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REVIEW

Coverage matters: identifying and mitigating sampling frame issues in recreational fishing surveys

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Abstract Surveys play an integral part in monitoring and maintaining sustainable recreational fisheries. For any probabilistic survey, the selection of a sampling frame (e.g., list of individuals or fishers) is an important decision because it influences the ability to provide unbiased estimates of recreational catch and effort. Undercoverage occurs when units of the target population (i.e., the population of interest) are missing from the frame population. This error can undermine the reliability of research advice generated from survey estimates. In this review, we: (i) define six sampling frame configurations that are commonly applied in probabilistic recreational fishing surveys; (ii) synthesise how coverage errors associated with each configuration have been addressed for marine recreational fisheries globally; (iii) outline approaches to identify and correct for coverage errors; and (iv) recommend how to future-proof coverage issues. In our six case studies, multiple types of undercoverage were identified and addressed to varying extents, depending on the characteristics of each fishery and type of sampling frame used. Generalised list frames (particularly phone lists) are arguably the most prone to undercoverage error. To assist in future-proofing surveys, we recommend: (1) considering coverage error during survey planning; (2) designing pilot surveys or scheduling concurrent surveys to evaluate and/or correct for potential bias; (3) recognising that coverage error often changes through time; (4) using technological or multi-frame approaches to mitigate coverage error; (5) considering model-based survey tools to correct for undercoverage; and

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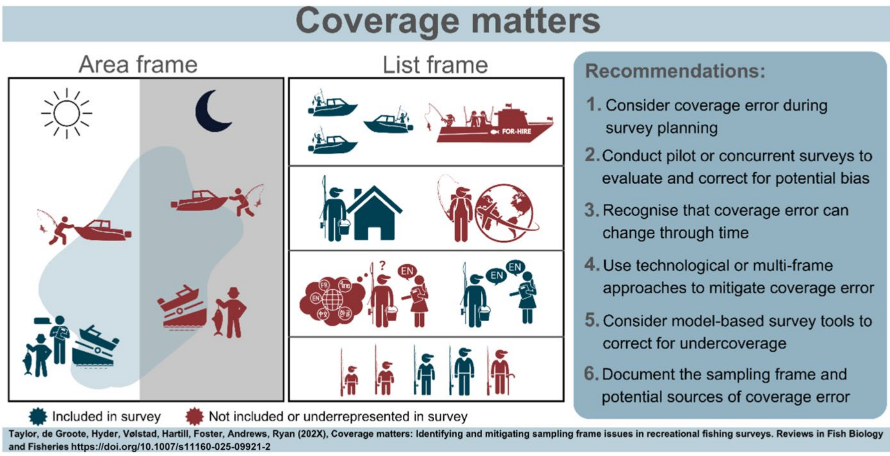
(6) documenting the sampling frame and potential sources of coverage error in publications. These recommendations extend to inland recreational fisheries, commercial fishing surveys and fisheries-independent surveys.

Graphical abstract



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Introduction

It is not possible to count and measure every fish caught in commercial and recreational fisheries. As such, probabilistic surveys (i.e., based on theory of probability) are frequently used to provide estimates of catch and biological information to inform stock assessments and fisheries management (Pollock et al. 1994; Jones and Pollock 2012; Murie et al. 2012). The selection of a sampling frame is a key requirement for any probabilistic survey. A frame may be a list of all units from which a random sample can be drawn (e.g., individuals or fishers) or an equivalent procedure for identifying the population units (Lohr 2010; Kalton 2023). An ideal sampling frame would list each unit only once but this seldom occurs, due to frame imperfections. Coverage error arises when units of the target population (the population of interest, e.g., fishers or boats) are missing from the frame population (undercoverage) or when units in the frame population are not members of the target population (overcoverage). If not accounted for, undercoverage can seriously undermine the quality of estimates generated from a survey (Kalton 2023). Recreational fishing surveys are prone to undercoverage because only a small proportion of the general population may consider themselves to be recreational fishers, and their existence can be exceedingly rare or cryptic. Recreational fisheries can be classified as hard-to-survey populations (Tourangeau et al. 2014) because the average national recreational participation rate is only around 11% (Arlinghaus et al. 2015, 2021).

Coverage error forms part of the total survey error paradigm alongside sampling, measurement and non-response error (Biemer 2010). In recreational fishing surveys, sampling error can be reduced through stratification and selecting an appropriate sample size, as well as the use of auxiliary information in the sampling design and during estimation (Pollock et al. 1994; Jones and Pollock 2012). Measurement error can be minimised using an appropriate survey instrument (Henry and Lyle 2003). Non-response error can be minimised by offering respondents incentives to participate or by implementing weighting strategies to ensure that those who do respond represent the target population (Pollock et al. 1994; Jones and Pollock 2012). However, coverage error, and in particular undercoverage, remains a less tractable source of bias that is often a source of concern about the suitability of the sampling frame that is used to implement a recreational fishery survey (Teixeira et al. 2016; The National Academy of Sciences, Engineering 2017). Coverage error can also be considered in the context of a missing data problem (Little and Rubin 2019). If data are missing-at-random, the generated statistics (e.g., catch, catch rate) will not be biased by undercoverage. However, if undercoverage has the characteristics of missing-not-at-random, bias in the generated statistics will be of greater concern (Little and Rubin 2019).

Sampling frames that provide a basis for recreational fishing surveys typically involve area frames, list frames or combinations of both. Area frames are often based on spatio-temporal frames (area x time), such as a list of fishing access points, including geographic locations and times when fishing occurs. These frames are used for on-site surveys whereby survey staff typically visit a location according to a predetermined, randomised schedule to interview fishers and record their catch (Jones and Pollock 2012; Sande et al. 2022). Complete coverage can be achieved by an on-site survey if all access points in a fishery are known and can be sampled (Jones and Pollock 2012; Georgeson et al. 2015). However, it is often hard to achieve this cost-effectively due to diffuse access to a fishery, private access points or fishing that occurs at night (Diogo and Pereira 2016; Lai et al. 2019).

List frames identify units in a population, including general listings (e.g., telephone directories and dwelling-location databases; Jones and Pollock 2012) or specialised listings (e.g., licence and registration databases; Ashford et al. 2009). List frames are typically used for off-site surveys of large-scale fisheries, whereby households or individuals are randomly selected. For off-site surveys, list frames of the general population can provide widespread but not necessarily complete coverage. However, they can be extremely inefficient for sampling recreational fishers, particularly for low-participation or specialised fisheries or for rarely caught species (Griffiths et al. 2012; Lyle and Tracey 2016; Sbragaglia et al. 2023). Exemptions to licence requirements (i.e., not all fishers require a licence) also create coverage issues when using a specialised list as a sampling frame (The National Academy of Sciences, Engineering 2017). In multi-frame surveys, samples are taken from two or more sampling frames which can provide a more efficient way to sample the target population and a means to reduce coverage error (Lohr and Brick 2014). However, their application in recreational fishing surveys has been limited (Lai and Andrews 2008; The National Academy of Sciences, Engineering 2017).

In this review, we: (i) define current and emerging sampling frame configurations that probabilistic recreational fishing surveys are usually based on; (ii) synthesise how coverage errors associated with each configuration have been addressed for Marine Recreational Fisheries (MRF) worldwide; (iii) outline approaches to identify and correct for coverage errors; and (iv) recommend ways to future-proof coverage issues to generate reliable estimates of recreational catch and fishing effort. Our six case-study examples do not include non-probabilistic methods of data collection (i.e., where research participants are selected non-randomly; Howarth et al. 2024) because these methods have not been widely adopted or tested to generate estimates of catch and effort (Skov et al. 2021; Brick et al. 2022a). The sampling frame configurations defined in (i) are also directly applicable to surveys of inland recreational fisheries (Embke et al. 2022).

To the best of our knowledge, this is the first review of coverage errors in recreational fishing surveys. Our research was motivated by expert input provided through the International Council for the Exploration of the Sea Working Group on Recreational Fishing Surveys (https://www.ices.dk/community/groups/Pages/WGRFS.aspx). This forum recognised the challenges of identifying and addressing coverage issues in surveys as an emerging issue that can potentially undermine the provision of scientific advice on fish stocks (ICES 2023).

Key concepts for sampling frames and sampling frame configurations

We created a component tree to delineate the relationship between the target population, survey population and the various types of sampling frames applied in recreational fishing surveys (Fig. 1). The target population is typically recreational fishers or fishing vessels. The survey population is the collection of all possible units that might have been chosen using a given sampling procedure (Lohr 2010; Kalton 2023). Understanding how the target population can be sampled is critical to understanding the risk of coverage error because those parts of the target population

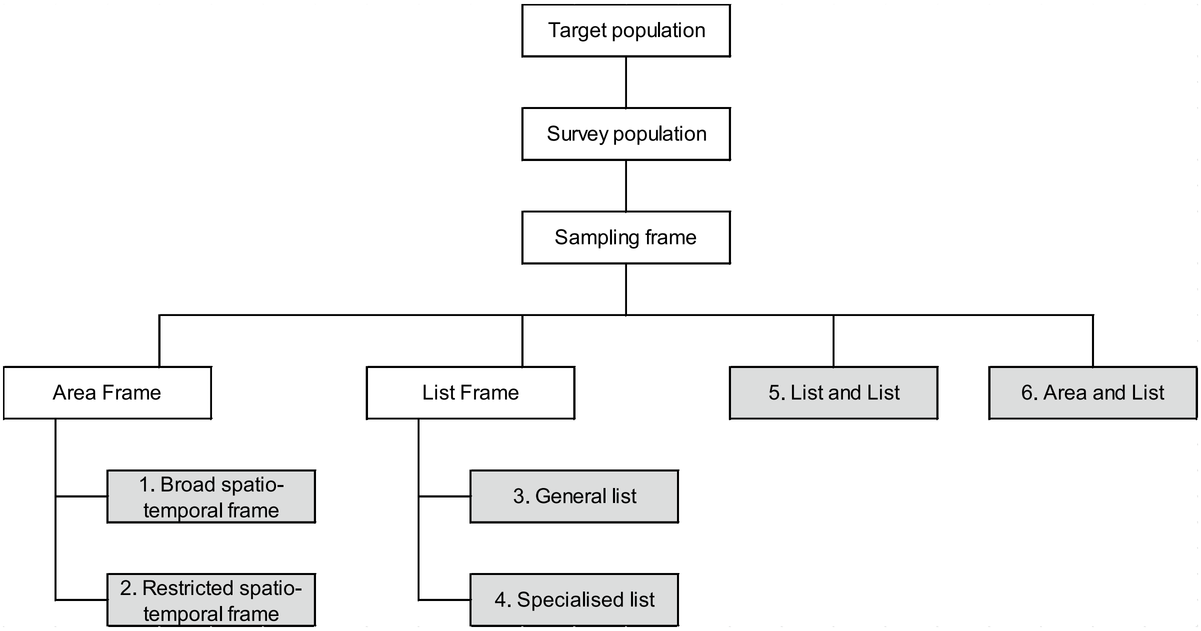

Fig. 1 Sampling frame configurations applied to recreational fishing surveys. Each of the six terminal boxes (shaded in grey) corresponds to a case study in Table 1

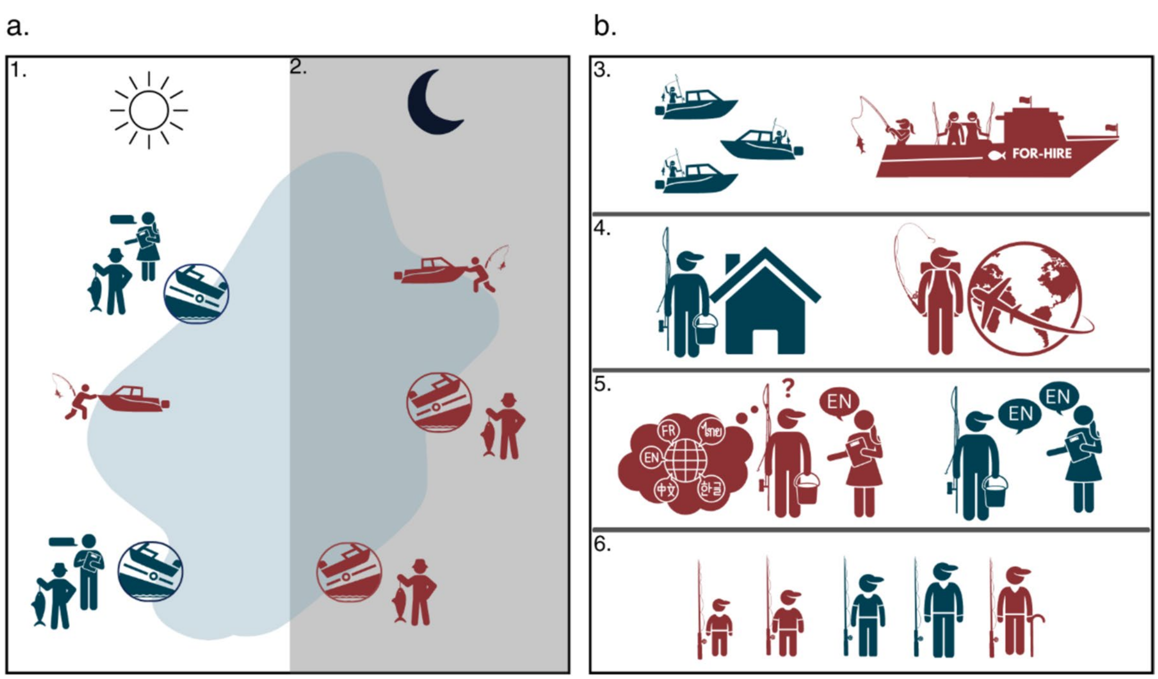

Fig. 2 Six common types of undercoverage in a recreational fishing survey using an area frame (**a**) and a list frame (**b**). Blue denotes activities included in a survey, red denotes undercoverage. 1 = accessing a fishery from a beach when survey staff are not present; 2 = nocturnal fishing when survey staff do not sample at night; 3 = 'for-hire' fishing (also referred to as 'charter' fishing)*;* 4 = tourist fishers; 5 = language barrier, 6 = age-based exemptions (e.g., excluding young and elderly from sample selection). Each of these types of undercoverage is discussed in the case studies, Table 1 and Table 2

included within the sampling frame determine coverage and define the survey population (Fig. 2).

The way in which the target population is accessed depends on the type and quality of the sampling frame. For a recreational fishery that occurs within a small area and/or for a restricted timeframe, an on-site survey based on an area-frame is the most cost-effective frame available. On-site surveys include creel surveys (Pollock et al. 1994; Jones and Pollock 2012) and digital camera or traffic counter surveys (whereby boating activity can be monitored during times when no face-to-face interviewing can occur; Steffe et al. 2008; Hartill et al. 2019). For a widespread recreational fishery with many fishers and multiple access points, an off-site survey based on a list-frame is often more appropriate because of the high cost of implementing an on-site survey across such a scale.

We define six sampling frame configurations (terminal shaded boxes in Fig. 1): area-frame (1. Broad spatio-temporal, 2. Restricted spatio-temporal), list-frame (3. General list, 4. Specialised list) and multi-frame (5. List and List, 6. Area and List) configurations. Configuration 1 includes broad-scale lists of access points and time periods (e.g., extended open season) while the second configuration includes fine-scale lists of access points and restricted time periods (e.g., limited open season). Potential exclusions (also referred to as "out-of-scope") for both of these area-frame configurations include certain access points (e.g., private access points) or times of day (e.g., nocturnal fishing), both of which can lead to undercoverage if not accounted for in the survey design. Configuration 3 includes lists of the general population from which fishers can be identified (e.g., telephone directories, electoral roles) in contrast to Configuration 4 which represents subsets of the general population from which intending fishers are known (e.g., licences or registries). Potential exclusions for Configuration 3 include parts of the general population not included in the list (e.g., unlisted or silent telephone numbers, individuals too young to interview) in contrast to Configuration 4 for which exclusions include exemptions or individuals with incomplete or inaccurate contact information.

The use of digital cameras or traffic counters in an on-site survey (Steffe et al. 2008; Taylor et al. 2021) is considered under the area-frame configurations because a single sampling frame is used for both modes of data collection (i.e., cameras and face-to-face interviews). Multi-frame configurations, defined as having two or more area- and/or list-frames (i.e., Configurations 5 and 6), include situations whereby independent samples were drawn from each frame or when auxiliary information from a separate frame was used to supplement a standalone sampling frame (i.e., samples are not independent). Although other possible configurations can be applied, the six configurations described here are those which are most used or there is evidence of their emerging use.

Broad overview of case studies

We considered and reviewed real-world global case studies corresponding to the various types of sampling frame configurations (Table 1). The selection of case studies was informed by the desire to provide a global synthesis (i.e. wide geographical spread), illustration of recreational catch and effort studies, a variety of ways to address coverage, and studies that have been published. Background material for these case studies was sourced from peer-reviewed literature and technical reports.

The selected case studies focused on recreational fisheries in Norway, Australia, New Zealand, the United States (U.S.) and Sweden. Collectively, these fisheries involve a variety of targeted species, including Western Baltic Cod (*Gadus morhua*), snapper (*Chrysophrys auratus*, *Lutjanus* spp.), dhufish (*Glaucosoma hebraicum*), kahawai (*Arripis trutta*), spiny rock lobster (*Jasus edwardsii*) and pipi (*Paphies australis*).

For each case study, we identified the target population, coverage issue encountered, along with the steps taken to mitigate it, and whether any coverage issues remained (Table 1).

Case study 1: Area frame (broad spatio-temporal): Norway

Approximately 1.29 million people in Norway fish recreationally at least once a year, equating to a participation rate of 33% for MRF (Hyder et al. 2018). Statistically robust multispecies surveys of tourist and residential recreational fishing are conducted in selected regions annually. Mandatory reporting for the tourist fishery was implemented nationally in

Table 1 Overview of case study fisheries, sampling frame configurations and undercoverage issues

Sampling frame	Case study	Target population	Survey design	Undercoverage issue addressed	Remaining undercoverage issues	Publications
Area frame (broad spatio-temporal)	1. Norway (Troms and Hordaland Counties, and in the Oslofjord)	Marine boat-based recreational fishers in the case-study region. Also shore-based fishers in the Oslofjord	On-site intercept survey	Lack of public access points (i.e., fishers launch from private locations) Adjusted for temporal undercoverage of effort (trips) within primary sampling units	Nighttime fishing (seasonal), adverse weather restricts sampling, language barrier for tourist fishers, under-age fishers (<16 years old)	Vølstad et al. (2020) Ferter et al. (2023)
Area frame (restricted spatio-temporal)	2. Shark Bay, Western Australia	Marine boat-based recreational fishers in the case-study region	Various on-site surveys (including remote cameras)	Unable to estimate stock-specific snapper catches using the licence frame outlined in Case study 4 Fishers launch from remote beaches	Boats on private moorings, charter fishing	Taylor et al. (2021)
List frame (generalised list)	3. New Zealand	Recreational fishers (boat- and shore-based, marine and freshwater)	National Panel Survey based on a dwelling meshblock frame	The previously used phone list frame was incomplete (e.g., unlisted numbers) Compulsory reporting introduced to address charter boat catch	Fishers <15 years excluded, international fishers	Wynne-Jones et al. (2019) Hartill and Edwards (2015)
List frame (specialised list)	4. Western Australia	Boat-based fishers (marine and freshwater) for the entire state	Phone-diary survey based on licence frame for boat-based fishing	Phone list sampling frame has many exclusions (e.g., unlisted numbers) Previous onsite surveys restricted to key boat ramps only with daytime sampling	Licence holders <5 or >95 years excluded, international fishers	Taylor and Ryan (2019)
Multi-frame (list and list frame)	5. United States	Marine recreational fishers (boat- and shore-based)	Mail survey incorporating auxiliary information from a separate sampling frame	Licence exemptions and illegal fishing activity	Anglers residing in group quarters, addresses that don't receive regular mail, residences with drop points, new construction/vacant plots	Andrews et al. (2014), Brick et al. (2016), Papacostas and Foster (2018)

Table 1 (continued)

Sampling frame	Case study	Target population	Survey design	Undercoverage issue addressed	Remaining undercoverage issues	Publications
Multi-frame (area and list frame)	6. Sweden (Öresund and the Baltic Sea west of Bornholm)	Marine boat-based recreational fishers in the case-study region	Multi-stage survey incorporating area and list frame	Unable to estimate regional Western Baltic Cod catches using national survey based on a population register	Nighttime fishing (seasonal)	Sande et al. (2022)

2017. This fishery involves registered tourist camps, which are primarily visited by overseas fishers. A national study conducted in 2018–2019 used complementary off-site and on-site methods and multiple sampling frames (Vølstad et al. 2020; Ferter et al. 2023). This study revealed substantially biased results from off-site methods in several regions. This bias was linked with undercoverage because the off-site sampling frame was restricted to Norwegian residents, excluding catches from non-resident fishers and from resident marine recreational fishers born outside of Norway (Vølstad et al. 2020).

On-site methods are being used to quantify catches of the coastal populations of Atlantic cod (Stenseth et al. 1999) in the MRF. Due to the high dispersion of residential recreational fishing effort across Norway's expansive coastline, classical on-site access-point surveys (Pollock et al. 1994) are not viable. Furthermore, surveys of the tourist fishery based on list frames (registry of fish camps) are complicated by severe errors in the registry that requires costly surveys for quality assurance. Roving creel surveys were conducted from 2018 to 2019 in the counties of Troms, Hordaland, and the counties comprising the Oslofjord, representing Northern, Western, and South-East regions of Norway, using a novel spatial sampling frame (Vølstad et al. 2020). These surveys were designed to overcome the undercoverage issue resulting from the lack of publicly accessible access points (Table 1). Regional study areas were defined as coastal waters within the coastal baseline. Each study area was divided into polygons of 4 km^2 on average, with polygons or clusters of polygons as the primary sampling units (PSUs). Regional roving creel surveys of anglers were conducted using a survey design where interviews of intercepted anglers were obtained quarterly from a spatially stratified random sample of PSUs searched by boat.

The novel spatial sampling frame contained PSUs with continuous sea-surface area that could be searched by boat, enabling boat-based catches and fishing effort to be estimated in each region. Shore-based catches were estimated in the Oslofjord because the smaller size of the area enabled boat- and shore-based regions to be included in the polygons. Complete trip data based on post-trip interviews were used to correct for temporal undercoverage of boats or fishing parties within sampled PSUs. Remaining undercoverage issues include nighttime fishing which commonly occurs between May and September due to the extended daylight periods (Table 1), adverse weather which restricted sampling of some of the offshore polygons on pre-selected days, the language barrier which prevents some tourists from participating in surveys, and under-aged fishers (< 16 years old) that could not be interviewed. In addition, cost and the precision of catch estimates remain issues because a relatively large proportion of sampled PSUs in each survey area had little or no fishing effort, resulting in few interviews. In the future, drones and citizen science will likely be used to map the spatial effort distribution, enabling the spatial sampling frame of polygons to be stratified by expected recreational fishing effort, or to employ unequal probability sampling.

Case study 2: Area frame (restricted spatio-temporal): Shark Bay, Western Australia

In Western Australia, the sheltered inner gulfs of Shark Bay lie within a World Heritage Area and attract boat-based fishers (~ 8,000–10,000 trips each year), many of whom target snapper (*Chrysophrys auratus*). Three separate stocks of this sparid occur within the inner gulfs. These stocks are particularly vulnerable to exploitation because the species aggregates to spawn in predictable locations in winter. Concerns that snapper in each of these stocks were being overfished led to a range of recreational fishing surveys since 1996. The absence of a licence frame of fishers specific to the region creates a sampling challenge for this remote fishery. Ongoing statewide surveys (refer to Case study 4) cannot be used to obtain reliable catch estimates for all three stocks because the sampling frame results in an insufficient number of fishers who report snapper catches within Shark Bay (a source of undercoverage, Table 1).

Between 1998 and 2010, 11 on-site surveys were conducted at the three boat ramps providing direct access to the fishery (Wise et al. 2012). A harvest tag system was implemented between 2003 and 2016 for one of the stocks, restricting the total catch of snapper to 5 tonnes via a ballot (Jackson et al. 2016). In 2018–19, a new on-site survey design was applied after the cessation of the harvest tag system. This survey enabled fishery-wide catches to be estimated for one of the stocks, inclusive of fishers launching their boat from the beach (a source of undercoverage; Table 1). It incorporated a supplementary access point (SAP) survey design, using remote cameras to estimate ramp-based fishing effort and expanding the temporal coverage of the sampling frame at each ramp (Taylor et al. 2021). An aerial survey was also used to upwardly adjust the SAP estimates, accounting for catches from fishers launching their boats from remote beaches. The incorporation of these additional catches more than tripled the estimated kept catch for one of the snapper stocks (Taylor et al. 2021). Analysing camera footage between surveys represents a cost-effective way of monitoring recreational fishing effort (Afrifa-Yamoah et al. 2021; Taylor et al. 2021).

Lessons learned over 30 years of recreational fishing research have contributed towards a recovery in stocks following over-exploitation. A key reflection has been the need to consider changes in fisher behaviour (e.g., shift to beach launches) that can create undercoverage and, if unaccounted for, compromise the ability to provide robust catch estimates. Remaining undercoverage issues include boats on private moorings (i.e., unavailable to sample during on-site surveys) and recreational catches taken while charter fishing. The magnitude of any missing catches from boats on private moorings is considered to be minimal and charter catches are provided through compulsory catch returns (see Case study 4).

Case study 3: List frame (generalised list): New Zealand

Approximately 350,000 people in New Zealand went marine fishing in 2022–23, equating to a participation rate of 6.8% (Heinemann and Gray 2024). Early attempts to estimate recreational harvests in New Zealand focused on off-site surveys based on telephone book listing sampling frames. Concerns about implausibly high harvest estimates for some of the larger recreational fisheries led to the adoption of more reliable on-site aerial-access survey methods (Hartill et al. 2011). Harvest estimates produced by these surveys were considered to be far more plausible as they were based on direct observations of the fishery across its full spatial extent, following a probabilistic spatio-temporal sampling design. However, it was also recognised that the on-site method used was only cost-effective when surveying stretches of coastline up to ~ 1,000 km long. This led to the development of the National Panel Survey

(NPS) off-site survey method (Wynne-Jones et al. 2019) which overcame the undercoverage issue encountered in previous phone surveys (increase in unlisted numbers; Table 1).

The NPS follows a two-phase approach. The first phase is a face-to-face screening survey of the inhabitants of over 30,000 households that are sampled from a highly stratified dwelling-location sampling frame that is mapped and maintained as part of New Zealand's five-yearly national census programme. This screening survey is used to estimate the number of residents who claim to be saltwater fishers. The second phase is to then randomly select a fisher from each fishing household to be one of 7,000 panellists (referred to as 'diarists' in Case study 4) who report their catch during a twelve-month period.

A key advantage with this NPS approach is the ability to calculate probabilistic sampling weights for each panellist given the national census sampling frame on which their enrolment was based and that can then be used to scale up the annual catch reported by each panellist in a statistically rigorous manner. The accuracy of the NPS estimates has been independently corroborated by concurrent on-site aerial-access surveys of New Zealand's largest recreational fisheries, with the estimates being within 5% and 10% of each other for the snapper (SNA 1) stock and 2% and 24% of each other for the kahawai (KAH 1) stock, in 2011–12 and 2017–18, respectively (Hartill and Bian 2020). While there are many advantages with basing the NPS on a routinely maintained and enumerated national census database, there are gaps in this sampling frame. Other data sources are therefore required to quantify some sources of un-estimated harvest. Ethics standards in New Zealand prohibit the interviewing of anyone who is younger than 15 years without a guardian present but the harvest by these younger fishers can still be estimated in a relative sense from creel survey data. Any catches from overseas fishers are not included in the NPS. Another form of recreational harvesting that is only partially estimated by NPS surveys is that taken from charter boats. Charter-boat trip catches are therefore not included in NPS harvest estimates, and the harvest estimates for this type of fishing are now based on compulsory catch records that are provided by the charter operators on behalf of their clients.

Case study 4—List frame (specialised list): Western Australia

Approximately 650,000 people in Western Australia fish recreationally at least once a year, equating to a participation rate of 25% (Newman et al. 2023). Prior to 2010, a key challenge for fisheries management was the lack of an appropriate sampling frame for boat-based fishers. Previous stock assessments had revealed concerns about the sustainability of the multispecies, multi-sector West Coast Demersal Scalefish fishery (Wise et al. 2007). Historical estimates of catch were obtained from on-site surveys which had undercoverage errors associated with boats launching from private access points and fishing occurring outside of daylight hours (Table 1). This led to concerns about the accuracy of previous estimates of catch (Lai et al. 2019). A Recreational Boat Fishing (RBF) licence was introduced in 2010 to support regular monitoring of West Coast demersal scalefish, in addition to other fisheries across the state. The licence is mandatory for recreational fishing from a motorised vessel anywhere in Western Australia (Taylor and Ryan 2019). Additional unlicensed fishers are allowed to fish, provided the total catch from the vessel is within the bag- and boat-limits of the licensed fishers. The purchase and renewal of fishing licences is mostly done online using two-factor authentication and is linked to other licence registrations (i.e., driving licence, recreational boat licence). Official inspection and offence data have revealed high recreational compliance rates (~95%; Green and McKinlay 2009).

The RBF licence provides a suitable sampling frame for comprehensive statewide surveys conducted every 2–3 years. It covers Western Australian residents and tourist fishers from other Australian states. A first-phase screening survey is used to estimate the number of boat-based fishers and randomly select a fisher to be one of ~3,000 diarists (referred to as "panellists" in Case study 3) who report their catch during a second-phase 12-month survey using a phone-diary method. The RBF licence provides good coverage of fishers targeting demersal species (Lai et al. 2021). Corroborative studies have shown broad agreement between estimates of catch from concurrent statewide surveys and more recent on-site surveys that have addressed undercoverage issues encountered in historical on-site surveys (Lai et al. 2021). The RBF licence has provided a reliable means to inform stock assessments and fisheries policy change (Fairclough et al. 2021), and address state and national reporting requirements (Piddocke et al. 2021; Newman et al. 2023). Sample selection in the screening survey excludes licence holders younger than five or older than 95 years and overseas fishers. Collectively, these exclusions comprise less than 1% of licence holders. As for Case study 3, charter-boat catches are not included in estimates reported from the statewide surveys because they are provided through compulsory catch returns (Table 1). Obtaining robust estimates of catch for species that are caught by shore-based (i.e., unlicensed) fishers remains an ongoing challenge. Recreational catches from overseas fishers are also not included in survey estimates (Table 1).

Case study 5—Multi-frame (list and list frame): United States

Approximately 13 million United States (U.S.) residents aged 16 and older go recreational saltwater fishing at least once a year, comprising a participation rate of approximately 5% (U.S. Department of the Interior 2022). The Marine Recreational Information Program (MRIP) was established in 2007 to provide estimates of marine recreational fishing catch and effort in U.S. waters. Generally, MRIP uses complementary survey designs that include off-site and on-site surveys to estimate fishing effort and catch-per-unit of effort, respectively (Papacostas and Foster 2018). Estimates from the component surveys are combined to estimate effort by fishing mode (e.g., shore-based, private boat and 'for-hire' (referred to as "charter" in other countries) and catch (landings and discards) by species).

In 2009, MRIP initiated a sequence of pilot studies to evaluate new methods for estimating shore-based and private boat fishing effort, addressing the rapid deterioration of random digital dial (RDD) telephone surveys. A primary feature of this research was use of the National Saltwater Angler Registry (NSAR), which was mandated by the U.S. Congress and envisioned as a comprehensive sampling frame for recreational fishing surveys (National Research Council 2006, H.R. 5946 2006). Using this NSAR sampling frame was more efficient than household sampling but undercoverage rates were high (up to 70%) for some activities, due to licence exemptions and illegal fishing activity (Table 1). Subsequent approaches reduced coverage error via dual-frame designs that included registry samples and either RDD samples or address-based samples (ABS) selected from frames derived from a computerised delivery sequence file (see Harter et al. 2016 for a description of address-based sampling in the U.S.). However, identifying the portion of the population that could be sampled from both the registry and general population frame—the overlapping population—was prone to either matching error (e.g., different sample-unit address information between frames) or measurement error (e.g., self-reporting licence status), resulting in inaccurate selection probabilities and biased estimates (Brick et al. 2016). Additionally, the complexities and cost of administering multiple, independent surveys was impractical for long-term monitoring.

Recognising the utility of registry samples, as well as the challenges and costs of dual-frame designs, MRIP developed a mail survey design that uses NSAR as auxiliary information rather than as a standalone sampling frame (Andrews et al. 2014; Brick et al. 2016; Papacostas and Foster 2018). In this design, known as the Fishing Effort Survey (FES), NSAR is matched to ABS frames by exact address matching, partitioning the frame into true strata that vary with respect to expected fishing activity. While matching errors still occur, they only reduce sampling efficiency and do not introduce bias. Matched strata are equivalent to registry frames, yielding highly efficient samples, while unmatched strata ensure coverage of unregistered or otherwise unmatched anglers.

The ABS frame provides nearly 100% coverage of all residential addresses in the country (https://www.m-s-g.com/Pages/genesys/address_based_sample). Maximising coverage was a priority because research into non-sampling errors concluded that non-coverage of unlicensed anglers would largely result in greater bias than non-response, even if non-coverage resulted in substantially lower rates of missing data than non-response (Brick et al. 2022c). Coverage approached 100% in most areas although there were exceptions, particularly in some rural areas. The stratified design also provides sampling flexibility capable of achieving diverse goals, such as maximising the quantity of fishing data or optimising sample allocations to reduce costs and/or maximize the precision of estimates (Kalton 2023).

Case study 6—Multi-frame (area and list frame): Sweden

Approximately 1.2 million people in Sweden fish recreationally at least once a year, equating to a participation rate of ~ 11% (Swedish Agency for Marine and Water Management and Statistics Sweden, 2023). Official statistics on recreational fishing are obtained from a national mixed-mode (web and postal) questionnaire survey that has been run annually since 2014. Recreational catch and effort estimates are also needed for small geographical areas and specific stocks, such as the marine recreational catch of Western Baltic Cod (WBC; *Gadus morhua*) in ICES Subdivisions (SDs) 23 and 24, corresponding to Öresund and the Baltic Sea west of Bornholm, respectively. The national survey cannot be used to obtain these estimates because the sampling frame (population register) results in an insufficient number of fishers who report WBC catches.

A multi-stage survey design was developed to address undercoverage of WBC catches (Table 1) and provide the first estimation of the marine recreational catch of WBC by private boats for the Swedish southwest coast (Sande et al. 2022). This involved the creation of an area and list frame in three stages. In Stage I, a list frame of municipalities bordering ICES SD 23 and 24 was constructed with municipalities selected by stratified simple random sampling with replacement, using stratification defined by ICES SD. In Stage II, a list frame of access points was constructed for every municipality selected in Stage I with access points selected by stratified simple random sampling without replacement. Additionally, for every municipality selected in Stage I, a list of all days in the quarter was used as a frame. From this frame, one day was randomly selected for a municipality and applied to all access points selected for this drawing in Stage II. In Stage III, for every combination of access point and day selected in the preceding stages, one of three 8-h work shifts was randomly selected.

This sampling scheme resulted in selected combinations of access points and work shifts. For each of these combinations, observers collected data on-site on the number of cod caught by all recreational fishers arriving with a private boat. This enabled the estimation of total catch by ICES SD, quarter, and year. Coverage error was almost completely mitigated, except for low levels of nighttime fishing that were observed but not accounted for in the design (Table 1). The pilot study is a successful example of use of a multi-stage design when a sampling frame of the observation units (in this case, the private boats) is missing. When the pilot study was designed, limited auxiliary information was available about the activity patterns of the boats. When this auxiliary information is available, it can be used in the sampling and the estimation to improve the precision of the estimates.

Identifying and correcting coverage issues

Survey practitioners almost inevitably have to choose a suitable sampling frame in the absence of a readily available "gold standard" list of the target population. We propose several generalisations by summarising key learnings from the case studies and the literature (Table 2). Undercoverage is a common issue that was addressed in each of our case studies to reduce the potential impacts of biased estimates. However, in most instances, some form of undercoverage always remains. A more realistic prospect is to reduce undercoverage to a level at which survey estimates are deemed to be suitable for management purposes without making a survey cost-prohibitive to implement. Being able to acknowledge, detect and account for undercoverage is particularly important for building trust with stakeholders and for assisting scientists in incorporating recreational catch estimates into stock assessment models.

Generalised list frames offer the advantage of generating estimates of catch and effort across multiple spatial scales and for different modes of fishing (Lynch et al. 2019). However, the cost for sampling a target population of recreational fishers using these frames can be substantial. Phone-list sampling frames with exclusions are the most prone to undercoverage issues, leading some agencies to shift to alternative frames (as illustrated in Case studies 3 and 5). Another recent example from Queensland, Australia, illustrates the extent of undercoverage when using a phone-list sampling frame. As only ~ 49% of Australian adults had a landline telephone in 2019 (Australian

Table 2 Coverage issues and potential solutions to be considered when choosing a sampling frame. The features of a sampling frame are broadly consistent with Kalton (2023). Potential solutions are cross-referenced with the case study examples and other published studies

	Area-frame		List-frame	
Feature	Issue	Potential solution	Issue	Potential solution
Currency	No suitable existing frame for estimating catches based on current knowledge	Create an area frame (Case study 1) or area and list frame (Case study 6)	Out-of-date contact information for a licensed fishery	Use an online licence system which makes it easier to pay licences and manage contact details (Case study 4)
Completeness	Increasing level of undercoverage (e.g., boats launching from private access points or from shore)	Can the alternative access points be sampled in another way? Consider using an aerial survey to quantify effort from all access points. Consider alternative approach to assess out-of-scope units (Case study 4 or Ashford et al. 2010)	Increasing level of undercoverage (e.g., generalised phone list)	Consider alternative frame, such as dwelling-location sampling frame (Case study 3)
Contains only relevant units	Sampling access points that are not used to directly access the fishery/species of interest	Is there a priori information to confirm that the fishery/species of interest is not accessible from a given location? If so, divert resources elsewhere	Generalised list frame has a high proportion of non-fishers	Consider using a multi-frame approach, incorporating a specialised list (Case study 5)
Accessible	Requirement to monitor fishing between surveys and fishing in hazardous conditions (e.g., rock fishing)	Consider using cameras to monitor effort between surveys (Case study 2) and for situations when the safety of interviewers may be at risk	Privacy issues restrict access to a list frame	Consider use of alternative frame
Suitable information	Unknown levels of fishing activity to inform sampling approach in an on-site survey	Conduct pilot survey to determine spatial and temporal variation in fishing activity. Consider using emerging technology (e.g., drones; Case study 1) to inform sampling approach	Unable to determine type of fisher from the frame (e.g., multi-purpose fishing licence)	Mandatory requirement to record fishing characteristics upon renewal of a fishing licence

Communications and Media Authority 2020), the Queensland study used a tri-frame sample, whereby random samples of phone numbers were drawn from an RDD landline frame, an RDD mobile frame and a listed mobile frame, with all frames sourced from a market research database (Misson et al. 2020). As our case study examples illustrate, non-resident/tourist fishers are often excluded from generalised list frames. When a substantial part of fishing activity results from these fishers, catch estimates for particular species may underestimate actual catches, but to an unknown degree (West et al. 2022).

Conceptually, the compilation and maintenance of a specialised list (i.e., a registry of all recreational fishers) would provide an ideal sampling frame (Ashford et al. 2009; Taylor and Ryan 2019), notwithstanding the ethical and political considerations that surround this issue. The quality of such a frame can vary and needs to be considered carefully, as illustrated by Case studies 4 and 5 which have different levels of licence-holder exemptions. Data protection policies can also restrict access to some general and specialised list frames (Gordoa et al. 2019; Bachiller et al. 2022).

Area-based frames are particularly useful for estimating the recreational catch over smaller areas. On-site surveys that use these types of frames enable fishers to be interviewed during or shortly after each fishing event, minimising the potential for recall bias. These surveys also allow the kept component of the catch (i.e., number caught and species identification) to be verified. However, the relative cost of implementing on-site surveys is often far higher than for off-site surveys (Pollock et al. 1994; Jones and Pollock 2012; Bellanger and Levrel 2017) and will likely increase in the future given growing labour costs. Coverage error also arises in area frames (Table 2); for example, when a new boat ramp is built, when private launching facilities are commonly used, or when fishers launch their boats from unexpected locations, such as the shift towards beach launching as found in Case study 2.

Beyond the field of recreational fisheries research, multiple-frame sampling approaches are increasingly being used to identify and address deficiencies in the quality of information in one of the frames. This involves drawing independent samples from each frame (Lohr 2021) or, in line with Case study 5, linking sub-sets of information between multiple frames. Ultimately, both approaches can lead to a more cost-effective design and recreational catch estimates that are less prone to bias. Evaluation of bias is an important consideration, particularly for periodic surveys that provide a time series of recreational catch estimates. This evaluation is increasingly being conducted in recreational fishing surveys by scheduling concurrent corroboration or validation surveys (Hartill and Edwards 2015; Taylor et al. 2021; Lai et al. 2021). This involves the deliberate application of two surveys on the same fishery at the same time with comparable spatial and temporal coverage which enables undercoverage to be identified and accounted for when estimating fishing effort or catch. While the short-term cost of scheduling multiple surveys may present fiscal challenges, being able to detect and explain sources of bias provides ongoing quality assurance of these crucial survey data. Evaluation of bias is also an important consideration when combining or comparing estimates sourced from different surveys. For example, semi-quantitative assessments of bias have been considered when comparing estimated participation rates, fishing effort and the impact of marine recreational fishing on key fish stocks in European waters (Hyder et al. 2018; Radford et al. 2018).

How much does coverage matter and what does the future hold?

We advocate that coverage is a key consideration in any probabilistic recreational fishing survey, particularly when unbiased recreational catch estimates are required for a stock assessment, when the exploitation rate for a fish stock is high, and when formal resource allocation occurs between the recreational and commercial fishing sectors. In these instances, the ecological, economic and political implications of basing management actions on flawed recreational catch estimates can be high. Coverage is also a salient issue for other types of recreational fishing surveys, for example, when estimating the average weight of species harvested (Desfosses et al. 2022) or catch rate (Tate et al. 2020) for a particular species. In these situations, part of the area sampling frame may deliberately be omitted for the survey design to maximise sampling efficiency (Smallwood and Ryan 2020). However, deliberate undercoverage can be a false economy. This can arise when cost savings in the scheduling of surveys are outweighed by the potential for biased estimates (Bellanger and Levrel 2017). Undercoverage should be explicitly acknowledged if there is no attempt to test the assumption that sampling is representative of the target population.

Technological and societal changes have implications for the way surveys are designed and how the results are accepted by the broader public (Brick et al. 2022a). In particular, the decline in coverage afforded by generalised list frames, such as landline listings, has implications for the cost of surveys, the accuracy of survey estimates and the ongoing viability of survey designs (Cornesse et al. 2020; Brick et al. 2022b; Boyd et al. 2023). We predict that probabilistic sampling will continue to play a key role in the provision of recreational catch estimates, with an increased focus on multi-frame designs. The use of non-probabilistic surveys is increasing which has led to a greater uptake in citizen science (Pecl et al. 2019), the incorporation of fishers' local ecological knowledge into management decisions (Stephenson et al. 2016) and the development of angler smartphone apps (Skov et al. 2021). The reliability of recreational catch estimates generated from smartphone apps is often largely unknown because it is difficult to generalise research findings from non-probabilistic surveys and to assess sampling variability and identify possible biases.

We recommend further evaluations of potential bias in probabilistic and non-probabilistic methods (e.g., Beckman et al. 2024), and greater exploration of approaches to integrate estimates from these fundamentally different sampling approaches. This evaluation should include consideration of the mandatory reporting regimes that are already in place for some charter boat recreational fisheries (Tracey et al. 2021). An expansion of this approach is often proposed as an alternative mode of data collection for the broader recreational sector. The potential for coverage error should still be acknowledged as a potential source of bias in mandatory reporting, resulting from non-compliant behaviour of some fishers. More broadly, illegal fishing activity is typically out-of-scope for most surveys, but the implications of non-compliant activity warrants further attention (Mackay et al. 2021; Ban et al. 2022), particularly when sustainability concerns or resource conflict lead to contentious fisheries management decisions.

Key recommendations to future-proof coverage errors

We recommend six steps to ensure that coverage errors are identified and mitigated to the greatest extent possible. These recommendations have relevance to other areas of fisheries research, such as the design of fisheries-independent surveys or quantifying released catches/discards and interactions with protected species (Catchpole and Cadrin 2014; van Helmond et al. 2020; Giovos et al. 2024).

1. ***Consider coverage error during survey planning***

In all six case studies, coverage error and other forms of non-sampling error were considered during the planning stage of each survey. Survey practitioners should consult with other relevant experts at the outset to ensure that the choice of a sampling frame and survey design remains contemporary and, to the best extent possible, that any undercoverage error is minimised or mitigated.

2. ***Design and conduct pilot or concurrent surveys to evaluate and/or correct for potential bias***

Pilot studies can be used to assess the appropriateness of an intended sampling frame. For example, if an area frame is to be used, a pilot study could be done to determine whether the intended access points match the actual locations from which the fishery is accessed. Where there are known coverage issues in the available sampling frames, validation surveys can enhance the scientific credibility and acceptance of survey outputs (Georgeson et al. 2015). In a validation survey, one of the methods is 'best practice' and of superior quality. The estimates from the 'best practice' method can be used to evaluate bias, or at least understand, the magnitude of the missing effort or catch component. Potentially, a correction factor can also be applied to correct for any bias (Georgeson et al. 2015). The scope of each survey, including fishery components and attributes, should be defined consistently between concurrent validation surveys, so that the estimates they produce are directly comparable (Hartill and Edwards 2015).

3. ***Recognise that coverage error can change through time***

The apparent cost savings associated with the adoption of an existing or a previously used sampling frame may not be justified given the unreliability of the estimates obtained. This was a key lesson learned in Case study 3 where a steady decline in the number of households with publicly listed landline phone numbers was considered enough of an issue to re-design the national survey and switch to a dwelling-location sampling frame.

4. ***Using technological or multi-frame approaches to mitigate coverage error***

Technological advances can assist in identifying and mitigating coverage issues, notwithstanding the limitations/non-sampling errors that are associated with their application. For example, the analysis of imagery collected from drones (Provost et al. 2020; Cooke et al. 2021), cameras (Taylor et al. 2018; Hartill et al. 2019) or satellites (Keramidas et al. 2018) could be used to design an appropriate sampling strategy. In particular, the increased uptake of multi-frame approaches to minimise or eliminate bias warrants further attention, noting that compared with other studies in the broader discipline of surveys, few recreational fishing studies have adopted this approach (Lohr 2011).

5. ***Consider model-based survey tools to correct for undercoverage***

The exploration of model-based survey sampling tools is also suggested when the more commonly used design-based approach yields unsatisfactory results. For example, a Bayesian approach could be adopted to correct for undercoverage (Salvatore et al. 2024; Zio et al. 2024).

6. ***Document the sampling frame and potential sources of coverage error in publications***

To provide quality assurance and promote consistency in reporting, any publication resulting from the use of a probabilistic recreational fishing survey should define the target population, sampling frame, in- and out-of-scope activity, and any potential bias that may have occurred due to coverage error. This should also include recommendations to address the errors or specifying assumptions about their likely impacts.

Summary perspective

The choice of a suitable sampling frame is a key component in the design of a survey because the accuracy of recreational catch and effort estimates is often predicated on the assumption that coverage error is not significant. Without due attention, this potential source of bias remains cryptic and can undermine the suitability of research and management advice generated from the catch and effort estimates. We show that the issue is not insurmountable if practitioners carefully consider potential issues and solutions before commencing a recreational fishing survey (Table 2). Real-world examples (Table 1) illustrate where coverage error has been both identified and mitigated, and lead to our six recommendations that should assist researchers in future-proofing recreational fishing surveys.

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Declarations

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