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Gaps and Methodological Approach: A Critical Analysis of Methods for Surveys of Fisheries and Aquaculture

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Introduction

The ultimate aim of the Global Strategy research project on developing master sampling frames for surveys of fisheries and aquaculture is to prepare guidelines for developing countries to use when conducting surveys of fisheries and aquaculture. The guidelines are intended to provide breadth, discussing a variety of approaches being used in different continents. This breadth is meant to help users apply the broad ideas in the guidelines to the specific situation in their own country. The guidelines will help fisheries statisticians improve and defend data collection approaches. The first part of this research (Global Strategy, 2016, Technical Report (TR) 1) documents the results of a literature search on surveys of fisheries and aquaculture. The next stage involves planning and implementing a pilot project. In this report, the literature search is linked to the pilot project by identifying salient issues and gaps in surveys of fisheries and aquaculture. Also discussed in the report are ways in which various methods for conducting surveys of fisheries and aquaculture deal with different aspects of these challenges.

The analysis in this report is focused on the possible approaches to developing a sampling frame, recognizing that the frame is intrinsically linked to all stages of the survey process. Section 1 provides background information, as it includes an explanation of the role of the frame in the survey process. In section 2, several possible approaches for constructing frames are analysed, offering insights into connections to the overall survey process and the strengths and weaknesses of each approach. Because combining multiple sources can be a valuable way to leverage the strengths of different approaches, section 3 is focused on combining data sources when building a master sampling frame. The analysis discussed in sections 1-3 reveals gaps in existing methodology and a general approach is suggested for addressing some of the gaps. In section 4, four gaps in literature on surveys of fisheries and aquaculture are identified and a general survey approach is proposed. Section 5 concludes with thoughts on how this analysis may guide the pilot projects that will constitute the next stage of this research.

1
The Overall Survey Process

The overall approach to a survey of fisheries or aquaculture (as with any survey) involves several components. In designing a survey, an approach for each component must be selected. The stages of the survey process are classified into five major steps:

1. *Defining objectives*: This includes identifying primary variables of interest along with units of measurement. Defining the target population and population elements is also an important part of defining the objectives.

2. *Selecting the frame*: The frame is the list of sampling units from which the sample is selected. The frame should cover the entire target population and exclude ineligible elements.

3. *Designing the sample*: The sample design is driven partly by the structure of the frame. Available auxiliary information depends on the auxiliary information available in the frame. Multiple stages of selection may be needed if the ultimate population elements are grouped into "clusters" on the frame.

4. *Developing and implementing a data collection protocol*: The choice of the data collection procedure may guide and be limited by the choice of the frame. Different data collection procedures can introduce different sources of measurement errors.

5. *Estimating parameters of interest*: Estimation procedures should be compatible with the sample design. They may also account for nonsampling errors that arise through the data collection procedure, such as selection bias or measurement error, and for imperfections in the sampling frame, such as over-coverage or under-coverage.

The nature of the frame is central to many aspects of the survey process. The objectives may guide the choice of the frame. Subsequently, the choice of the frame has implications on the data collection, sample design and estimation.

The main discussion of approaches for surveys of fisheries and aquaculture is structured around the options for sampling frames. This main body of this discussion is in Section 2 of this document. The implications of each frame type for other stages of the survey process are discussed, and the primary strengths and weaknesses of each type of frame are reviewed briefly.

As a prerequisite, the report begins with a discussion of aspects of the overall survey process that will have a recurring role in the analysis of frames. Sections 1.1 and 1.2 contain discussions on the parameters and target populations, respectively. Section 1.3 covers issues related to sample design and estimation. In Section 1.4, important data collection methods used in surveys of fisheries and aquaculture are reviewed. In Section 1.5, the organization of the remainder of this report is reiterated.

1.1. Parameters of interest

Management and policy pertaining to fisheries and aquaculture are intrinsically linked to the social, environmental, and economic aspects of these sectors. Obtaining a complete picture of the fishery and aquaculture sectors for the purpose to develop effective policy and management plans requires information related to the people engaged in these sectors and data on productivity and the impacts on natural resources. For this report, the general approach of the Global Strategy (2016; TR 1) is followed and objectives for surveys of fisheries and aquaculture are classified into three categories: production-related variables; biological and environmental data and socio-economic variables. A brief description of each category is provided below. For further details, please refer to Global Strategy (2016; TR 1).

Variables related to production may be considered the most fundamental variables for the fishery and aquaculture sectors. Production-related variables for fisheries include harvest (kept catch), discards, bycatch and effort. Classifications of these variables by domains are often useful. For example, catch may be broken down by species or disposition type, and effort may be decomposed into categories defined by dominant gear type or target species. For aquaculture, production is often represented as the weight of produced organisms (fish, shrimp), although volume is used in some cases as well. Measures of aquaculture production include the size of the operation, the type of operation, weight or level of inputs. An important derivative of catch and effort is catch per unit effort (CPUE). Monitoring CPUE over long time periods can indicate changes in stock size. In interpreting CPUE as an indicator of stock size, however, it is important to recall that both catch and effort exhibit a great deal of spatial variability. Therefore, changes in CPUE can be confused with variations in fishing patterns across space. Caution is also needed when comparing CPUE estimates at small levels of geographic or temporal detail.

Biological and environmental variables are related to the composition of stock and the health of the surrounding environment. For fisheries, the variables of length, weight, sex and age are used to estimate the age, sex and size structure of a fish population, which, along with external information on fecundity by age, and natural mortality, are key inputs to stock assessment models. Oceanographic and meteorological variables can provide information on habitat extent, habitat conditions and pollution levels.

Socio-economic variables describe the individuals involved in the fisheries and aquaculture sectors, including fishers, dealers and processors. A basic parameter in this area is the total number of individuals who depend on the sector for their livelihood. More nuanced parameters relate to prices paid, prices received, age, sex, level of education, access to markets, availability of freezers, level of cooperation among fishers, level of coordination between fishers and government agencies and availability of employment opportunities outside the fishery or aquaculture sectors.

As indicated in Section 2, the nature of the objectives has important implications on the choice of a frame. Certain frame structures are better suited for surveys focusing on socio-economic characteristics, while others are more appropriate for studies related to production. A challenge in developing a master sampling frame for government-sponsored national surveys is establishing a framework that can lead to good compromise designs – that is, designs that do not necessarily optimal for one parameter but balance competing objectives.

1.2. Target populations and subpopulations

The terms "fishery" and "aquaculture" are very broad and need to be defined precisely for the purpose of conducting a statistically sound survey. The target population is defined as the collection of eligible population elements. Population elements for a fishery survey are the basic operational units of a fishery – the smallest level of physical entities that conduct fishing. For example, a population element may be a boat, a boat trip or a fisher, depending on the context. For aquaculture, a unit may be an aquaculture facility or "an aquafarm," as in the Quarterly Agricultural Survey in the Philippines. In some cases, defining the population element can be complex. For instance, if a vessel employs multiple gear types, a population element may be defined as the intersection of vessel and gear type (de Graaf *et al*. 2015). Because of the enormous variability in the size and nature of fisheries and aquaculture operations globally, defining classifications can help in identifying target populations and relevant subpopulations.

Zeller & Pauly (2016) classify fisheries into four groups: () large-scale commercial; (b) small-scale commercial; (c) subsistence; and (d) recreational. Recreational fisheries are excluded from the scope of this work because they are judged to have relatively less importance in developing countries of interest in this project. Classifying a fishery as small or large scale is challenging because of the wide variation in the size and nature of fisheries globally (Carvalho, Edwards-Jones & Isidor 2011; Chuenpagdee *et al*. 2006). Nonetheless, it is an important division for reporting purposes, as the Food and Agriculture Organization of the United Nations (FAO) member States have been advised to report production to the organization separately for small- and large-scale subpopulations (Pauly & Charles 2015). A relatively common division is to associate small-scale fisheries with boats of 15 metres or less (Jacquet & Pauly 2008). Gear types can also assist in classifying fisheries. Large-scale commercial fishing is characterized by active gear types that require large, motorized vessels that may traverse country boundaries. In contrast, small-scale commercial fishing is characterized by more passive gear types, such as hand-lines and gillnets, which are used within the country boundaries. (Zeller & Pauly, 2016).

The term "artisanal" is commonly used in the context of studies of small-scale fishing. In contrast to "small-scale", the term "artisanal" has socio-economic origins and suggests "a simple, individual (self-employed) or family type of enterprise" (Garcia *et al*. 2008). While artisanal makes no explicit reference to size, it is typically associated with small-scale operations.

Figure 1: Types of capture fisheries by country. Source: Kaiser (2016). *Notes:* MV, marine vessel; MB, marine boat; MD, marine diver: IB, inland boat; ITS, inland trap shore; Y, yes; N, NO.

Country	MV	MB	MD	IB	ITS
Afghanistan	N	N	N	??	??
Bhutan	N	N	N	N?	Y?
Cambodia	N	N	N	Y?	Y?
Georgia	Y?	Y	N	N	N
Indonesia	T	Y	Y?	N?	Y?
Lao People's Democratic Republic	N	N	N	Y?	Y?
Myanmar	Y?	Y	N?	Y?	Y?
Philippines	Y	Y	Y	Y?	Y
Samoa	Y?	Y	Y	Y?	Y
Sri Lanka	Y?	Y	Y?	Y	Y
Viet Nam	Y	Y	N?	Y?	Y?

Fisheries can also be classified according to type of equipment. Six important categories are marine vessels, marine boats, marine divers, inland boats and inland trap or shore. Figure 1 shows the diversity in capture fisheries globally.

Several populations that may be viewed as important from different perspectives have received relatively less attention from large-scale data collection programmes. In some countries, artisanal fishing communities are nomadic.

Inland fisheries constitute an important sector in many countries, but they receive relatively less attention from data collection programmes than coastal fisheries. In West Africa, subsistence fishing essentially does not exist, as most fishers (even small-scale ones) sell a nontrivial portion of their catch.

Several divisions of aquaculture have potential use for survey design and analysis. One division includes (a) fixed-location aquaculture, (b) variable-location aquaculture and (c) sea-ranching. Fixed and variable location aquaculture may occur in either marine or fresh water environments. Aquaculture facilities can also be classified according to level of permanency of facilities. Species type can also define a natural classification for the aquaculture sector.

Complexities associated with the nature of the populations exist. In some countries, a single individual may practice both aquaculture and fishing. The extent to which fisheries and aquaculture data should be integrated is an open question. Often, a one-to-one relationship does not exist between a vessel or boat and a household.

In the discussion of frames in Section 2, the types of frames that are more or less appropriate for different target populations as defined by different divisions of the fishery and aquaculture sectors are evaluated. For instance, frame structures may differ for large scale, small scale and subsistence fisheries. The division in Figure 1 may also be used to guide the selection of the frame. Different target populations naturally generate different kinds of administrative data. Some target populations are more easily identified through censuses or through geographic information systems than others.

1.3. Sample design and estimation

Global Strategy (2016; TR 1) includes a discussion on sample design issues that are important for surveys of fisheries and aquaculture. Pollock, Jones & Brown (1994) provides more comprehensive information with an introduction to the theory of survey sampling. In this section, the concepts that have particular relevance to the discussion of frames in Section 2 are highlighted. These include stratification, probability proportional to size sampling, clustering and the use of auxiliary information in estimation.

An auxiliary variable in survey sampling refers to a variable that is obtained from a source external to the survey. The sampling frame is an important source of auxiliary information in surveys. Auxiliary variables may be known at the element-level for all elements in the population, or summaries of the auxiliary variables may be known at the population level, namely the population mean. Auxiliary variables can be used in the sample design and estimation to improve the efficiency of estimators. The frame structure determines the auxiliary information that is available for design. The use of categorical and continuous auxiliary variables for improving the efficiency of the sample design is considered.

Classification variables available on the frame can be used for stratification. If the stratification variable explains variability in the response variable of interest (i.e., if the within-stratum variance is much smaller than the variability in the whole population), then estimators of overall population means or totals based on a stratified sample are more efficient than estimators based on a simple random sample of the same size. Depending on the information available at the time of sample selection, potentially useful stratification variables for surveys of fisheries or aquaculture include target species, geographic region, gear type, or time or season.

It is important to distinguish a stratification variable from a domain variable. A stratification variable is known for all population elements, in advance of the survey. A domain variable, in contrast, is a classification variable collected during the survey. Potential domain variables are type of species caught, disposition of catch (i.e., export, market, commercial processing, barter or trade, direct consumption, bait), or the education level of the fisher. Gear type may also be a domain variable, for example, on vessels that can use more than one type of gear.

A second common type of auxiliary variable used in survey design is an auxiliary variable that is believed to be related to the size of the response variable of interest. (Of course, a continuous variable can be subdivided into categories to define strata, but that is not the topic here.) Selecting larger population elements with relatively high probabilities can improve the efficiency of estimators of totals. Sample designs that select elements with probobability proportional to a size measure are called probability proportional to size samples. Examples of possible size measures for surveys of aquaculture and fisheries, respectively, are the number of employees of an aquaculture facility or an indicator of fishing effort.

Auxiliary information can be used at the estimation stage to improve the efficiency of estimators or to account for nonsampling errors, such as selection bias or measurement errors. A classic example of this is poststratification, in which weights of sampled elements are adjusted to known population totals for groups that were not used as design strata. Weighting adjustments, such as poststratification, can reduce selection bias arising from factors, such as under-coverage or nonresponse.

In many frame structures, population elements are grouped into clusters. Rather than sample a population element directly, the primary sampling unit is a group of population elements. The population element is then sampled in secondary or tertiary stages. One common example of this form of multistage sampling occurs when the primary sampling unit is a landing site and the population element is a boat trip, nested within landing sites.

Section 2 contains a discussion on how the choice of the frame relates to the sample design in terms of the available auxiliary information and the possible need for clustering. For certain frame structures, the designer may have modest control over the auxiliary information available. For others, the auxiliary information is determined by the process that generates the sampling frame.

1.4. Data collection methods

A wide variety of data collection methods have been used in surveys of fisheries and, to a lesser extent, in surveys of aquaculture. The data collection method is closely tied to the choice of the frame. It also has implications for the types of nonsampling errors that are likely to arise. In this section, several data collection methods for surveys of fisheries and aquaculture are reviewed along with issues associated with the choice of measurement units. See Global Strategy (2016, TR 1) for further details.

1.4.1. Data collection methods for household surveys

First, we first consider data collection methods where the population element is contacted at locations other than the fishing site. We focus on household survey methods because the population element is often contacted at his or her household in off-site surveys. Household survey methods are often less expensive to implement than on-site data collection. A common concern in household surveys is that measures of production-related variables may be inaccurate because of recall bias or because the individual contacted does not have primary responsibilities for record-keeping. Non-response can also be a problem in household surveys, and positive correlations between response probabilities and fishing avidity have been documented, which can lead to "avidity" bias in estimators of parameters related to avidity if ignored in estimation.

Four data collection methods for household surveys, listed in ascending order by reliability, are email, mail, telephone, and in-person interviews. Email is typically the least reliable and has been associated with low response rates and high under-coverage. Avidity bias in mail and telephone surveys has been documented to occur. In-person interviews are typically the most reliable of the household survey approaches listed here; however, the reliability of the data can depend on the choice of the enumerator.

1.4.2. Data collection methods for on-site surveys

We list several common data collection methods for on-site surveys. These methods pertain primarily to surveys of fisheries, although limited research (Palerud *et al.* 2008) suggests that they have potential applicability in surveys on aquaculture as well. On-site methods are typically more accurate than household surveys for measuring production-related variables. On the other hand, on-site methods can be more expensive. The material below is repeated from Global Strategy (2016, TR 1) to ensure internal consistency of this report.

- On-board observers – On-board observation is conducted by trained personnel placed on vessels as they are sent out on fishing trips. Traditionally, on-board observers have been used for the collection of data on bycatch and discard in commercial marine fisheries of industrialized countries (Zollett *et al*. 2015; Brooke, 2012). Total catch and effort variables can sometimes also be recorded by on-board observers, or observers may collect biological data, but these are generally considered secondary to discard variables.

- Dockside monitors – Dockside monitors are used in access point surveys, in which the fisher is intercepted at a landing site immediately after completion of the fishing trip. Primary variables collected in an access point survey are harvest and effort. Discards, needed for total catch, can also be obtained. Limited economic data or information on fisher attitudes can be obtained as a secondary objective during an access point survey. First sale price can also be collected at landing sites (de Graaf *et al*. 2015). Access point surveys are well-suited in situations in which the fishers in the target population use public docks or piers. Designing an access point survey requires a defined enumeration of access points for known waterbodies of interest.

- Aerial surveys In an aerial survey, an airplane flies over randomly selected segments of a fishery's area, and observers make instantaneous counts of fishers or boats within the selected segments. Effort is the only variable collected through an aerial survey. Aerial surveys are optimal for collecting data for large numbers of fishers over large areas. They can provide an independent measure of effort that is subject to no recall bias. Aerial surveys can be useful for identifying and measuring fishing intensity for times or areas. The results of aerial surveys can provide useful information for constructing sampling frames or sample designs for subsequent surveys. Visibility bias can be an important source of measurement error when constructing estimates from aerial surveys.

- Roving creel surveys – In a roving creel survey, the creel clerk contacts fishers during the fishing trip by boat or by foot. Catch rate is the primary variable collected during a roving creel survey. Effort (required for total catch) is also obtained. As for access point surveys, limited socio-economic data can be obtained during interviews with fishers, but a more common approach is to collect limited contact information for use in a follow-up survey. Roving creel surveys are recommended if fishing is dispersed or if the number of access points is too large to accommodate an access point survey. Fishers with longer fishing trips have higher probabilities of selection. An assumption of a constant catch rate over the time of the fishing trip underlies many estimators. Robson (1961), Hoenig *et al*. (1997), and Hoenig *et al.* (1993) discuss estimation procedures for roving creel surveys.

- Electronic monitors – Increasingly, electronic monitoring is being used for on-site data collection. Videos may be located at the dock or on boats. It has been advocated to avert some of the costs and complexities associated with onboard observers. Dinsdale, Catarino & Needle (2013) compare costs of onboard observers in Scotland to costs of using remote electronic monitors, which have high set-up costs in the first year but the per haul costs are lower as compared with using observers. They explain that while remote electronic monitors may have lower costs, observers can collect more detailed information on age, sex, and maturity. Osmund *et al*. (2016) describe a project, piloted in the Gulf of California, Mexico and Indonesia, which is intended to develop cost-effective electronic monitoring systems for small-scale fisheries.

- Electronic logsheets – Brogan (2016) discusses monitoring of artisanal tuna fisheries in Western and Central Pacific. The value of artisanal tuna fishing in this region is thought to equal the value of industrial tuna catch. The need for quantitative data to support this supposition motivated the initiation of a monitoring programme in seven Pacific countries. The programme entailed using log sheet data and on-site data collected at a random sample of boat landings and beach sites. Use of electronic data collection through smartphone or tablet applications have been successful in eliminating the need for data entry and transferring paper to and from remote Islands.

As for in-person interviews, the reliability of the data collected from on-site methods depends on the choice of the enumerator. As a consequence, it is important to consider the choice of the enumerator as part of the operational plan when developing an on-site data collection programme. Similarly, training enumerators is important for obtaining data of an acceptable quality. For instance, if randomly selecting fishers from a boat is part of the operational plan, then data collectors should be trained in implementing the selection randomly rather than in a haphazard manner.

1.4.3. Data collected from administrative sources

When using administrative data, it is tempting to use information that is collected directly from the administrative source. However, it is important to recall that such data are self-reported. As a consequence, administrative data can be contaminated with errors because of intentional or accidental misreporting. These problems can be avoided by using trained data collectors who have objective viewpoints.

1.4.4. Measurement units for effort and catch

A wide range of measures for effort and catch exist. The choice of measurement units has implications for the definitions of the population elements. This subsequently affects the choice of the sampling frame.

Examples of metrics for effort are number of trips, number of hooks, number of fishers, active fishing hours, trap or soak hours and number of active boats. Measuring effort in terms of number of trips may be appropriate for marine vessels, boats or divers. Use of the number of hooks or sets may be best suited for marine divers or marine boats using longlines. Number of fishers, active fishing hours, or trap or soak hours may be used in combination with inland trap or shore. Active fishing or soak hours may be relevant measures for marine divers or marine boats, respectively. Number of active boats may be obtained from an aerial observation of marine boats. There is a trade-off in defining effort with quantities that are more mechanistically connected to the process of catching fish, such as number of hooks in a longline, soak time or traps, versus quantities that can be collected in a more consistent manner over time, such as number of trips and number of active boats. In the former case, it should be noted that the relation between effort and catch is expected to be more precise at a disaggregated level (i.e., at the observation level). However, such variables are typically difficult to measure and to obtain samples of that are representative of a larger population. Variables that are farther removed from the mechanism of fish capture, such as number of trips, are expected to have greater variability in their relation to the actual catch, but are easier to measure and parameters such as totals or means across aggregations of units can be more consistently estimated over time. An interpretable and useful measure of effort would be an index that can be consistently estimated over time. (Kaiser 2016)

Catch may be measured as weights or as numbers. Weights may be most appropriately used for marine vessels or aquaculture. Examples of variables that may be reasonably measured as weights include catch of shellfish, hauls from trawlers or processed catch. Variables that may be more sensibly measured as numbers include large ocean pelagics, demersal fish and reef fish. The operational units listed in Table 1 can support measurements of catch in terms of the number of fish caught (Kaiser 2016).

1.5. Outline of the present report

The analysis for this report focuses on possible approaches for developing a sampling frame, recognizing that the frame is intrinsically linked to all stages of the survey process. Section 2 contains an analysis of several possible approaches for constructing frames, with comments on connections to the overall survey process and the strengths and weaknesses of each approach. Because combining multiple sources can be a valuable way to leverage the strengths of different approaches, the discussion in Section 3 focuses on combining data sources when building a master sampling frame. The analysis contained in Sections 1-3 reveals gaps in existing methodology and suggests a general approach with potential to address some of the gaps. In Section 4, four gaps in literature on surveys of fisheries and aquaculture are identified and a general survey approach is proposed. Section 5 includes concluding comments, with thoughts on how this analysis may guide the pilot projects that will comprise the next stage of research. A summary is given in Section 6.

2

Analysis of Approaches to Frame Construction for Surveys of Fisheries and Aquaculture

Several approaches to constructing frames for surveys of fisheries and aquaculture are discussed. The principal issues associated with each approach are discussed, while noting conditions under which the approach is relatively more appropriate and its primary limitations. Also discussed are relations to other aspects of the survey process, including formulation of objectives, defining relevant target populations, sampling, data collection and estimation. Aquaculture and fisheries are discussed together, distinguishing between the two sectors as necessary.

2.1. Direct enumeration of operations

The direct enumeration approach involves conducting a census to obtain basic information on the structure of the industry. This census is often called a "frame survey" in the fisheries literature. To avoid confusion with survey samples, in this report, this approach is referred to as "a direct enumeration" or "a census". The result of such a census is an enumeration of all units operating in the sector along with limited auxiliary information about the units. An example of a unit in a census for fisheries might be a vessel, and auxiliary information about the vessel might include the vessel size, the dominant gears used, or the average number of boat trips per month. For aquaculture, a unit might be an aquaculture facility or "an aquafarm", as in the Quarterly Agricultural Survey in the Philippines.

Stamopolous (2002; Sect. 8) describes the direct enumeration approach in the context of fisheries surveys 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 the fishery census may include the extent of landing sites, times of the day or year when fishing activity occurs, gear types, employment, access to markets, and demographic characteristics (Stamopoulous 2002). The results of a fishery census may indicate a need to exclude homeports that are no longer in operation or to reflect changes to boat or gear classifications. Complete enumerations of fishing activities through censuses may be legally required, possibly for regulatory purposes.

2.1.1. Principal issues: optimal conditions and primary limitations

The census approach is best-suited for industries with relatively large operations that are easy to identify and stable over time. This is particularly important for censuses targeting aquaculture facilities. For example, large coastal marine enclosures for the finfish culture can be located through aerial monitoring and are not easily moved.

Expense is the primary limiting factor associated with the census approach. Because of the high cost associated with conducting a census, intercensal periods can be lengthy and irregular. This can lead to over-coverage or under-coverage of relatively ephemeral or transient units. As a consequence, the census approach is often more practical in situations in which such censuses are required by law.

2.1.2. Relationships to the overall survey process (objectives, design, data collection, estimation)

In cases in which the national statistical agency has control over the census, the designer may have input into the nature of the auxiliary information collected during the census. Collecting appropriate auxiliary information during the census can enhance options that would make the sample designs that use the results of the census as a sampling frame more efficient. For example, if strata related to operation characteristics are desired, then information related to gear type or vessel characteristics should be collected during the census. In this case, a census unit might be defined as the cross-classification of gear type and vessel. However, for a subsequent sample survey, the gear type to be used by a vessel may not be available information at the time of the sample selection, rendering this definition of a unit problematic for a sampling frame. Consequently, it is important to consider the use of the sampling frame when conducting the census, not only the census logistics themselves. In this example, it would seem preferable to define a census unit as a vessel, and consider gear type a variable of observation (or domain variable as previously described in Section 1.3)

The choice of the primary sampling unit for a survey that uses the result of a direct enumeration as the frame is limited to some extent by the definition of the units identified during the census. Defining the units is not always straightforward. For instance, in a fishery, a vessel may have more than one major gear type. In this case, the unit may be defined as the cross-classification of gear type and vessel.

2.1.3. Implications for nonsampling errors

Information obtained in the census may become outdated. Operations go out of business or new operations are established. To mitigate the potential for under-coverage or over-coverage when using the results of the census as a sampling frame, the direct enumeration should be conducted regularly and as frequently as possible. Augmenting the census data with other sources of information, such as administrative data, can improve coverage.

2.2. Administrative records

Lists constructed for nonstatistical purposes, such as management or record-keeping, can be used to construct sampling frames. Examples for fisheries are registrations of boats and vessels, mandatory logbooks or fishing licenses. Examples for aquaculture are aquaculture facility registration or taxes. Processor registration or taxes may be useful for either surveys of fisheries or aquaculture, particularly if measuring value is important. Use of administrative data to construct a sampling frame often involves combining multiple lists to improve the coverage level.

2.2.1. Principal issues: optimal conditions and primary limitations

The most commonly stated reason to use administrative data sources may be that the statistical office does not need to incur the cost of data collection because the data are collected naturally for the purpose of an administrative process. While the direct enumeration method may be the most expensive procedure for constructing a frame, use of administrative data may be the cheapest. The cost savings associated with data collection, however, may be offset by additional work in record linkage or data cleaning. Administrative data are most reliable if the administrative process underlying the data collection is consistent and completely covers the target population. In practice, combining multiple administrative lists is often necessary to obtain complete coverage. This can be accomplished through record linkage or multiple-frame survey designs. Because the lists and associated data elements are maintained for an administrative purpose, rather than a statistical reasons, definitions used by the administrative agency may be misaligned with definitions used by the statistical office. Similarly, identifying variables may be poorly maintained, and a one-to-one correspondence between identifying variables used in the administrative source and identifying variables used by the statistical office may not exist. Related practical issues involve the centralization (or lack thereof) of records from various levels of government, archival and storage media and policies, and the frequency with which official records are updated.

2.2.2. Relationships to the overall survey process (objectives, design, data collection, estimation)

Frames based on administrative lists can be used to address multiple objectives. Administrative data are used in situations in which primary target variables are related to production or commercial value. Administrative lists can support the collection of data on socio-economic characteristics, particularly if the administrative list contains contact information (telephone, email, address) for population elements.

Issues associated with sample design and estimation relate to the availability of auxiliary information and processes necessary to link multiple files. The availability of auxiliary information to use in design or estimation depends on what is collected on the administrative data source. Definitions of units (population elements labeled with identifying variables) may vary between administrative data sources, which can complicate record linkage when combining lists to construct a single sampling frame. If different administrative processes use different measurement units, construction of conversion factors may be a necessary part of the estimation process.

If variables of interest are recorded on the administrative file, such as catch on a logbook, it may be tempting to use the administrative data directly for estimation. However, as mentioned earlier, it is important to recall that administrative data are typically self-reported and can be contaminated with intentional or non-intentional reporting errors. One common example occurring in recreational fisheries surveys is "prestige bias" resulting from intentionally inflating catch on a catch card. Even if administrative data are contaminated with measurement errors, they potentially can provide useful auxiliary information in estimation when used in combination with variables that are accurately measured in the survey.

Administrative data can support household surveys if the administrative file contains contact information, such as telephone numbers, email addresses or street addresses, for the population elements of interest. This can make is possible to use administrative lists as frames for socio-economic studies. Use of administrative lists as frames for household surveys is a relatively common approach for targeting recreational anglers in developed countries. This approach has not been attempted in a developing country, perhaps because the administrative processes necessary to support it are unreliable or nonexistent.

2.2.3. Implications for nonsampling Errors

Coverage is an important potential source of nonsampling error when using administrative data. Administrative data can lead to either over-coverage or under-coverage. For instance, administrative records of fishing equipment can contain equipment not currently in use (over-coverage) or fail to represent fishers with un-registered equipment (under-coverage). Selection bias because of under-coverage is a particular concern if participation in the administrative process is voluntary. In the context of agriculture, Barboza & Harris (2009) provides a good example of how selection bias because of under-coverage can arise when using a single administrative list directly as a sampling frame. Registers typically do not cover small boats with short lifespans.

Potential bias because of measurement error is an important concern when using administrative data directly to construct estimates. Intentional reporting errors resulting from incentives associated with the administrative process can lead to biased estimators. Unintentional reporting errors can make data cleaning a prohibitive task. Further errors can arise through the process of linking multiple administrative files with different identifying variables.

2.3. Agricultural or population surveys or censuses

Frames covering households include lists of telephone numbers, addresses or villages. Important sources of lists of households, which are the focus of this section, are agricultural or population surveys or censuses. If a population or agricultural survey or census collects information on participation in activities related to fishing or aquaculture, then the survey or census data can be used as a frame for a subsequent survey targeting fishing or aquaculture. Agriculture surveys or censuses have traditionally collected information on aquaculture: a traditional approach to sampling aquaculture operations is to sample agricultural operations that contribute to aquaculture production. To improve coverage for fisheries surveys, using a population survey or census is a better approach than using an agricultural survey or census as the basis for the sampling frame.

2.3.1. Principal issues: optimal conditions and primary limitations

Household surveys are most appropriate for situations in which socio-economic characteristics are of primary interest and population and agricultural surveys or censuses are conducted on a relatively routine basis (i.e., annual surveys). Using a household survey of census as a sampling frame for a subsequent survey of fisheries or aquaculture is typically less expensive than using the direct enumeration approach (Section 2.1) or a spatio-temporal frame (Section 2.4). A separate data collection effort is not required to build the frame, as for the direct enumeration approach (Section2.1). Collecting data at the location where fishing takes place, is not needed, as is often the case when using spatio-temporal frames, such as those discussed in Section 2.4.

Obtaining accurate information related to the production of fisheries through household surveys is often documented as being difficult. Recall bias is a widely documented problem. Response rates are often documented to be positively correlated with fishing avidity, which, if not accounted for, can lead to estimates of fishing effort with a positive bias. A one-to-one correspondence probably does not exist between a household and a fishing vessel or aquaculture facility. In some cases, individuals may participate in multiple aspects of fishing or aquaculture. Individuals who participate in fishing or aquaculture activities may have only tangential connections to record-keeping.

Despite the potential for nonsampling errors, obtaining information on production from household surveys is sometimes the best or only feasible approach. Because of the potential for cost-savings, Bayley & Petrere (1989) advocate the use of household surveys for estimating fishing catch and effort in developing countries, despite the measurement issues. The household survey approach may be necessary if a frame survey is too expensive or if nationally consistent administrative processes do not exist.

2.3.2. Relations to other aspects of the survey process (objectives, design, data collection, estimation)

In the process of subsetting agricultural or population surveys, estimation procedures need to take into account the design of the original survey. For estimation and variance estimation, the primary sampling unit for the subsetis the primary sampling unit in the agricultural survey or census. Variance estimators should account for the hierarchical nature of the selection process.

The distinction between multiphase and multistage sampling is important for the analysis of data from surveys that use a previous survey as the sampling frame. The distinguishing feature of a multiphase sample is that variables collected in the first survey determine the design of the second level of data collection. Use of an agricultural or demographic survey to identify individuals active in aquaculture or fisheries is an example of a multiphase approach. Sarndal, Swensson & Wretman (2003) provides estimation procedures for multiphase designs.

2.3.3. Implications for nonsampling errors

Household surveys are often less expensive to conduct than surveys that require data collection at the location where fishing takes place. However, serious measurement errors in estimators of catch or effort tend to be widely documented when production data are collected from household surveys. As discussed in Section 2.3.1, possible sources of measurement error include recall bias and correlations between fishing avidity and the probability of responding. Inaccurate data can also arise if the individual contacted is not directly responsible for record-keeping activities.

2.4. Spatial or spatio-temporal frames

A spatio-temporal frame consists of the cross-classification of subsets of geographic regions and time points. A primary sampling unit in a spatio-temporal frame is an intersection of a spatial location and a time point. A spatial frame is a spatio-temporal frame when the time dimension is ignored. The spatial dimension of a spatio-temporal frame for a fishery survey may be composed of well-defined landing sites or waterbodies. The temporal dimension may be defined by boat trips, hours, days, or months.

2.4.1. Principal issues: optimal conditions and primary limitations

Spatio-temporal frames typically support the on-site data collection methods, such as those described in Section 1.4.2. As a consequence, they are best suited for estimating parameters related to production (i.e., catch or effort), although limited socio-economic data can be obtained as a secondary objective. When the landing site defines the spatial dimension, spatio-temporal frames are most appropriate for target populations with landing sites that are clearly defined and easy to access.

Potential limitations are associated with cost and respondent burden. Because data collection often involves visiting the location, use of spatio-temporal frames can be costly. To reduce respondent burden, maintaining short interviews is advised, which limits the extent of socio-economic data that can be collected. One way to overcome this limitation is to collect contact information during the on-site study and collect more detailed data related to socio-economic variables during a follow-up survey.

2.4.2. Relationships to the overall survey process (objectives, data collection, design and estimation).

The implications for sampling and estimation depend on the specific type of survey. Many surveys that use spatio-temporal frames involve multiple stages of selection. For instance, the first stage may be a landing site on a particular day, the second stage may be a boat trip, and the third stage may be a fisher. In some data collection methods, such as roving creel, the probability of selection is related to fishing effort. Estimation for such surveys requires precaution because estimators that do not account for this unequal selection probabilities can be biased, while estimators that use time spent fishing directly as the selection probability can have large variances because of small values (Robson 1961; Hoenig *et al*. 1997, and Hoenig *et al*. 1993).

Stratification by both geographic and temporal dimensions can be used. Examples of geographic strata are an administrative region or a water body. Examples of temporal strata are months, times of day, or weekdays or weekends.

Typically, the on-site data collection methods, described in Section 1.4.2, are used in combination with spatio-temporal frames. Measures of catch, bycatch, discards and effort are often subject to fewer sources of measurement bias than corresponding measures obtained from off-site methods because the data are collected by a trained data collector with an objective viewpoint. Socio-economic data can be collected on-site or through a follow-up survey.

2.4.3. Implications for nonsampling Errors

Several types of nonsampling errors can arise in surveys based on spatio-temporal frames. Aerial surveys can introduce visibility bias. Under-coverage can occur if data collectors cannot access locations where fishing takes place. Typically, the spatial aspect of spatio-temporal frames can be managed more easily than the temporal aspect. The relation of landings sites, lakes or river access points to the type of catch changes slowly relative to the relation of time with catch type, except perhaps for migratory species. Determination of the population to be sampled must again be considered to ensure that potential nonsampling errors are identified.

3

Combining Sources

The possible sources of frames discussed in Section 2 have different strengths and weaknesses with respect to the various stages of the survey process. Combining multiple sources of information can help take advantage of the strengths of the different data sources. Reasons to combine multiple data sources when constructing a master sampling frame are as follows:

- Improve coverage – The union of multiple lists often has better coverage than a single list. Two ways to combine lists are through multiple-frame survey designs and record linkage. In the multiple frame survey approach, discussed in more detail in Section 3.1, separate samples are drawn from different lists and estimates are combined. Record linkage is the process of combining multiple lists to create a single frame. Record linkage is often complicated by factors, such as errors in identifying variables and inconsistencies across lists. Because of these issues, record linkage is a vast topic. Rather than discuss record linkage here, the reader may wish to refer to Berg & Li (2015), Fellegi & Sunter (1969), and Day (1995).

- Understand measurement error properties – As discussed in Section 2, different frame types are typically associated with different data collection methods. As a consequence, the choice of the frame has an impact on the types of nonsampling errors that are more or less likely to arise in the survey. Collecting the same target variable (i.e., catch or price received) with more than one data collection method can inform on potential biases due to measurement errors.

- Address diverse objectives – Section 2 shows that different frames and their associated data collection methods are better suited to different objectives. For example, some frames are more appropriate for estimating catch, while others are better for estimating socio-economic characteristics. Similarly, certain frame structures are amenable to target populations with large, stable operations, while others can target small or transient population elements.

- Improve efficiency of estimators with auxiliary information – Combining multiple data sources is also useful at the estimation stage.

Information in a list that could contribute to a sampling frame can be used as auxiliary information in estimation, even if the list was not used as the sampling frame. Examples include imputation and the types of model based procedures that are commonly used to construct estimates for domains with small sample sizes (small area estimation; Rao 2003).

3.1. Multiple frame surveys

The main reason to conduct a multiple-frame survey is to improve coverage. Multiple frame surveys are appropriate for situations in which the union of multiple lists covers the entire target population and no single list is considered adequate. The main idea of a multiple frame survey is to select separate samples from each list and then combine the estimators at the estimation stage.

A central component to multiple frame estimation involves constructing estimators for the sub-domain of the population consisting of elements that are contained in both frames. To explain the idea, consider estimation of a total, t, using dual frame survey, and denote the two frames by frame A and frame B. At the time of the survey, membership in the two frames is recorded for each sampled element. This allows the construction of estimates of three domains: (A) the set of elements in frame A but not frame B, (B) the set of elements in frame B but not frame A, and (AB) the set of elements in the intersection of the two frames. An estimator of the total for the full population is given by

$$\hat{t} = \hat{t}_A + \hat{t}_B + \hat{t}_{AB},$$

where $\hat{t}_k$ is the estimator of the total for domain k, where $k = A, B, AB$. See Lohr (2009) for further discussion of estimation and variance estimation for multiple frame surveys.

One application of the multiple frame approach is to estimation of the under-coverage of an incomplete frame. This approach requires one of the frames to have complete coverage. Capture-recapture methods can then be applied to estimate the under-coverage of an incomplete frame. Multiple frame surveys are relatively common in surveys of agriculture (Global Strategy, 2015; Young *et al.* 2012). Breidt *et al.* (undated) apply this essential idea to estimate the proportion of fishing trips covered by a list frame of telephone numbers.

3.1.1. Linking the Multiple-Frame Approach to the Context of Fisheries/Aquaculture

Consider an administrative list based on vessel registration and a spatio-temporal frame. Suppose the spatio-temporal frame is judged to have essentially complete coverage, while the vessel registration system is thought to be incomplete because registration of vessels is voluntary. Although the administrative list is judged incomplete, the list may have benefits, such as richer auxiliary information than the spatio-temporal frame. To take advantage of the strengths of each type of frame, a dual-frame survey may be conducted to estimate the under-coverage of the administrative list, assuming the spatio-temporal frame has complete coverage.

3.2. Complemented Survey

For this report, we follow Pollock, Jones & Brown (1994) and define a complemented survey that measures different variables using different data collection methods is defined. As discussed in Section 1.4 and in Section 2, different data collection methods are better suited to measuring different variables. For instance, onboard observers can provide more accurate information about by-catch than self-reports, while household surveys can provide a better framework for estimating socio-economic characteristics. Complemented survey designs employ multiple data collection methods to take advantage of the strengths of each approach. They can provide a coherent framework for dealing with diverse objectives. The literature review in Global Strategy (2016, TR 1) indicates that complemented survey designs have been used extensively used in surveys of recreational fishers (Pollock, Jones & Brown 1994). Estimators for complemented survey designs are often nonlinear; standard linear approximations can be used to construct variance estimators (Pollock, Jones & Brown 1994; Global Strategy, 2016, TR 1).

3.2.1. Linking complemented survey designs to the context of fisheries and aquaculture

Many combinations of data collection modes can be used to define complemented survey designs for surveys of fisheries. Table 1 provides two examples of complemented survey designs. The first two columns include a description of the frame, the data collection procedure and the parameters for each component. The third column contains a list of an example of a previous study that uses the particular combination. The second example in Table 1 is relatively common and is called ``an aerial access design''.

Table 1: Examples of complemented survey designs.

Component 1	Component 2	Application
• Frame = telephone list • Parameters = effort • Data collection = telephone interview	• Frame = landing sites x day • Parameters = catch, effort • Data collection = dockside monitors	Marine Recreational Fisheries Statistics Survey conducted by the National Marine Fisheries Service in the United States (Breidt *et a*l. undated)
• Frame = spatio-temporal • Parameters = effort • Data collection = aerial photography	• Frame = landing sites x day • Parameters = catch, harvest	Recreational Angler Survey in the Delaware River (Volstad, Pollock & Richkus 2006)

A third example of a complemented survey design, not described in Table 1, is a structure in which a household survey is used to estimate socio-economic characteristics, while an on-site survey is used to estimate parameters related to production. Pollock, Jones & Brown (1994) discuss the application of this complemented survey design. In this setting, fisher contact information is collected during the on-site survey and then a follow-up survey is conducted to collect more detailed information about socio-economic characteristics This approach has the benefit of reducing respondent burden during on-site data collection.

3.3. Multiple measurements of a single variable

As discussed in Section 1.4 and in Section 2, selection errors and measurement errors are important considerations in surveys of fisheries and aquaculture. Measurement and selection errors can be decomposed into variance and bias. A bias occurs if the error causes the estimators obtained from the survey to differ systematically from the corresponding true parameters, on average. Selection bias can occur, for example, if the population of respondents differ systematically from the overall population with regard to characteristics related to the variables of interest. One documented form of selection bias in surveys of recreational anglers is avidity bias, which occurs when more avid fishers are more likely to respond to surveys about fishing. Measurement bias occurs if the data collection procedure causes the values that are actually recorded to differ systematically from the corresponding target variables. For example, it is often assumed that a self-reported catch can be contaminated with prestige bias, which means that the value that is reported is systematically larger than the true catch.

Obtaining different measurements of the same target variable using different methods can inform on possible biases introduced by the different approaches. A difference in estimated means based on two different approaches that exceed what one could reasonably explain with sampling variability alone suggests the existence of a bias in one or both of the measurement procedures. For instance, a comparison of self-reported estimates of catch to estimates of catch obtained from an objective observer may lend credibility to a hypothesis that prestige bias exists in a self-reported catch.

3.3.1. Linking multiple measurements of a single variable to the context of fisheries and aquaculture

Measuring the same variables with multiple data collection methods can provide information on possible sources of bias resulting from nonsampling errors. This approach has been widely used in designing surveys of recreational anglers. In one such a survey in New Zealand, Hartill, Thomas & Edwards (2015) compare estimates obtained from an off-site panel survey to corresponding estimates from an aerial-access design. Andrews, Brick & Mathiowetz (2014) compare estimates from a list frame based on fishing licenses to estimates based on random digit dialing. Pollock, Jones, & Brown (1994) provides further discussion of this basic idea.

4

Challenges, Methodological Gaps, and Possible Approaches

In the analysis discussed in Sections 1-3, suggestions of areas for further methodological research with the aim to improve surveys of fisheries and aquaculture in developing countries are given. In Section 4.1, issues that appear to be inadequately addressed in existing literature on surveys of fisheries and aquaculture are explained. In Section 4.2, we propose a general approach for possible investigation that may have the potential to address some of these gaps.

4.1. Gaps

Based on the analysis of Sections 1-and the literature search documented in Global Strategy (2016; TR 1), we have identified four major gaps in existing methods for surveys of fisheries and aquaculture. The first two gaps pertain broadly to surveys of recreational anglers in developing countries and to the target populations of interest for this project (Section 1.2). The second two gaps relate specifically to issues arising in developing countries.

4.1.1. Use of models for data integration and combination

Literature on surveys of recreational anglers in developing countries contains an extensive discussion of nonsampling errors. Different types of frames have been documented to produce different types of selection biases. For instance, frames based on licences can lead to under-coverage if the registration process is voluntary. Different data collection procedures have been documented to produce different types of measurement biases. For instance, estimators of catch based on household surveys are sometimes contaminated with recall bias. As discussed in Section 3.3.1, the literature on biases due to non-sampling errors focuses on ascertaining the nature of the measurement errors by comparing estimates obtained in different ways.

To date, it appears that no work in the fisheries literature has been directed towards constructing a single estimate by combining estimates with different measurement error properties. Models (i.e., Fuller 1987, Chapters 1.2.1, 1.5) provide an avenue for combining related estimates of the same parameter. The approach can be applied at the level of a single measurement of an individual element in the population or at the level of an aggregated estimate. The approach can be used to address selection bias and measurement bias, although the terminology of the discussion focuses on measurement errors.

The model-based approach to combining multiple sources of information requires assumptions about relationships between estimators and a certain amount of replication. Perhaps, the most important assumption is that one of the estimators is an unbiased measure of the target variable of interest. In the context of a fisheries survey, a reasonable assumption may be that an estimator of catch obtained from dockside monitors is unbiased. Parameters in the latent variable model represent the biases of the other measurement procedures.

One motivation for this approach is that unbiased measurement procedures are often too expensive to support sample sizes large enough to produce estimators with adequate reliability. Less expensive measurement procedures support larger sample sizes for the same cost but may lead to biased results. The aim of incorporating the data from the biased measurement procedures through a model-based approach is to obtain an approximately unbiased estimator that has a smaller variance than an estimator based only on the unbiased data collection procedure.

This approach has been investigated for agricultural and land use surveys in the United States of America. Kim, Zhu, & Yang (2013) apply a structural measurement error model to combine survey estimators that are assumed unbiased with biased estimators based on administrative and remotely sensed data. Yu & Legg (2010) use model-based procedures to combine a new method for estimating urban area with a historical procedure. The United States Department of Agriculture National Agricultural Statistics Service has explored the use of such methods to combine estimates based on farmer interview surveys with estimates based on physical measurements of plant growth for the purpose of forecasting crop yields. Keller & Olkin (2002) accomplish this by using a frequentist framework, while Wang *et al.* (2013) incorporates covariates and uses a Bayesian approach.

In Section 4.2, have proposed that the approach of using latent variable models to combine estimators of fishery or aquaculture parameters based on different data collection procedures be considered. This proposal is motivated in part by the observation of Bayley and Petrere (1989) that developing countries cannot always afford to conduct on-site surveys with large enough sample sizes to support reliable estimators. Rather than "give up" and use a household survey exclusively, as suggested by Bayley & Petrere (1989), the authors propose to combine estimates from a small on-site survey with estimates from a larger household survey with the aim to obtain unbiased estimators with adequate reliability through an affordable means.

The potential for using models to synthesize multiple sources of information extends beyond the context of multiple measurements of related variables. Models can potentially be used to integrate data with different temporal resolutions and to account for bias in dynamic models of catch. Estimates of trend over temporal or spatial domains can also benefit from the expanded use of models.

4.1.2. Sample designs and estimation procedures that address change over time

An ultimate objective of surveys that monitor fisheries and aquaculture is to develop sustainable management plans. Estimating time series of fishery parameters and change over time are clearly important for this purpose. Zeller & Pauly (2016) and Ulman & Divovich (2015) reconstruct time series for fishery parameters using data from disparate surveys.

Despite the value of estimating change, the literature on design and estimation for surveys of fisheries and aquaculture for the most part fail to make explicit reference to the temporal component. In particular, no literature reviewed as part of this project indicates that explicit efforts have been made to design a survey around the objective of estimating change over time. Designing national survey programmes with estimation of change over time in mind removes the need to make corrections at the estimation stage for changes in survey design and procedures, as encountered by Zeller & Pauly (2016) and Ulman & Divovich (2015).

The selection of the sampling frame has implications for estimating change over time. In theory, maintaining a unified master sampling frame supports surveys with consistent methodologies over time. This, in turn, makes the estimators more coherent over time and ensures that estimates of change are not confused with changes in methodology.

The National Resources Inventory (supported by the United States Department of Agriculture Natural Resources Conservation Service) illustrates a situation in which the choice of the frame and the design of the survey are guided by the objective to estimate change over time. The National Resources Inventory is a longitudinal survey for monitoring changes in land cover and land use over time, emphasizing characteristics related to natural resources and agriculture. It uses an area frame in which primary sampling units are permanently-defined areas of land called segments. This type of frame is well suited for estimating changes in natural resource characteristics because the sampling units remain fixed while the activity taking place within the sampling units can change over time. The Natural Resources Inventory survey design is a complemented survey design in which segments in the "core panel" are revisited every year while segments in "rotation panels" are sampled less frequently. The objective of this design is to obtain efficient estimators of change in a cost-effective manner. Observing all segments every year would be too expensive. In the supplemented panel design, the core panel improves the efficiency of estimators of change over time, while adding the rotation segments improves estimators of level for each year. See Nusser & Goebel (1997) and Breidt & Fuller (1999) for further discussion on the relations between the Natural Resources Inventory design and estimation of change over time.

4.1.3. Evaluation of measurement errors in a developing country context

As discussed in Section 3.3 and Section 4.1.1, the research on measurement issues is fairly extensive in surveys of recreational anglers in developed countries. However, it appears that little research on evaluating measurement properties of different data collection procedures exists with regard to developing countries. Brogan (2016) discusses the value of electronic logbooks for reducing the burden on data collectors, and Osmund *et al*. (2016) discusses a programme to develop efficient electronic monitoring systems for small-scale fisheries. These studies, however, do not conduct a formal comparison of different approaches. Volstad *et al.* (2014) discuss under-coverage but not measurement error. A formal evaluation of measurement errors, similar to the studies of recreational anglers noted in Section 3.3, would be a welcome addition to the body of literature on fisheries and aquaculture in developing countries.

A further innovation in this area may involve applying different data collection techniques to the same sampled elements. In the studies described in Section 3.3, different data collection procedures are applied to separate samples. As a consequence, any biases associated with the different frames are confused with biases in the measurement method. One way to address this is to collect data in two different ways from the same sampled elements. Specifically, one can consider collecting catch in an objective fashion from a dockside monitor and collecting self-reported catch for the same fishers through a follow-up household survey. Of course, this introduces issues associated with respondent burden and possible bias because the fisher knows that his or her catch was recorded objectively. Nonetheless, the possibility of applying the approach in the framework proposed is discussed in Section 4.2.

4.1.4. Methodology to for neglected populations – inland and nomadic fishers

The fishery and aquaculture sectors are composed of multiple, diverse populations. Marine and recreational fisheries have received attention by government institutions and scientific researchers. Inland and nomadic fishers are two important populations that have been neglected in previous studies. Challenges associated with inland and nomadic fisheries include their geographically dispersed nature, lack of connections to government institutions, loose connections to formal markets and transient landing sites. Because of these challenges, the applicability of methodology vetted for industrial or recreational fisheries in developed countries to inland or nomadic fisheries is largely unknown. Scientific principles, such as probability sampling and accounting for nonsampling errors apply to the case of developing countries. However, an application of these concepts in a developing country would need to take into account the specific issues arising in a particular situation. The roving creel survey of the Lake Liambezi Gillnet Fishery in Namibia represents one effort to apply methodology traditionally used to sample from certain types of recreational fisheries to an inland fishery in a developing country (Simasiku *et al.* 2017). Further research in this direction is merited.

4.2. Possible framework for investigation

We propose a general approach for possible investigation that takes advantage of the different strengths and weaknesses of the frame sources discussed in Section 2. The approach consists of two main components: an on-site survey and a household survey. The objective of the on-site survey, discussed in Section 4.2.1, is to estimate production-related parameters, while the household survey, discussed in Section 4.2.2, is directed primarily at estimating socio-economic variables. Section 4.1.3 contains a discussion on issues and possible approaches for estimation. One of the motivations for this approach is that use of a large household survey in combination with a smaller on-site survey may be less costly than implementing a large-scale on-site survey. Cost is an important consideration, particularly in developing countries.

4.2.1. On-site study

The main objective of the on-site study is to collect production-related variables at the fishing site. Care should be taken to construct a frame with complete coverage of the target population. This would likely involve partial use of a direct enumeration approach in combination with an analysis of geographic information to construct a spatio-temporal sampling frame. During the on-site survey, an objective data collector would collect information related to production, such as catch, bycatch, and effort. Simultaneously, the data collector would obtain contact information for a follow-up survey.

The follow-up survey would focus on socio-economic variables. It may also include queries about production-related variables with the aim to evaluate systematic differences between measures of catch obtained from data collectors and self-reported catch.

The on-site study is likely to be the most expensive component of the survey. This may limit the possible sample size. Augmenting the on-site study, the household survey aims to obtain estimators with adequate reliability while maintaining a small sample size for the on-site component.

4.2.2. Household Survey

The main objectives of the household survey are to collect socio-economic variables and provide auxiliary information for estimating variables related to production. The frame for the household survey may be based on a prior agricultural or population survey, or census or administrative data, depending on the context. Collected data will include production-related variables and socio-economic variables. Presumably, the household survey is less expensive to design and implement than the on-site survey, so the household survey is assumed to have a large sample size.

4.2.3. Estimation

We propose that production-related variables be estimated using the latent variable models described in Section 4.1.1. The critical assumption underlying this approach is that the production-related variables from the on-site survey are unbiased. The household survey data should be incorporated as auxiliary information to reduce the variance of the estimators. Estimation requires some amount of replication, such as estimates over time or across space.

The household survey is the primary resource for estimating socio-economic parameters. Socio-economic parameters can be estimated by applying standard methods for one survey to the household survey data alone, if the list underlying the household survey is judged to have adequate coverage. An alternative approach is to use dual frame methods to incorporate the data from the follow-up to the on-site component.

Additional auxiliary information may be available from sources that are not used directly for the sampling frame. For instance, the frame for the household survey may be based on a population census, while the frame for the on-site component may be based on geographic information. Some administrative data may not have adequate coverage to use as a sampling frame but they contain useful auxiliary information. Such auxiliary information can be incorporated at the estimation stage, even if it is not used as part of the sampling process. Examples of estimation procedures that can make use of this type of auxiliary information include weighting adjustments, imputation and small area estimation. If the auxiliary source contains data related to production, this can be incorporated as a third source in the latent variable models used for estimating production.

5

Thoughts on Possible Pilot Projects

The discussion in Sections 1-4 makes clear that vast issues surround surveys of fisheries and aquaculture. A pilot project that aims to address the full extent of these complexities is far beyond the scope of this Global Strategy research project. For instance, piloting all of the approaches discussed in Section 2 would take years.

We intend to develop a pilot project that will shed light on one of the salient issues inherent in conducting surveys of fisheries and aquaculture in developing countries. They are focusing on n issues related to the lists that contribute to sampling frames. Ultimately, We are hoping to define a relatively small pilot project that would provide insight into one aspect of the vast complexities associated with surveys of fisheries and aquaculture. Their thoughts on the direction of this project are given below. The next report for this project will entail developing a more detailed protocol.

5.1. Evaluate data sources for a specific country

One option is to define and analyse the data sources available for constructing frames for one specific country. The nature of the work would involve further literature review and possibly communication with officials from the selected country, rather than simulations or data analysis. Nonetheless, some statistical thinking would be required to analyse the strengths and weaknesses of the data sources with respect to constructing a sampling frame.

One resource that might be helpful for devising this approach is Richmond, De Villiers & Mkenda (2003), which describes a project to evaluate the feasibility of using fishery aggregation devises in the United Republic of Tanzania. Richmond, De Villiers & Mkenda (2003) use a framework that involves assessing five types of assets: natural; social; physical; financial; and human. Aspects from this framework may provide guidelines for structuring an analysis of data sources as potential sources for building master sampling frames.

Three countries that may be relatively well-suited to this project are Brazil, Namibia and the United Republic of Tanzania. FAO has existing relationships with representatives from each of these three countries, which could facilitate any necessary communication. In addition, published literature exists describing the structure of fisheries in Namibia (Boyer & Hampton 2001), the United Republic of Tanzania (Richmond, De Villiers & Mkenda 2003), and the Amazon (Bayley & Petrere 1989). The possibility of a future research project related to crab fishing in the Amazon was once discussed, and conducting a pilot project related to Brazil could help facilitate a possible future project. It is also worth noting that the Namibia Statistics Agency provided the data collected on the aquaculture module of the 2013/2014 Namibia Census of Agriculture to Iowa State; these data could potentially be used for this project.

5.2. Explore methodology through a simulation study

One option to consider would be to explore the approach described in Section 4.2 using purely simulated data. In that section, a very general and abstract approach is layed out. One idea would be to explore an aspect of this approach (or a related approach) using purely simulated data. This would involve computational work in simulating data, selecting samples and constructing estimates with selected samples. One avenue for investigation is to try to determine conditions under which the proposed procedure can lead to efficiency gains relative to estimators based only on the on-site component. For instance, what data structures and model assumptions are needed to obtain efficiency gains at different levels of detail? A related issue involves determining the sample sizes for the household and on-site components required to achieve specified levels of precision for the model-based estimators. Other statistical issues for investigation may include sensitivity to model assumptions and estimation with correlated sampling errors.

Another possibility is to use simulation to explore a methodology only tangentially related or unrelated to the approach described in Section 4.2. One option in this direction would be to select one of the gaps identified in Section 4.1 and devise a simulation study that addresses this gap. An alternative would be to select an approach to frame construction that has been used for a developed country and apply it to data generated to represent situations likely to arise in a developing country. In the context of the simulation, the applicability and limitations of the approach for addressing issues that may arise in surveys of fisheries and aquaculture in developing countries could be reviewed.

Using a real data structure as the basis for the simulation may be useful. Projects conducted by MRAG Americas may provide resources for structuring the simulation. First, Richmond, De Villiers & Mkenda (2003) includes the results of a frame survey in the United Republic of Tanzania that was conducted as part of an MRAG project to evaluate the potential for using fisheries aggregation devices in the country. Second, a set documents (MRAG 1999a; MRAG 199b; Halls, Lewins & Jones 2000) describes the results of pilot projects that aim to develop a general database structure for use in developing countries. The database system, which is called the “Fishery Information Management System”, supports data for biological and socio-economic attributes and information related to production. Pilot projects were conducted in Bangladesh and in the Turk and Caicos Islands. Articles describing the structure of fisheries in developing countries, such as Boyer & Hampton (2001), Bayley & Petrere, (1989), and Volstad *et al*. (2014), may also be useful for designing the simulation. The data from the Namibia Statistics Agency mentioned in Section 5.1 may also help in designing a simulation study.

6
Summary and Discussion

In the present report, the approaches to surveys of fisheries and aquaculture are analysed in an effort to bridge the literature review of Global Strategy (2016, TR1) to the pilot project that will constitute the next stage of research. We focus our analysis on the frames, discussing the relationships between the choice of the frame and other aspects of the survey process. Because different data sources have different merits, we discuss options for combining multiple data sources. We identify four gaps in existing methods for surveys of fisheries and aquaculture and propose a general approach with the potential to address some of these issues. In anticipation of the next step of this research, we offer thoughts in the direction of developing a manageable pilot project that will shed light on issues arising in surveys of fisheries and aquaculture.

Challenges associated specifically with estimation for fisheries and aquaculture in developing countries include their geographically dispersed nature, lack of connections to government institutions, and lack of financial resources. For instance, the difficulty in accessing landing sites that leads to the coverage problems in Volstad *et al.* (2014) may be in partly because fishing in developing countries takes place in remote locations. These issues may make procedures developed for either commercial or recreational fisheries in developed countries difficult to apply in developing countries. Bayley & Petrere (1989) observe that sample sizes needed to obtain reliable estimates of production-related variables often exceed allowable budgets in developing countries. As a consequence, they advocate household surveys to estimate production-related variables, despite the potential for nonresponse and measurement error due to factors such as recall bias. The framework proposed in Section 4.2 aims to combine information from household surveys with information from on-site surveys to provide a cost-effective way to obtain reliable estimators of parameters related to production. While efforts directed at these issues exist, the topic is broad and there is room for further thought on how to address challenges specific to developing countries.

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