or raceways. Species or groups of species are occasionally used to stratify a population in repeated surveys.

Variables connected with environmental and ecological effects of aquaculture do not appear to be routinely collected in most government-sponsored surveys; they are, however, observed and reported in individual studies (Palerud *et al*. 2008). Important variables include water depth, current speeds and directions and water quality variables such as secchi[3] depth, nitrogen, phosphorus, salinity and dissolved oxygen; in some cases ammonia and particulate matter have also been measured (Jansen *et al*., 2016).The structure of benthic communities[4] is characterized by the presence of species and numbers of individuals in sediment samples, which may also provide chemical information such as total organic carbon and nitrogen.

If a survey of aquaculture includes interviews with operators or households (see Section 5.2.3), any socio-economic or demographic variables may be included in data collection; core data items are the number of individuals involved or employed and their sexes, ages, educational attainment and incomes (FAO, 2015). Another set of variables covers finance and difficulties faced in setting up and expanding aquaculture businesses. Because the specific variables relevant to

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[3] An opaque disc, typically white, used to gauge the transparency of water by measuring the depth at which it ceases to be visible from the surface.
[4] Organisms that live in and on the ocean floor such as worms, clams, crabs, lobsters, sponges and microscopic animals.

aquaculture are highly dependent on national political and economic systems, it is difficult to identify variables that are generally applicable.

8.2. Frames for aquaculture surveys

Three primary methods for constructing sampling frames for surveys of aquaculture may be termed: i) direct enumeration of facilities; ii) identification from administrative records; and iii) sub-setting of agricultural surveys.

8.2.1. Direct enumeration of facilities

In some types of aquaculture the locations of facilities are easily identified: large coastal enclosures for finfish culture, for example, are in fixed locations and can be located by aerial monitoring; the regions suitable for them are limited, and a complete sampling frame may be constructed from a single mapping operation – often called a frame survey (FAO, 2002) – augmented in many cases with information from administrative or other records. The Quarterly Aquaculture Survey in the Philippines, for example, takes population units to consist of "aquafarms."

8.2.2. Identification of facilities from administrative records

In some countries aquaculture operations in certain categories must be licenced or registered. In such cases construction of a sampling frame is straightforward. Practical issues involve policies, the centralization or otherwise of government records, archives and electronic storage facilities, and the frequency with which records are updated. As with direct enumeration, this method of frame construction is most amenable to large and static aquaculture operations.

8.2.3. Sub-setting of agricultural surveys or censuses

Sampling aquaculture operations is akin to sampling agricultural operations, and sampling frames can be developed for aquaculture surveys as subsets of agricultural surveys or censuses. In many countries, agricultural surveys use multi-stage sampling with households as observational units, and such "aquaculture households" can become a sampling frame for a separate survey or used to define a stratum in a combined survey. In this approach "households" may be replaced by "business" or some other designator of a unit in the target population.

A variation of this strategy in FAO (2015) involves the use of less frequent censuses to construct sampling frames for more frequent surveys. It focuses on collecting information about individuals engaged in aquaculture who do not own land or facilities or engage in commerce. Such individuals may practise aquaculture part-time or occasionally, usually on a small-scale, and either consume their production or sell or barter it.

If households are used as enumeration sampling units, the strategy may combine frames: if aquaculture holdings – commercial or large facilities – are identified by asking members of sampled households about their involvement in aquaculture management, it is possible to identify aquaculture holdings from which an additional frame can be constructed for future use, as in FAO (2015).

8.3. Sampling designs and contact methods

Many aquaculture production surveys are similar in design to those used in other agricultural sectors. Multi-stage samples are typical, with primary sampling units possibly stratified by geographic area or aquaculture type. Secondary units are often households randomly selected after a complete enumeration within a primary unit or chosen from a systematic scheme. One-stage samples may be used when what is considered a list frame has been constructed from a periodic census. We found no examples of sampling designs using primary sampling in space and/or time.

The surveys studied used several methods for recording information from sampled units. Interviews were common in programmes conducted as part of larger agricultural surveys or aquaculture surveys of large fish farms, for example in Indonesia and the Philippines. Countries that require registration or licensing for aquaculture operations may use mail surveys – Scotland is an example – or web-based surveys, as in Ireland.

8.4. Divisions of aquaculture

Attempts have been made to categorize aquaculture into "types". One is based on the characteristics of the water required – fresh, brackish or marine (FAO 1989), whereas others use categorization based on the degree to which nutrition is provided from external natural sources as opposed to manual sources (Coordinating Working Party on Fishery Statistics [CWP], 2012), or the target species for production, which may be cross-classified with water type (Funge-Smith and Phillips, 2001). It is also possible to categorize aquaculture on the basis of techniques used, which is linked to equipment types and facilities required (Department of Agriculture and Fisheries, Australia, 2013; CWP, 2013). Each approach makes sense in particular contexts, and most seem to be motivated by the need to organize the diversity of locations and techniques of aquaculture or to provide statistical reporting on production and costs. No consideration has been given, as far as we are aware, to groupings of aquaculture based on similarities and differences in sampling methods that might be useful in regular surveys.

8.5. Estimation

The literature lacks discussion of estimation for aquaculture surveys, probably because aquaculture surveys are often seen as components of agricultural surveys. Estimation would then follow from the sampling theories used in standard survey estimation such as estimation of population totals for stratified or multi-stage sampling designs. Palerud *et al*. (2008) wanted to relate environmental measurements to aquaculture production in several areas of the Philippines, one of which used aquatic cages in Lake Taal. The number and water area of the cages were estimated using aerial photography. This suggests that estimation may be done by using an overall estimate of effort multiplied by an estimate of production per unit from a sample of cages, as with estimation of total catch in small-scale fisheries. This possibility, and others that deal with estimation for aquaculture from the viewpoint of fisheries sampling rather than agricultural interviews, have not been developed.

8.6. Issues in aquaculture sampling and estimation

The literature on survey design and analysis for aquaculture reveals various issues to be addressed in the development of master sampling frames that include aquaculture.

8.6.1. Use of agricultural survey methods

A major question is whether the requirements of aquaculture sampling can be met by agricultural production survey methods, particularly multi-stage sampling with households as terminal sampling units used alone or augmented by list frames of major aquaculture facilities. If this type of design is used as the central component of a survey plan, the potential issues will include the accuracy of recalled information, sample size in areas where household participation in aquaculture is rare, and duplicated or fragmented information about large operations from individuals involved in record keeping. The potential benefits of this approach include the fact that survey personnel in many countries are familiar with it, the ease with which demographic questions can be included in interviews and the potential for sharing logistical and financial burdens with other survey programmes.

8.6.2. Incorporation of environmental variables

It is not clear how or even if variables important to the assessment of environmental effects should be incorporated into aquaculture surveys. Most such variables do not lend themselves to the interview format, but many are useful for large aquaculture operations; cooperative monitoring programmes at major facilities could also be considered. An alternative might consist of environmental sampling separate from production surveys in aquaculture, but with coordinated use of list frames for registered operations. Remote sensing might also be used if circumstances permit.

8.6.3. Sampling and estimation based on fisheries approaches

The survey and sampling methods used in catch fisheries have not been evaluated with regard to aquaculture. It might be possible to use the "effort x catch per unit effort" estimation strategy for some types of aquaculture such as operations in coastal areas or those using mobile equipment. The approach might involve some form of intercept sampling, which can be costly, but recall bias by individuals or households could be largely eliminated.

8.6.4. Development of adjustment factors for administrative data

In commercial aquaculture, examination of administrative data such as records of production, sales and exports could be a cost-effective way of obtaining production data. A difficulty, however, is that records are often kept of different quantities such as heads-on or heads-off weight. As an alternative to establishing uniform reporting procedures, which is probably impractical, special studies could be carried out to develop relations among common recording formats to enable the combination of data of different types, possibly with built-in quantification of uncertainty. This makes use of basic ideas in fisheries mensuration such as length-weight regression to allow the conversion of length measurements – which are easily obtained – to weight, which is useful in stock assessment.

8.6.5. Effects of types of aquaculture on survey sampling

Categorizations of aquaculture operations have focused on types of water, equipment and organisms (see Section 8.4), factors that do not reflect sampling requirements such as permanence of equipment; the "Definition of ongrowing units" in CWP (2013) could, however, be used to define such a grouping. If direct sampling of aquaculture is considered, the permanence, density and size of operations will almost certainly affect sampling designs such as list frames of units as opposed to area/time sampling.

8.6.6. Combining information from different surveys

Because aquaculture methods are so diverse and readily integrated into systems such as rice paddies, information about it could be gathered through individual surveys of other sectors as well as surveys targeting aquaculture. This could involve assigning some division of aquaculture to different survey types: an agricultural survey, for example, could become the data-collection tool for aquafarms, and a survey of marine enclosures could cover coastal aquaculture. Whether this would be an effective strategy, or whether information on the same sector of aquaculture drawn from different surveys could be combined in an overall estimation procedure, have yet to be decided. The latter would make it possible, for example, to collect information on small-scale or temporary operations in a household survey and a survey of inland catch fisheries such as a creel survey.

9 Synthesis

The populations considered in this review include large-scale capture fisheries, small-scale commercial fisheries, subsistence fisheries, recreational fisheries and aquaculture. The focus of this paper is not recreational fisheries, but they have been included because there is a large literature on surveys of recreational anglers, and many of the concepts apply more generally. The primary issues arising in surveys of large-scale capture fisheries, small-scale fisheries and aquaculture are summarized below.

Data on landed catch from large-scale capture fisheries is often obtained from administrative sources such as processors. The main issues with regard to sampling of such fisheries are related to estimation of bycatch and discards, which have implications for assessments of the health of ecosystems. On-board observation is known to be the most accurate way to measure bycatch and discard, but matters of compliance and safety complicate the issue.

Small-scale commercial and subsistence fisheries, which are often characterized by passive gear types and small vessels with low engine power, are subsumed in the term "artisanal". The collection of data from artisanal fisheries is challenging because they are often located in remote areas and do not necessarily comply with formal registration procedures or institutional arrangements. Limited research, for example in Volstad *et al*. (2014), suggests that survey methods developed for recreational fishing could be used to assess artisanal fisheries in developing countries. Because financial constraints often limit capacities for on-site surveys in developing countries, household surveys have been recommended to contain costs in spite of the problems associated with recall bias (Bayley and Petrere, 1989).

Aquaculture surveys are usually carried out in conjunction with censuses or agricultural surveys, which are used to identify individuals involved in aquaculture. This is an efficient way to collect demographic data, and costs can be shared. Problems arising with this approach include recall bias and difficulties in collecting information when individuals are only partly involved with aquaculture or are not responsible for record keeping. Limited research suggests that direct contact methods such as those used for fisheries could also be used in surveys of aquaculture (Palerud *et al*., 2008).

Combining information from several sources could address many of these issues. The use of multiple contact methods can balance the strengths and weaknesses of different data collection modalities: data from surveys or censuses have been used in combination with administrative data to create socio-economic indicators for fishing communities. In view of the diversity of aquaculture facilities and the interactions with other sectors of agriculture, aquaculture data could be gathered through surveys of other sectors as well as surveys targeting aquaculture.

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