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FACULTY OF NATURAL RESOURCES AND AGRICULTURAL SCIENCES

# The ones that didn't get away

Assessing recreational fisheries and biological  
impacts in coastal ecosystems

HEGE SANDE



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impacts in coastal ecosystems

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## Abstract

Recreational fisheries constitute a substantial yet often poorly quantified component of global fisheries, with the potential to influence stock dynamics, ecosystem structure, and management outcomes. However, their disperse nature, heterogeneous participants, and incomplete sampling frames make them difficult to monitor and integrate into fisheries science. The aim of this thesis is to improve the understanding of recreational fisheries and their biological implications in coastal ecosystems by addressing key methodological and biological challenges.

This thesis combines empirical studies and methodological development across four research papers. I) A probabilistic on-site survey based on an indirect spatial sampling frame, which provided the first unbiased estimates of Swedish recreational catches of Western Baltic cod. II) A structured decision framework based on Total Survey Quality, which enabled transparent comparison and selection of survey designs aligned with management objectives. III) A participatory monitoring program for European lobster on the Swedish west coast, that demonstrated how volunteers can generate spatially expanded, fisheries-independent data comparable to scientific surveys. IV) Long term data on Western Baltic cod, which revealed pronounced changes in life-history traits, including reduced size structure, declining length-at-age, lower body condition, and earlier maturation, with both commercial and recreational fisheries selectively removing larger individuals, with additional selectivity for fish in better condition observed in recreational catches.

Together, these results highlight that recreational fisheries contribute to fishing mortality and selective pressures, while uncertainty remains a defining feature of their assessment. Reliable, management-relevant knowledge depends on integrating complementary data sources and approaches. Improving monitoring is not only a technical challenge, but a prerequisite for understanding biological change and supporting precautionary management. Recreational fisheries should be considered not only a source of pressure, but also a potential contributor to data, knowledge, and more inclusive governance of coastal fisheries.

**Keywords:** recreational fisheries, survey design, sampling frames, citizen science, selective harvesting, life-history shifts, western Baltic cod, fisheries management

# The ones that didn't get away

## Abstract

Fritidsfiske utgör en betydande men ofta bristfälligt kvantifierad del av de globala fiskerierna, med potential att påverka beståndsdynamik, ekosystemstruktur och förvaltningsutfall. Samtidigt gör dess spridda karaktär, heterogena utövare och ofullständiga urvalsramar det svårt att undersöka och integrera i fiskerivetenskapen. Syftet med denna avhandling är att förbättra förståelsen av fritidsfiske och dess biologiska konsekvenser i kustnära ekosystem genom att adressera centrala metodologiska och biologiska utmaningar.

Avhandlingen kombinerar empiriska studier och metodutveckling i fyra delstudier. I) En probabilistisk, plats-baserad provtagningsmetod med en indirekt spatial urvalsram som möjliggjorde de första obundna skattningarna av svenska fritidsfångster av västlig Östersjötorsk. II) Ett strukturerat beslutsstöd baserat på Total Survey Quality som möjliggjorde en transparent jämförelse och val av undersökningsdesign i relation till förvaltningsmål. III) Ett deltagarbaserat övervakningsprogram för europeisk hummer visade att frivilliga kan generera fiskerieroberoende data med utökad rumslig täckning och av jämförbar kvalitet med vetenskapliga undersökningar. IV) Långtidsdata för västlig Östersjötorsk som visade tydliga förändringar i livshistoriska egenskaper, inklusive minskad storleksstruktur, minskad längd vid ålder, sämre kondition och tidigare könsmognad, där både kommersiellt fiske och fritidsfiske selekterade större individer, och fritidsfisket uppvisade dessutom selektion för fisk i bättre kondition.

Sammantaget visar resultaten att fritidsfisket bidrar till fiskeridödlighet och selektiva processer, samtidigt som osäkerhet kvarstår som en central del av dess skattning. Tillförlitlig och förvaltningsrelevant kunskap förutsätter därför att kompletterande datakällor och metoder integreras. Att förbättra övervakningen är därmed inte enbart en teknisk utmaning, utan en förutsättning för att förstå biologiska förändringar och stödja en försiktighetsbaserad förvaltning. Fritidsfisket bör därför betraktas inte bara som en potentiell påverkan, utan även som en möjlig källa till data, kunskap, och en mer inkluderande förvaltning av kustfiskerier.

**Nyckelord:** fritidsfiske, undersökningsdesign, urvalsramar, medborgarforskning, selektivt fiske, livshistoriska förändringar, västlig Östersjötorsk, fiskeriförvaltning.

# The ones that didn't get away

## Abstract

Fritidsfiske utgjer ein betydeleg, men ofte dårleg kvantifisert del av dei globale fiskeria, med potensial til å påverke bestandsdynamikk, økosystemstruktur og forvaltningsutfall. Samstundes gjer den spreidde karakteren, dei heterogene deltakarane og ufullstendige utvalsrammer det vanskeleg å undersøkje og integrere fritidsfisket i fiskerivitskapen. Føremålet med denne avhandlinga er å betre forståinga av fritidsfisket og dei biologiske konsekvensane i kystnære økosystem ved å ta for seg sentrale metodiske og biologiske utfordringar.

Avhandlinga kombinerar empiriske studiar og metodeutvikling i fire delstudiar. I) Ein probabilistisk, stadbasert utvalsmetode med ei indirekte romleg utvalsramme som gjorde det mogleg å berekne dei første upartiske estimata av svensk fritidsfiskefangst av vestleg baltisk torsk. II) Eit strukturert rammeverk basert på Total Survey Quality som gjorde det mogleg å samanlikne og velje undersøkningsdesign på ein transparent måte i tråd med forvaltningsmål. III) Eit deltakande overvåkingsprogram for europeisk hummar som viste at frivillige kan generere fiskeriuavhengige data med utvida romleg dekning og samanliknbar kvalitet med vitskaplege undersøkingar. IV) Langtidsdata for vestleg baltisk torsk som synte tydelege endringar i livshistorietrekk, inkludert redusert storleiksstruktur, lågare lengd ved alder, dårlegare kondisjon og tidlegare kjønnsmodning. Både kommersielt fiske og fritidsfiske selekterte større individ, og fritidsfisket viste i tillegg seleksjon for fisk i betre kondisjon.

Samla sett viser resultatata at fritidsfisket bidreg til fiskeridødelegheit og selektive prosessar, samstundes som uvisse framleis er ein sentral del av vurderingane. Truverdige og forvaltningsrelevante kunnskapar krev difor at komplementære datakjelder og metodar vert integrerte. Å betre overvakinga er såleis ikkje berre ei teknisk utfordring, men ein føresetnad for å forstå biologiske endringar og støtte ei føre-var-forvaltning. Fritidsfisket bør difor ikkje berre sjåast som ei kjelde til påverknad, men òg som ein mogleg bidragsytar til data, kunnskap og ei meir inkluderande forvaltning av kystfiskeria.

**Nøkkelord:** fritidsfiske, undersøkningsdesign, utvalsrammer, borgarforskning, selektivt fiske, livshistorieendringar, vestlig baltisk torsk, fiskeriforvaltning.



# Preface

When I was a little girl, my father helped me make a fishing rod from a branch and some fishing line from our garage. The hook belonged to my great-grandfather, one of the rusty ones he had discarded after mending and rigging the longline. My great-grandfather would sit on his stairs, wearing the worn heavy-duty work shirt, once blue, and a six-pence cap, meticulously tying new hooks to the snoods while we gathered around listening to his stories. His stories were mostly made up, like the one about how he'd once jumped across the entire fjord by skipping from shoal to shoal, knowing every skerry and shallow beneath the surface.

When fathers and grandfathers returned home after months at sea, the real stories of the men and boats lost, storms endured, and injuries attained were quietly told, alongside stories about the catches, the odd bycatch, or the places visited. *Havet gir, havet tar* – the Sea gives, the Sea takes. This knowledge was ingrained in our bones. Yet with this knowledge came not only respect, but a deep love and curiosity towards the Sea – the Sea that shaped every-day life, persistently, with work and wonder. The smell of salt was carried by the wind and settled on the windows, in the spring we'd clear sea-rocks from the meadow, thrown ashore by winter storms, and in late summer we went crab-hunting equipped with torchlights and garden rakes.

I didn't catch any fish on the rudimentary rod. But my sister caught one with her bare hands while we were playing on the shore. It was promptly brought home; it was dissected; its organs inspected, and stomach content analysed. I appreciated the potential need to re-inspect samples – so we saved the fish for later. To my father's surprise, 6-year-old me saved it in his toolbox. While I forgot about the fish, I never forgot the love and curiosity I have for the Sea. Ultimately, it is what led me to become an aquatic ecologist, and to study fisheries and marine life. This thesis is a small contribution towards better understanding human use of coastal ecosystems and its biological consequences. A story written in scientific data.

Hege Sande, Lysekil, March 2026

“The sea, once it casts its spell, holds one in its net of wonder forever.”  
— Jacques Cousteau



# Dedication

To Viva, Louis & Levi  
without whom this thesis would have been completed in half the time –  
but with infinitely less joy.  
Kärlek

“Many men go fishing all of their lives without knowing that it is not fish they are  
after” – Henry David Thoreau



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# List of publications

This thesis is based on the work contained in the following papers, referred to by Roman numerals in the text:

- I. **Sande, H.A.**, Prista, N., de Groot, A., Casini, M., Jones, C., Sundelöf, A. (2022). Frameless—finding and refining a sampling frame for surveying recreational fisheries: lessons from estimating Swedish harvest of western Baltic cod. *ICES Journal of Marine Science*, 79, 1217–1231. <https://doi.org/10.1093/icesjms/fsac044>
- II. **Sande, H.A.**, de Groot, A., Prista, N., Pärn, H., Sundelöf, A. A decision framework for choosing survey approaches for fisheries catch estimation. (manuscript)
- III. Sundelöf, A., Pärn, H., Börjesson, P, **Sande, H.** From Volunteers to Observations - Scaling European lobster monitoring through the Citizen science initiative LOBSERVE. (manuscript)
- IV. **Sande, H.A.**, Sundelöf, A., Jones, C., Vitale, F., Casini, M. Rapid Life History Shifts in a Declining Fish Stock: The Case of Western Baltic Cod in the Sound. (manuscript)

Paper I is published open access.

The contribution of Hege Sande to the papers included in this thesis was as follows:

- I. conceptualisation, data collection, data curation, formal analysis, visualization, and writing – original draft.
- II. conceptualisation, methodology, and writing – original draft.
- III. design, data curation, formal analysis, methodology, protocols and formal training of citizen scientists, visualisation, and writing – original draft preparation, review and editing.
- IV. conceptualisation, data curation, formal analysis, visualisation, and writing – original draft.

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# Abbreviations

A50	Age at 50% maturity
AIC	Akaike Information Criterion
CPUE	Catch Per Unit Effort
F	Fishing mortality
GAM	Generalized Additive Model
GLM	Generalized Linear Model
ICES	The International Council for the Exploration of the Sea
K	Fulton's condition factor
L50	Length at 50% maturity
LFD	Length Frequency Distribution
MRFS	Marine Recreational Fisheries Survey
MSY	Maximum Sustainable Yield
SCB	Statistics Sweden
SD	Subdivision
SES	Social-Ecological Systems
SLU	Swedish University of Agricultural Sciences
SSB	Spawning Stock Biomass
SwAM	Swedish Agency for Marine and Water Management
TAC	Total Allowable Catch
TDM	Text and Data Mining
TSE	Total Survey Error
TSQ	Total Survey Quality



# AI declaration

This thesis reflects my own scholarly work, and I am responsible for its content and accuracy throughout. Generative AI tools were used in a limited and supportive capacity during the preparation of this thesis. Specifically, AI-based language models (ChatGPT, OpenAI) were used to assist with language refinement, editing, and improving clarity in selected sections of the text.

All scientific content, analyses, interpretations, and conclusions presented in this thesis are my sole responsibility. The use of AI tools did not replace critical thinking, subject-specific expertise, or independent writing. No AI tools were used for data analysis, data generation, or the production of original scientific results.



# 1. Introduction

Recreational fishing culture is rich in anecdotes about “the one that got away” – a fish with size often inversely related to the number of witnesses. While the stories are humorous, they illustrate an important point: the majority of the recreational fishing activity occurs without formal observation. Some fish are landed, some are released, and most are never recorded.

Recreational fisheries are commonly defined as the fishing of aquatic animals that do not constitute an individual’s primary means of subsistence and are not generally sold or traded (FAO, 2024). In practice, this includes fishing for leisure, personal consumption, tourism, or competition, typically conducted outside of the commercial fishing sector (Swedish Agency for Marine and Water Management (SwAM) and Statistics Sweden (SCB), 2025).

Yet the scale of recreational fishing is immense. Globally, more than 220 million people participate in recreational fishing each year (World Bank, 2012). This is likely to be an underestimate, considering 118 million are estimated to fish in Europe, North America and Oceania (Arlinghaus et al., 2015), while 220 million are estimated to fish in China alone (Arlinghaus et al., 2021). This pastime activity generates substantial economic value with estimates suggesting annual expenditures and associated economic impacts in the order of hundreds of billions of USD – and results in the capture of more than 47 billion individual fish each year (Cooke and Cowx, 2004; FAO, 2024; Lovell et al., 2017). The participation rate varies widely among countries, ranging from 1.8% in South Africa to 32.2% in Norway (Arlinghaus et al., 2015), highlighting strong regional differences in fishing pressure and management relevance.

Recreational fisheries represent an important component of global fish harvest, accounting for an estimated 12% of the total catches (Cooke and Cowx, 2004). In the past they have been assumed to be self-sustaining (Post et al., 2002), but are increasingly incorporated into stock assessments (Figueira and Coleman, 2010; Griffiths and Fay, 2015; Radford et al., 2018). For some stocks, recreational fisheries are the main source of mortality (Coleman et al., 2004; Shertzer et al., 2019). In Europe, marine recreational fisheries account for between 2% and 43% of the total removals (Radford et al., 2018), and in some cases contributing substantially to the total mortality.

Failure to account for this source of mortality can lead to misrepresentation of total fishing pressure, potentially biasing stock assessments and ultimately resulting in ineffective or unsustainable management decisions.

Beyond the ecological importance, recreational fisheries hold deep social and cultural significance, connecting people with aquatic environments through leisure, tradition and food provisioning (Arlinghaus et al., 2021). Humans and ecological systems are strongly coupled in social-ecological systems (SESs), and recreational fishing has been shown to have spill-over effects on physiological as well as psychological well-being (Sbragaglia et al., 2025). Participation in recreational fisheries can also promote engagement in environmental stewardship, and encourage involvement in conservation, research and community initiatives related to aquatic ecosystems (Granek et al., 2008).

Moreover, recreational fisheries can generate substantial economic value through tourism, local employment, and equipment production and sales (Sbragaglia et al., 2025). For example, Strehlow et al. (2023), in the German Baltic Sea (Mecklenburg–Western Pomerania) showed that the economic impact of non-residential recreational anglers was eight times higher than residential anglers, and that marine recreational fisheries economic impact of marine recreational fishers exceeded that of small-scale commercial fisheries.

Despite the obvious importance of recreational fishing, it remains one of the least well quantified components of global fisheries. Recreational catches can represent a substantial subcomponent of total catches in some systems, but the available data is often sparse or comes with high uncertainty. This uncertainty does not only limit understanding of recreational fisheries, but also complicates their integration into stock assessments and management decisions. To understand the true scale and the real impact of recreational fisheries, reliable information is needed on who fishes, what they catch, and how fishing affects populations, and how this varies across individuals, locations and time. Developing robust monitoring approaches capable of capturing both catch and fishing behaviour therefore becomes essential for informed fisheries management and sustainable use of aquatic resources.

A key challenge is that recreational fisheries differ fundamentally from commercial fisheries in their structure and observability. They are typically characterised by a large number of dispersed participants, diverse fishing practices, and highly variable effort across space and time. As a result,

recreational fishing activities are difficult to monitor using conventional approaches, and sampling frames are often incomplete or entirely lacking (Taylor et al., 2025). This creates a fundamental mismatch between the scale of the activity and the ability to quantify it.

Understanding the scale, dynamics, and impacts of recreational fisheries is therefore crucial not only for ecological sustainability and stock management, but also for maintaining fishing opportunities, supporting local economics, and preserving cultural and social value associated with recreational fishing. Addressing these challenges require not only improved data collection, but also clearer understanding of how different monitoring approaches can be designed, combined, and interpreted to support effective fisheries management.

This thesis addresses some of the key challenges associated with understanding and quantifying recreational fisheries. It focuses on the lack of effective sampling frames, the difficulty of selecting appropriate survey designs, and the need to capture diverse fishing activities. It further explores how participatory monitoring can complement traditional approaches by expanding data collection. Finally, long-term survey data is used to document life-history shifts, and recreational data from recent years show patterns of selectivity in catches. Together, this thesis examines how different monitoring approaches can be developed and combined to better quantify recreational fisheries and support their integration into stock assessment and management.

“I started fishing with my grandfather when I was seven. Now I fish with my son—we haul the pots and then stop on an island for a fika (coffee break).” – Oscar (born 1984)



## 2. Aim of thesis

The overall aim of this thesis is to improve the understanding of recreational fisheries and their biological implications in coastal ecosystems. Specifically, the thesis examines methodological challenges associated with estimating recreational fisheries effort and catch, explores methods to select appropriate survey design, evaluates the potential of participatory monitoring through citizen science, and investigates biological responses to fishing pressure. Together, the included papers contribute to developing approaches that better quantify recreational fisheries and integrate their impacts into fisheries science and management.

### *Research aims by Paper:*

- I. To develop a probabilistic on-site sampling approach for estimating recreational fishing effort and catch in data-limited contexts, using an indirect spatial sampling frame, and to specifically estimate Swedish recreational cod catches in the Western Baltic stock area.
- II. To propose and apply a structured decision framework for selecting survey approaches for fisheries catch estimation based on multiple dimensions of survey quality, aiding the alignment of management objectives and survey design.
- III. To assess the feasibility and performance of citizen science as a fisheries-independent monitoring approach for generating spatially extensive stock indicators for European lobster.
- IV. To investigate temporal changes in life-history traits of a declining fish stock in the context of commercial and recreational catches and their influences on biological responses.



### 3. The Complexities of Recreational Fisheries

A fundamental challenge in monitoring recreational fisheries is their highly dispersed and heterogenous nature. While commercial fisheries operate under national and international regulated fleets and mandatory reporting systems, recreational fishing, often open access, involves a large number of individuals using diverse fishing methods across extensive areas and time periods. Fishing activity, i.e., effort and catches, is rarely observed, and the outcomes of fishing trips often vary widely in terms of harvest, release, and species composition. The complexity of recreational fisheries creates substantial challenges for estimating fishing effort, catch and ecological impact.

#### 3.1 Diversity of Fishers and Fishing Practices

Participants in recreational fisheries range from the occasional angler to highly specialised fishers targeting particular species or using specialized gear, reflecting substantial heterogeneity in both participation and behaviour. Despite this diversity, survey data frequently reveal recurring demographic patterns among respondents. Surveys frequently report strong gender imbalance and broad age distributions among participants. In western Australia, the typical respondent in a recreational fishing telephone survey of license holders was a male over 45 years of age fishing more than 15 days the past year (Ryan et al., 2025). In the Gulf of Maine, more than 90% of respondents answering an online survey of license holders were male, and over 70% were 40 years or older (Capizzano et al., 2022). The respondents also had high levels of education and income, long experience (average 28 years) and high avidity. In Sweden, 35% of respondents reporting fishing at least once during 2024 in a combined mail and web survey (described in **Paper II**), were female (Swedish Agency for Marine and Water Management (SwAM) and Statistics Sweden (SCB), 2025). However, men spent more than four times as many days fishing than women.

In the onsite survey described in **Paper I**, we encountered and interviewed fishers of ages ranging from 9 to 84, and although the survey was geographically limited, we encountered fishers from across Sweden as

well as several non-swedes (Fig. 1). Comparisons between anglers participating in off-site diary surveys and those encountered on-site has also revealed demographic differences, with diary participants generally being older and sometimes more avid than anglers intercepted at fishing locations (Lewin et al., 2021a). These demographic differences suggest that the recreational fishers consist of multiple participation groups that may be reached differently depending on survey design.

Similar patterns are observed in participatory monitoring initiatives. In the citizen science lobster survey described in **Paper III**, participants are almost exclusively male and predominantly middle-aged, with most reporting more than 20 years of experience in lobster fishery. These self-selected participants therefore represent a relatively experienced and specialized subset of the recreational fishing population, and illustrate how voluntary participation schemes may attract highly engaged fishers rather than reflecting the broader diversity of recreational participants.

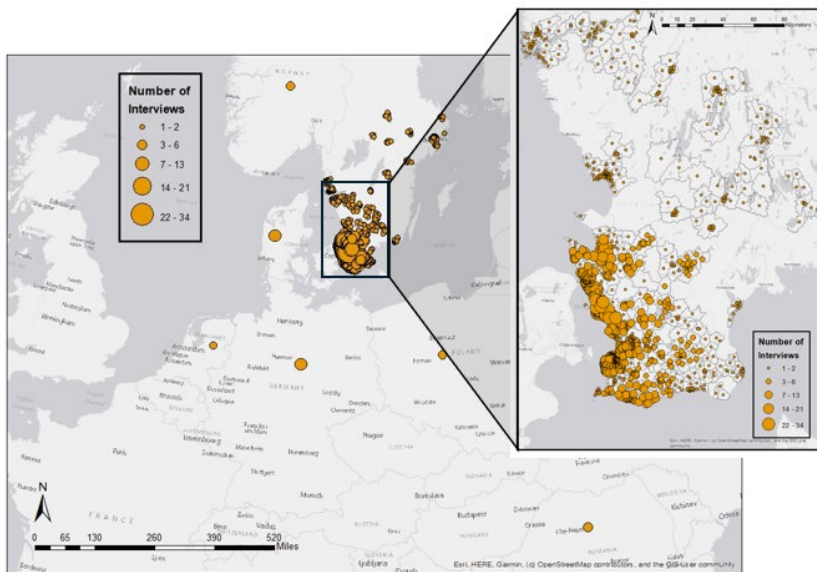


Figure 1. The postal codes of interviewed fishers in the SLU-MRFS described in **Paper I**. Fishers were mainly from the municipalities bordering or in close proximity to the surveyed coast, but a substantial number travelled further, also from abroad.

Beyond demographic variation, fishers also differ substantially in their fishing behaviour, including target species, fishing gear, and catch and release practices (Blyth et al., 2025). In the on-site survey described in **Paper I**, the encountered fishers targeted twelve core species, and reported catches of 20 different fish species. Rod and line was the most common fishing method followed by fishing nets (mostly gill nets). In the Swedish national mail and web survey, most respondents reported spin fishing as their primary method, followed by baited hooks and ice fishing. Other common types of fishing gear or methods used include fyke nets, pots, trolling, flyfishing or handlines. Spear fishing is common in some countries (Sbragaglia et al., 2023; Tarantino et al., 2025), as is shellfish gathering (Anderson and Plummer, 2017; Herfaut et al., 2013).

Fishing modes such as shore-based angling or netting, fishing from private boats, or onboard charter boats attract different types of participants, and be associated with distinct fishing behaviours and levels of specialization (Capizzano et al., 2022; Jiménez-Alvarado et al., 2019; Tink, 2015). Shore based fishing provides an accessible entry point, requiring less specialized equipment and lower cost, whereas charter boat fisheries frequently involve visiting anglers or occasional participants (Scheld et al., 2024; Strehlow et al., 2023). Private boat owners might display higher level of experience and avidity as well as investment in equipment (Soldo, 2022).

Moreover, fishers differ in their motivation for fishing (Birdsong et al., 2021; Blyth et al., 2025). Some fish for food provisioning, while others are motivated by sport or the enjoyment of nature and the outdoor recreation (Arlinghaus, 2006; Cooke et al., 2018; Young et al., 2016). Fishing can serve as a social activity, where time spent with family and friends is as important as the catch itself. The motivation of the fishing trip can influence the fishing behaviour such as choice of methods, target species and attitudes towards catch and release practices.

As a consequence, recreational fishers cannot be characterized by a single type of participant or fishing practice, but by a diverse range of participants whose motivations, knowledge, and behaviours influence how and why they fish. This complexity poses challenges for designing monitoring systems capable of adequately representing the population of fishers.

## 3.2 Spatial and Temporal Dispersion of Activity

Understanding where and when recreational fishing occurs is central to designing effective monitoring programs. Recreational fishing activity is typically dispersed across large spatial areas and varies considerably over time, complicating direct observation, monitoring or assessment of fishing effort. Fishing occurs across a wide range of aquatic environments, from small ponds, rivers, lakes, and estuaries, to coastal zones, archipelagos, and offshore waters (Huddart, 2019; Scheld et al., 2024).

Recreational fishers access fishing grounds through a wide range of formal or informal access points, including beaches, private jetties, marinas, large harbours and boat ramps. Boats may be moored, stored on land, or launched from slipways or shoreline sites, reflecting the diversity of access pathways. Even with geographically limited areas, the number of access points can be substantial. For example, the on-site survey described in **Paper I** included 88 unique access points within the study area (approximately 340 km of coastline), representing around 9000 vessels potentially involved in recreational fishing during periods of high activity (Fig. 2).



Figure 2 In SLU-MRFS a total of 88 access points were included in the indirect sampling frame. They ranged from simple beaches with occasional boats hauled ashore, to large and complex marinas.

The spatial distribution of effort may also be dynamic. Fishers may travel considerable distances to reach preferred fishing locations, particularly when

targeting specific species or fishing opportunities (Strehlow et al., 2023). In the survey described in **Paper I**, fishers encountered in southern Sweden included visitors from other regions of Sweden as well as international anglers (Fig. 1). Fishing locations may also shift spatially over time in response to perceived fishing opportunities, seasonal movements of target species, or changing environmental conditions (Beaudreau and Whitney, 2016; Townhill et al., 2019).

In addition to spatial dispersion, recreational fishing activities can vary substantially over time. Fishing occurs throughout the year but often exhibits strong seasonal patterns (Boukal et al., 2025; Ochwada-Doyle et al., 2021). In temperate and northern regions activity typically increases during spring and summer, when weather conditions are more favourable and daylight hours are longer. In **Paper I**, fishing activity was found to be concentrated during spring and summer, with an increase in cod (*Gadus morhua*) landings in southern Sweden during quarter 3 (Fig. 3).

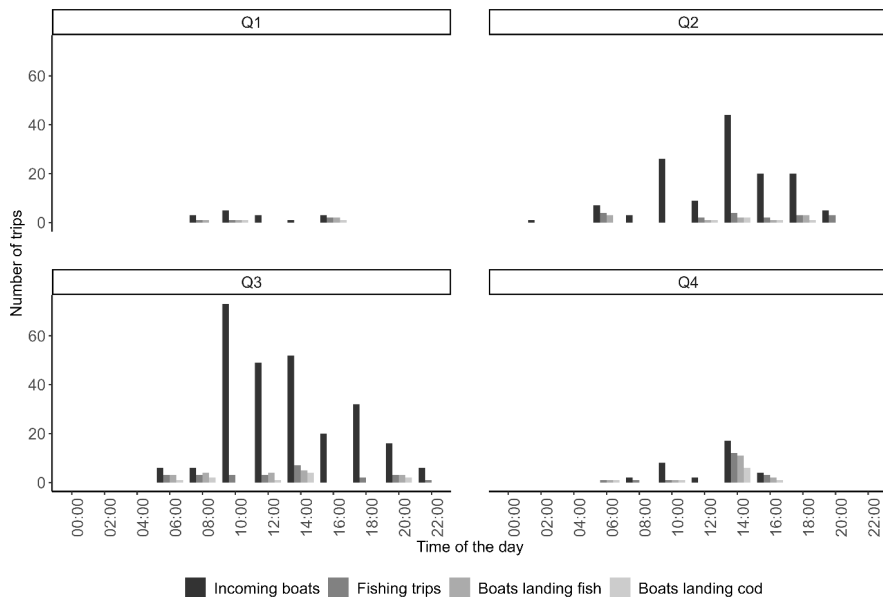


Figure 3 Fishing activity in southwest Sweden during the day, shown by quarters of the year. Boats landing fish includes cod. Modified from **Paper I**.

There are also variations in fishing activity within shorter time scales. Many recreational fisheries exhibit daily patterns, with fishing commonly

occurring during daylight hours and often peaking during early morning or late afternoon periods (Bucher, 2006; Martin, 2013). Higher activity may also occur during weekends, public holidays, or vacation periods when more participants have time available to fish (Bucher, 2006). In Nordic regions, extended daylight during summer months allows fishing activity to continue well into the night. However, the survey described in **Paper I** revealed very limited night fishing in southern Sweden, with fishing activity extending into late evening during summer but rarely occurring after approximately 23:00, despite continued daylight, suggesting that effort is constrained more by human behaviour than by environmental conditions (Fig. 3). In contrast, night fishing can be common in some fisheries or regions, particularly where target species are more active at night or where specialized fishing methods are used (Cooke et al., 2016).

Together, the wide spatial distribution of fishing locations and the strong temporal variability in fishing activity make it difficult to observe recreational fisheries comprehensively. These characteristics pose significant challenges for monitoring programs and require the use of carefully designed sampling programs capable of capturing variation in fishing effort across both space and time.

### 3.3 Catch Processes and Ecological Impact

Estimating the ecological impact of recreational fisheries requires understanding not only how many fish are caught, but also what happens to fish after capture. Because catches are only partially observed, key metrics such as total catch, harvest and release are inherently uncertain. Recreational fishing catches may follow several pathways after capture. Some fish are retained for consumption, while others are released either voluntarily or in response to regulations such as size limits, bag limits, or seasonal closures. As a result, the total number of fish caught during a fishing trip may differ substantially from the number of fish retained.

Harvesting behaviour varies among the recreational fishers, reflecting differences in experience, objectives, and regulatory context. Some focus on retaining fish for consumption, seeking food provisioning, while others primarily practice catch and release fishing motivated by sport, conservation, or in compliance with regulation (Birdsong et al., 2025). Released fish do not necessarily survive, however. Post-release mortality may occur due to

physical injury, physiological stress, predation, or delayed mortality following release (Bartholomew and Bohnsack, 2005). The probability of survival varies widely depending on species, gear type, environmental conditions such as temperature and depth, and handling practices, and is often unknown (Mohan et al., 2020; Schlenker et al., 2016; Weltersbach and Strehlow, 2013). Consequently, the ecological impact of recreational fisheries cannot be inferred from harvested catch alone, as released fish may also contribute substantially to fishing mortality. Empirical observations, including those presented in **Paper I**, show that many species are frequently released, yet key information such as size and post-release fate is often unknown, adding further uncertainty to estimates of total fishing mortality.

Catch processes also reflect differences in fisher behaviour and selectivity. More experienced or specialized fishers can employ more selective fishing techniques, or target specific species or size classes, influencing both catch composition and retention. For example, fishers may retain larger or more desirable individuals while releasing smaller fish (Flink et al., 2024). Such selective harvest can influence population structure, and is a key mechanism linking fishing activity to ecological and life-history change (Matsumura et al., 2011). Evidence from **Paper I** and **IV** suggest that recreational fishers may selectively remove faster-growing individuals or individuals with better condition, indicating that fishing impacts extend beyond simple abundance effects and may influence population traits and reproductive dynamics. Fast growth is often associated with behavioural traits such as higher activity level or risk-taking, which can increase encounter rates with both prey and fishing gear, and is also linked to reproductive fitness (Skjæraasen et al., 2024; Sutter et al., 2012). Similarly, the removal of large, dominant individuals may have disproportionate effects on reproductive success and recruitment (Rowe et al., 2008).

Catch processes can also be strongly shaped by regulations. For example, size limits, seasonal closures, and protection of specific groups (e.g., egg-bearing females) can systematically alter the composition of retained and released catch, leading to systematic differences between the population and the observed landings. This is illustrated in **Paper III** for European lobster (*Homarus gammarus*), where regulatory constraints lead to differences between observed catch and retained individuals; in Sweden the fishery is regulated through a short season, gear limits, minimum size, and a ban on retaining berried females. Data from the LOBSERVE citizen science project

show that catches prior to the season are dominated by larger males, reflecting their faster growth, whereas during the fishing season this pattern is reversed in fisheries dependent data as legal-sized males are preferentially retained while many females are released (Fig. 4).

These interacting processes – heterogenous participants, dispersed activity, complex catch outcomes and limited documentation – make recreational fisheries inherently difficult to quantify. As a result, total fishing mortality in recreational fishing cannot be inferred from harvested catch alone, and robust assessment requires accounting for both retained and released components of catch as well as processes that govern them. Representing the full population of fishers and catches in one monitoring system becomes an almost impossible task. Monitoring programs must therefore rely on carefully designed survey approaches capable of estimating effort, catch and ecological impacts in the absence of direct observations.

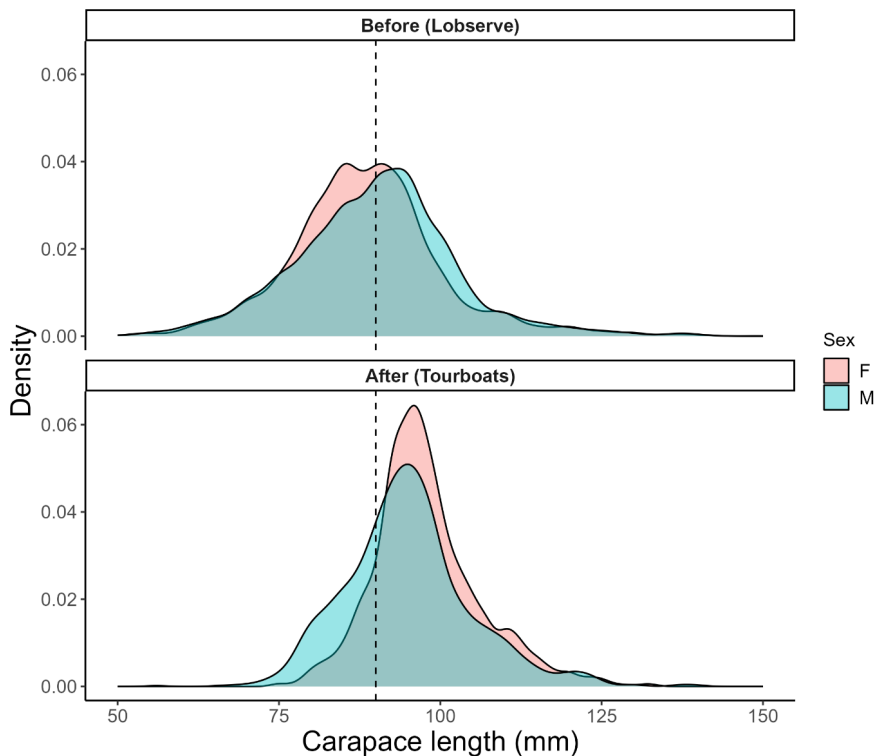


Figure 4 Length frequency distributions (LFD) for male and female European lobster, collected before the onset of the fishing season (top panel), and after the fishing premiere

(bottom panel). Dashed vertical line indicates minimum landing size. Reproduced from **Paper III**.

“I’ve fished since childhood, and more often since retiring 2012. In good weather we head out around nine, haul and rebait our pots, and troll for mackerel. We stop for “fika” on an island or in the boat.” – Jan (born 1949)



## 4. Assessing Recreational Fisheries

Assessing recreational fisheries present distinct methodological challenges compared to most commercial fisheries. Monitoring programs typically rely on survey-based approaches designed to estimate catch, effort, or collection of biological information (National Research Council, 2006; Pollock et al., 1994), but also examining human dimensions such as social, economic and behavioural characteristics (Griffiths et al., 2017; Roth et al., 2001).

The success of such programs depends on the survey design, including the availability of appropriate sampling frames, the choice of data collection mode, and careful consideration of the trade-offs between costs, precision and population coverage. These trade-offs are central to survey design in fisheries monitoring and directly influence the reliability and applicability of resulting estimates.

### 4.1 Survey approaches in recreational fisheries

Survey approaches used in recreational fisheries can be broadly categorized according to the mode of contact, i.e., whether fishers are contacted at the fishing site (on-site) or away from it (off-site) (Fig. 5) (Pollock et al., 1994). These approaches differ fundamentally in their sampling properties, types of bias, and logistical requirements, and are often combined within integrated or hybrid survey designs that capitalize on their complementary strengths.

#### 4.1.1 Off-site Surveys

Off-site surveys are conducted away from the fishing sites and typically involve contacting individuals through mail, telephone, web-based questionnaires, or face-to-face interviews at households. Alternatively, data may be collected through self-reporting mechanisms such as logbooks or catch diaries. An important characteristic of off-site surveys is anglers remembering and volunteering information usually after the completion of their trip (Pollock et al., 1994).

Off-site surveys are particularly advantageous for large-scale monitoring programs, where fishing activities are geographically dispersed and direct observation is impractical. Off-site surveys enable broad population coverage and can provide cost-effective estimates of participation, effort, and

total catch across wide spatial and temporal scales. Their scalability and low cost make them the cornerstones of many recreational fisheries programs (Connelly and Brown, 1995; National Research Council, 2006; Pollock et al., 1994).

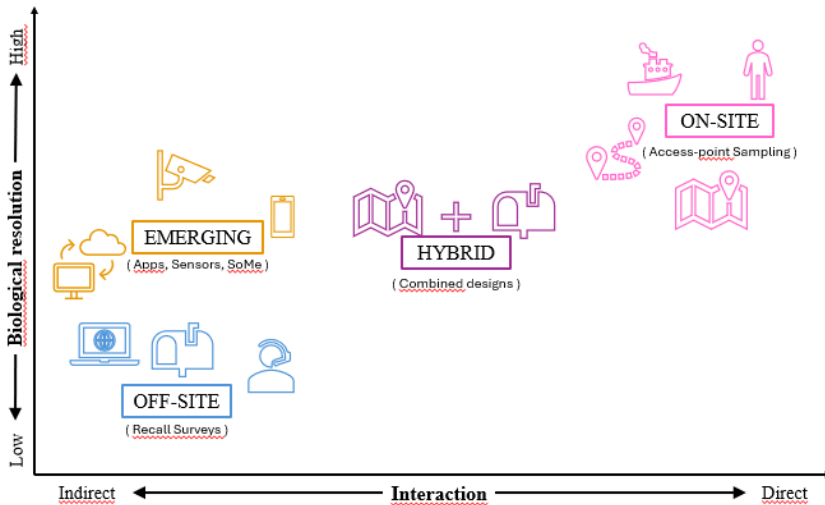


Figure 5 Conceptual overview of data collection approaches in recreational fisheries monitoring along two key dimensions: degree of interaction with the fisher (x-axis) and biological resolution (y-axis). Off-site approaches are characterised by low interaction and generally lower biological resolution, whereas on-site approaches involve direct interaction and provide higher-resolution biological data. Emerging approaches span intermediate positions, reflecting variability in both interaction and data quality, here placed far to the left on the interaction axis given the current dominance of recreational fisher apps among emerging approaches. Hybrid approaches combine elements of multiple designs to balance trade-offs and can achieve moderate to high biological resolution with varying levels of interaction. Chart by Hege Sande.

However, since the off-site surveys rely on self-reported data, several well-known sources of bias are introduced, including recall-bias (failure to accurately remember past events), non-response bias (failure to obtain data from selected units), and coverage errors related to incomplete or imperfect sampling frames. In particular, the absence of a well-defined sampling frame is a recurring challenge in recreational fisheries (see **Paper I**, and Taylor et al., 2025). This issue is discussed further in **Paper II**, where survey approaches are evaluated across multiple dimensions of survey quality.

These limitations necessitate careful survey design, including appropriate sampling frames and validation strategies.

A special type of off-site survey is app-based reporting; it is considered a form of self-reporting, which is traditionally considered as off-site surveys (Pollock et al., 1994), but approximates on-site data collection when entries are made in real time. Apps are further discussed under 4.1.3 emerging approaches.

### *Mail*

Mail surveys are typically based on license registries when available, or more general household sampling frames. Questionnaires are distributed (and returned) by post to a subsample of either recreational fishers (in the case of a license registry) or the general population (Ashford et al., 2009; Pollock et al., 1994). They are relatively low-cost and allow broad coverage, but often suffer from low response rates and long recall periods. An example of a national mail survey (with web options) is described in **Paper II**, demonstrating recall bias (four month reference period) as well as a high non-response (59% in the year considered, 2019).

### *Telephone*

Common methods in telephone surveys are based on random-digit dialling, directory frames, or license databases. The method enables rapid data collection and interviewer clarification, but is increasingly affected by declining response rates and coverage bias. In particular, the shift from landline to mobile phone use challenges traditional sampling frames, as mobile-only users may be underrepresented and phone numbers are less clearly linked to geographical location (Teixeira et al., 2016).

### *Web Surveys*

Web-based surveys can be distributed via email lists, panels, or open links. They can be cost-efficient and flexible, allowing complex questionnaires and rapid processing. However, they depend on internet access and are prone to self-selection bias unless probability-based panels are used, and tend to overrepresent more avid fishers (Ryan et al., 2024). Web surveys are often combined with mail-based approaches (see **Paper II**), where a probability-based sample is drawn and respondents are given multiple response options (e.g., web or paper), thereby retaining sampling control while improving response rates and coverage.

### *Log-books / Diaries*

Diaries are based on self-reporting over time, either retrospectively or in near real time (Connelly and Brown, 1995). These often involve recruited panels of fishers, and provide high temporal resolution data on effort and catch, but require high participant compliance and may suffer from reporting fatigue.

#### 4.1.2 On-site Surveys

On-site surveys involve direct sampling of fishers at or near the fishing location, including access-point surveys, roving creel surveys, or aerial surveys. These approaches allow direct observation and immediate reporting of effort and usually catches, often including biological measurements of harvested fish collected by trained staff (Robson and Jones, 1989; Kinloch et al., 1997; B. Hartill et al., 2020).

A key strength of on-site surveys is the high accuracy of catch and effort data, as information is collected in real time or shortly after the fishing activity occurs, thereby minimizing recall-bias. Additionally, these surveys provide unique opportunities to collect biological data, essential for assessing population status and understanding life-history responses to exploitation.

In data-limited contexts, a central challenge for on-site surveys is the absence of a conventional sampling frame such as a registry of fishers or vessels. In **Paper I** we address this by developing a probabilistic on-site survey based on an indirect sampling frame, using access points as the primary sampling units (Fig.2 and Fig. 6). This approach demonstrates how unbiased estimates of effort and catch can be obtained even when the target population is not directly observable or listed.

On-site surveys are however usually resource-intensive and logistically demanding. Their spatial and temporal coverage is often constrained, requiring well-defined sampling designs to ensure representativeness across locations and time periods as well as fisher groups. Certain segments of the fishery may remain underrepresented if sampling does not adequately cover all fishing modes or times (e.g., access points or sampling times (e.g., night) are not fully comprehensive). In **Paper I**, we did not assume any prior distribution of fishing activity (e.g., sampling effort proportional to access point size). This resulted in fewer observations, high uncertainty in estimates, and extended waiting times for on-site observers, often during inconvenient hours. While night time sampling was considered safe in Sweden, this may

not be the case in other contexts, and staff safety should be an integral consideration in survey design.

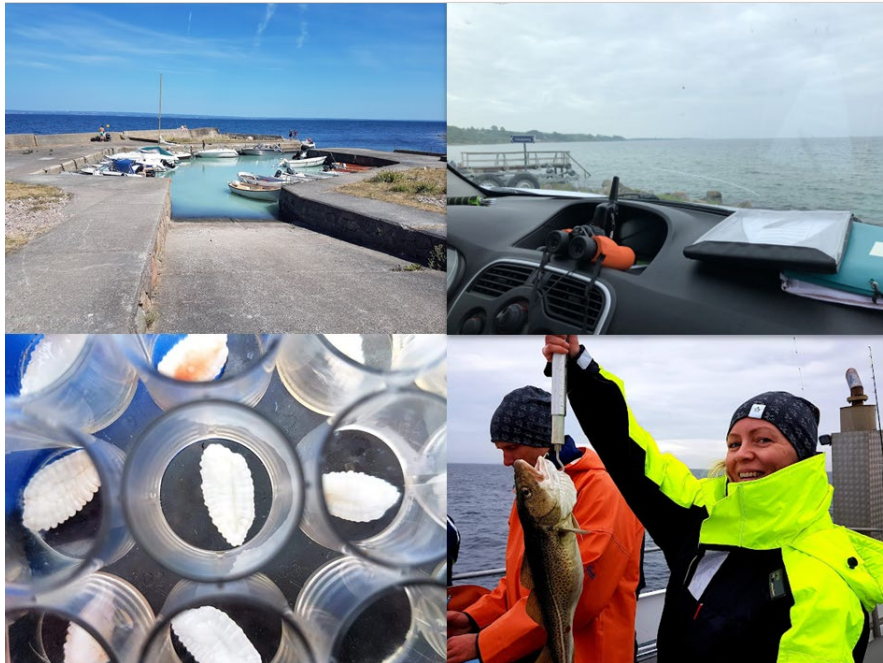


Figure 6 Upper left: Example of a small but active access point. During winter, no boats remained in this location. Upper right: View overlooking an access point, ready with binoculars and protocols to document any fishing activity in the area. Lower left: Otoliths collected from recreationally caught cod. Lower right: Observers from SLU measuring recreationally caught cod. Photo: Hege Sande, Åke Ottosson.

While on-site surveys provide detailed fishery-dependent data, broader biological interpretation often rely on integrating multiple data sources. In **Paper IV**, long-term scientific survey data are combined with commercial and recreational fisheries data to evaluate temporal changes in life-history traits and infer the role of selective fishing. This highlights how different monitoring approaches, including on-site surveys, contribute complementary information for understanding population responses to exploitation.

#### *Access-point Survey*

This survey type is based on predefined access points, such as boat ramps, marinas, or beaches, where fishers are intercepted, typically at trip completion (Fig. 2). The sampling frames are list frames (e.g., lists of access

points), and are typically combined with temporal stratification (e.g., times to sample across days or seasons). This design enables estimation of total effort and catch through expansion of observed trips, and generally provide reliable catch and effort data when coverage is adequate. However, it may miss fishers using unmonitored access points or informal launch sites, potentially leading to coverage bias (**Paper I**).

#### *Roving creel Survey*

In roving creel surveys, observers move between locations and interview fishers *during* the fishing activity. Sampling is spatially and temporally structured, but less tied to fixed points. It allows direct observation of active effort and partial catches, and can provide fine-scale spatial information on fishing activity. However, because trips are typically incomplete at the time of the sampling, estimation of total catch per trip requires assumptions or follow-up, introducing additional uncertainty (Hartill et al., 2020; Kinloch et al., 1997).

#### *Aerial Survey*

Aircrafts, drones, or remote imaging can be used to count fishers or vessels over large spatial scales (Vølstad et al., 2006). Sampling frames are typically spatial grids or transects. This type of survey is efficient for estimating effort distribution and total activity as well as identifying hot spots of fishing activity, but do not provide direct catch data, and require calibration with complementary methods. Aircrafts and drones are also sensitive to weather, limiting sampling to suitable weather-days.

### 4.1.3 Emerging Approaches

Recent developments in data collection, particularly mobile applications and electronic reporting systems, blur the distinction between on-site and off-site survey approaches. These methods are based on self-reporting and conceptually aligned with off-site surveys, but may allow near real-time data entry during fishing activities, thereby reducing bias caused by recall period, and approximating on-site data collection.

Angler apps provide a novel and efficient means of collecting high-resolution data on fishing activity, catches, and angler behaviour across broad spatial and temporal scales (Skov et al., 2021). By enabling near real-time, self-reported data collection, they can complement, or in some cases,

substitute conventional survey methods, often at a lower cost and with improved temporal resolution. App data support a wide range of applications, from estimating effort and catch to analysing fish distributions, environmental drivers, and angler behaviour, while facilitating stakeholder engagement and citizen science (Venturelli et al., 2017).

Such opt-in approaches can however be accompanied by significant challenges. App data are typically subject to participation and reporting biases, including avidity bias, non-random user populations and potential measurement errors. For example, Johnston et al. (2022) found bias in both the recruited angler segment and the data they reported. Additionally, underreporting of unsuccessful trips is common (Hartill and Thompson, 2016), which may lead to overestimation of Catch per Unit Effort (CPUE), particularly in low-catch fisheries such as that described in **Paper I** (only 11% of boat traffic was related to catch, and less than half of all confirmed fishing trips resulted in cod landings).

Another emerging method relies on passively collected digital data, including web scraping of online platforms (e.g., social media, forums, catch-sharing websites) and Text and Data Mining (TDM) (Monkman et al., 2018; Sbragaglia et al., 2020). These data can provide insights into spatial and temporal patterns of fishing activity and catches, at high resolution and often low cost. Such data are however inherently opportunistic and unstructured, and are subject to strong and often unknown biases related to behaviour, platform use, and selective reporting. Hence, they are best used as complementary data sources and require careful validation before use in inference.

With the advance of image analysis and artificial intelligence, approaches to identify and quantify recreational catches in real time are progressing. For example, automated image collection systems (e.g., cameras at cleaning stations) can provide continuous data collection and monitoring of catches (Baker et al., 2025), while AI-based tools may assist with species identification and size estimation from images (Signaroli et al., 2026). Similarly, vessel detection from camera monitoring or remote sensing data can support effort estimation through passive monitoring (Ezzeddini et al., 2024; B. W. Hartill et al., 2020).

These emerging approaches offer substantial potential to increase the spatial and temporal resolution of recreational fisheries data and to support more efficient, hybrid survey designs. Their utility depends on careful

integration with established methods, and on rigorous evaluation of the data quality, bias and underlying assumptions.

#### 4.1.4 Hybrid Approaches

Integrated or hybrid approaches combine on-site and off-site methods within a coordinated design to estimate different components of recreational fisheries, commonly effort and catch. These designs exploit the complementary strengths of each approach and are widely used to improve efficiency and data quality. For example, Hartill et al. (2016) combined continuous web camera monitoring of boat ramp activity with a low intensity creel survey to estimate effort and harvest, providing a cost-effective harvest index.

Comparisons between on-site anglers and off-site diary survey participants suggest that different survey designs may capture somewhat different segments of the fishing population. For instance, Lewin et al. (2021a) showed diary participants to be older and sometimes more avid than anglers encountered at fishing locations. Considering potential participation bias is therefore important when designing monitoring programs. However, they found largely similar catch outcomes once other factors were accounted for – the difference in demographic of the contacted fishing population did not necessarily translate into systematic differences in catch rate. Combining complementary survey approaches may therefore help capture both the diversity and reliable catch estimates, as well as providing methods validation.

Auxiliary data can play a central role in such hybrid design by informing sampling strategies and improving efficiency. When collected within a probabilistic framework, auxiliary data can be used to guide the allocation of sampling effort towards times, locations, or population segments with higher likelihood of fishing activity, or to support the separation of effort and catch rate estimation. This can substantially reduce the sampling costs while maintaining population coverage. A more formalised application is provided by supplemented access point surveys, which incorporate validated auxiliary effort data within a double-sampling framework to improve estimation, resulting in substantial gains in both accuracy and precision compared to traditional access point designs (Steffe et al., 2008).

The use of auxiliary data relies on assumptions about the relationship between observed indicators (e.g., boat counts, app reports) and actual

fishing activity. These assumptions must be empirically verified to avoid introducing bias (e.g., Hartill et al., 2016). For example, in **Paper I** auxiliary data revealed that fishing activity was not proportional to access point size (in terms of number of boats). The access point with the largest cod catches was only the 20th largest in the spatial sampling frame. Only when detailed information on boat characteristics indicative of fishing activity was incorporated (now ranked 8th largest) did a meaningful relationship emerge. Had sampling effort been allocated proportionally to access point size, this would likely have led to underrepresentation of active fishing sites and biased estimation of effort and catch.

In the case of the SLU-MRFS, the on-site study described in **Paper I**, probability-sampled auxiliary data subsequently informed the development of a hybrid approach, combining camera-based detection of effort with a targeted, but reduced, on-site survey, where sampling of access points was proportional to probability of encountering recreational fishing (Sundelöf et al., 2020).

Hybrid approaches thus combine advantages of broad coverage and scalability with improved temporal resolution of the data, but may introduce new challenges and requirements related to data validation, integration, and careful evaluation of underlying assumptions. The strengths and limitations of three different survey designs are explicitly evaluated in the framework presented in **Paper II**, and further discussed in section 4.2 and 4.3.

## 4.2 Sampling Challenges and Incomplete Sampling Frames

One of the most fundamental challenges in assessing recreational fisheries is the often-complete lack of comprehensive sampling frames identifying the population of fishers (Taylor et al., 2025) (**Paper I**). A sampling frame is the operational list or representation of population units from which the sample is drawn (Lohr, 2022) (Fig. 7). In probabilistic survey designs, the frame must correspond to the target population to ensure valid inference and measurable sampling error (Särndal et al., 2003). Undercoverage occurs when members of the target population are missing from the frame, while overcoverage occurs when units are duplicated or if units not belonging to the population are included (Lohr, 2022). If the excluded units differ systematically from those included in the frame, biased estimates will result.

Coverage error, together with sampling error and other sources of non-sampling error, contribute to Total Survey Error (TSE), and can affect the accuracy of survey estimates and, if substantial, may undermine the reliability of management advice generated (Taylor et al., 2025).

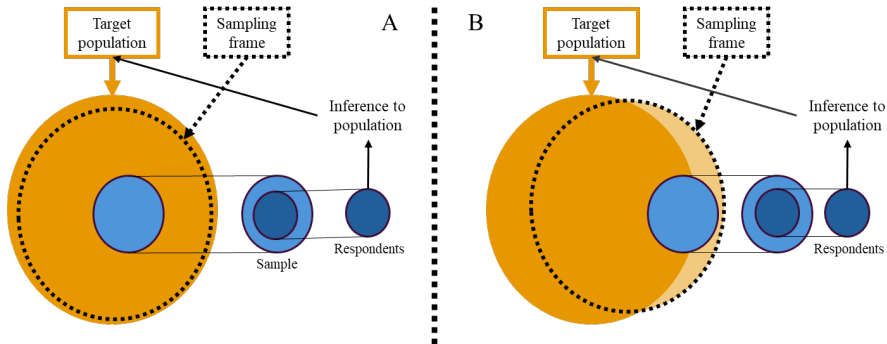


Figure 7 Sampling frames and inference in survey design. A sampling frame should adequately cover the target population and avoid inclusion of units outside that population. A sample is drawn from the sampling frame, of which a subset yields data (respondents), forming the basis for inference back to the target population. Left panel illustrates adequate alignment between target population and sampling frame, with slight under-coverage. The right panel shows misalignment, where incomplete coverage and inclusion errors in the sampling frame may lead to biased inference. Illustration by Hege Sande.

In practice, the assumption of complete sampling frame rarely holds for recreational fisheries surveys. Unlike many commercial fisheries, participation is often open access and not linked to licensing systems or mandatory reporting. As a result, comprehensive sampling frames such as national registries of fishers or fishing vessels, are often missing, particularly in marine systems (Pollock et al., 1994).

The absence of comprehensible sampling frames complicates the implementation of probabilistic survey designs, and requires alternative strategies to identify and access the population of interest. Indirect sampling frames such as household lists or telephone directories can be used (Hartill and Edwards, 2015; Lewin et al., 2021b; SwAM and SCB, 2025; Wynne-Jones et al., 2019), but these can be ineffective in reaching the real target population, increasing the risk of non-response and zero-observations.

Another approach to address missing frames is to construct indirect sampling frames based on locations where fishing activity occurs rather than

on registries of individual fishers (Steffe et al., 2008; Vølstad et al., 2020). **Paper I** demonstrates such an approach, where we constructed a spatial sampling frame of access points along the Swedish south-west coast (Fig. 2). By treating access points as sampling units and applying probabilistic selection of both sites, dates and work-shifts, the survey design enabled design-based estimates of recreational fishing effort and catch despite a complete lack of registries of fishers or vessels. In the absence of existing registries, the spatial frame was constructed through field trips informed and later validated by a priori knowledge and Google Earth satellite images (Fig. 2).

Different segments of recreational fisheries may require different sampling frames. During the access-point survey described in **Paper I**, complementary sampling was conducted aboard recreational tour boats targeting cod. Unlike private boat fisheries, charter operations are easier to enumerate because vessels operate on predictable and publicly available schedules. Biological data collected from these catches, including length and age, contributed to the analyses of life-history changes presented in **Paper IV**. This contrast illustrates how the availability and quality of sampling frames may vary substantially between sectors within the same recreational fishery, and highlights the benefit of multi-purpose sampling design.

Frame limitations also influence participatory monitoring approaches. In the LOBSERVE citizen science survey (**Paper III**), the absence of a registry of lobster fishers meant that participant recruitment relied on self-selection of fishers who met specific criteria, rather than probabilistic selection. Self-selected samples, i.e., volunteers, can infer bias to the survey estimates if the individuals who chose to participate are different from the ones who did not (Lohr, 2022). While such programs can generate valuable ecological data, the resulting samples may not be representative of the broader population, necessitating standardizing procedures with auxiliary data. Implications of participatory survey designs are discussed further in section 5.

A central challenge in monitoring recreational fisheries is hence the difficulty in defining operational sampling frames that adequately covers the target population. Addressing this challenge often involves the creative use of indirect sampling frames, sector-specific approaches, as well as iterative survey development as knowledge about the fishery increases.

### 4.3 Survey Design Choices: A Matter of Trade-Offs

The selection of survey approaches in recreational fisheries inherently involves trade-offs between competing objectives, including accuracy, precision, spatial and temporal coverage, and cost. No single study can simultaneously maximize all desirable properties, and survey design must therefore be guided by the specific objectives of the study, the characteristics of the fishery, and the available resources (**Paper II**).

Different survey approaches exhibit distinct strengths and limitations as outlined in sections 4.1 and 4.2. On-site methodology typically provide high-quality, detailed data but are resource intensive and spatially constrained, whereas off-site and emerging approaches enable broader coverage but are more prone to various sources of bias (National Research Council, 2006). Hybrid designs can improve efficiency by combining complementary methods, but introduce additional complexity in integration and validation (Hartill and Edwards, 2015).

A central technical challenge in evaluating survey design choice is balancing bias and variance. Designs that rely on strong assumptions or non-probabilistic data sources may achieve high apparent precision but risk biased estimates, whereas probabilistic designs ensure unbiasedness at the cost of higher variance and lower efficiency, particularly when sampling frames are incomplete or indirect (see section 4.2 and **Paper I**) (Lewin et al., 2021a; Taylor et al., 2025). However, the importance of this trade-off depends on the intended use of the data, and should therefore be considered in relation to management objectives and decision-making needs.

Moreover, high precision and accuracy are of limited value if estimates are not delivered in time for management decisions or at the appropriate spatial scale. Failing to account for end-user needs during survey design risk rendering the data unusable.

In this context, evaluation of survey design should be structured around key dimensions of survey quality, including *Accuracy* (i.e., Total Survey Error, e.g., sampling error, coverage error, measurement error and non-response error), *Comparability* across time and place, *Relevance* in terms of the data collected matching needs, *Timeliness* of data deliveries, and *Scalability* (the applicability of the survey design to additional species or areas, to long term monitoring, and extensibility to other questions). These dimensions, introduced in **Paper II**, provide a framework for identifying

potential sources of error and for assessing how different design choices influence the reliability and the usability of the resulting estimates (Fig. 8).

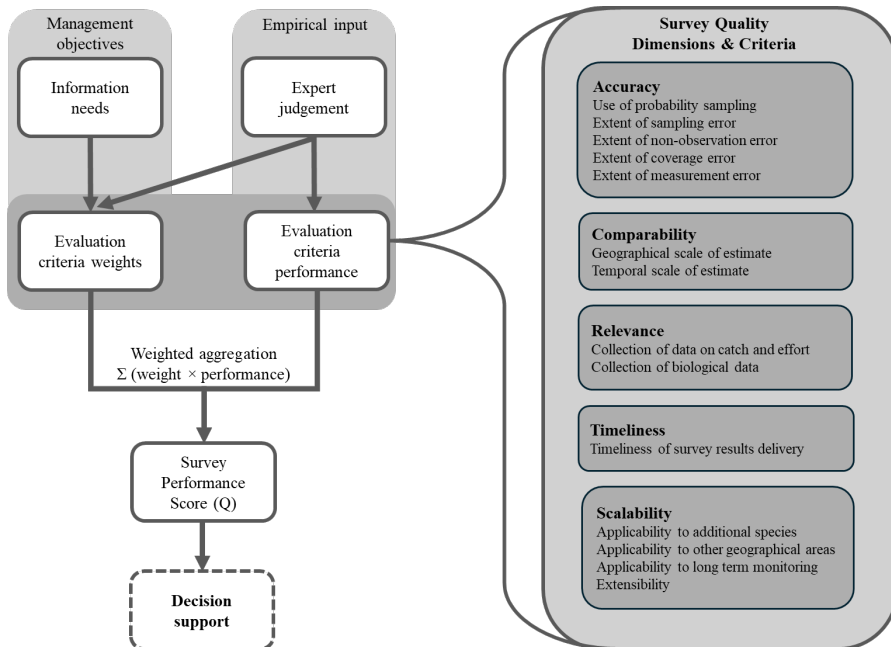


Figure 8 Conceptual workflow for applying the survey selection framework presented in **Paper II**. Information needs are defined by end users, and determine the relative importance of the evaluation criteria and hence the weights. Criterion performance scores, grouped in five quality dimensions, are provided by expert judgement of the candidate surveys. The sum of the product of the criterion weight and performance score form the Total Survey Quality measure, which is informing selection of survey design. Modified from **Paper II**.

Importantly, survey design is not static. As demonstrated in **Paper I**, initial probabilistic sampling – even if inefficient – can provide critical information about the fishery and enable collection of auxiliary data, allowing the safe development of more efficient hybrid approaches in the future. With such information, sampling at night could be excluded from the temporal frame of SLU-MRFS, and sampling effort in access points could be assigned with probability proportional to observed effort.

Survey design in recreational fisheries should be viewed as an iterative process, where early investments in unbiased data collection support gradual optimisation of efficiency, while maintaining transparency about the trade-

offs involved. The optimal design is therefore not a fixed solution, but a context-dependent balance between bias, precision, and feasibility, informed by empirical data and explicit assumptions.

“Fishing with family and friends, heading out from the boathouse in peace and quiet.” – Benkt-Åke (born 1951)

## 5. Participatory Monitoring and Fisher Knowledge

Recreational fishers represent a key stakeholder group in coastal SESs, acting both as subjects of monitoring (through e.g., effort and catch estimation) and as contributors to ecological data collection. Recreational fishers are central to participatory approaches to fisheries science, linking community engagement, outreach and co-management.

Participatory data sources can arise from opportunistic platforms such as recreational fishing apps, e.g., SPÖ-reg (Swedish Agricultural University), RecFishing (official EU app), RecFish (USA/NOAA), FishBrain, Fishbuddy, ANGLR, etc. Data from these apps are generated voluntarily from the user, often with no explicit sampling design. They can also arise from designed citizen science programs, with structured protocols, targeted data collection, and integration with scientific objectives (**Paper III**). While opportunistic data can provide scale and volume, designed programs provide control, standardisation and inference strength.

Citizen science has emerged as a cost-effective complement to traditional surveys, particularly in data-limited fisheries. Anglers can provide catch, effort and biological data across broad spatial and temporal scales (Harris et al., 2021). Citizen science can also support fishery-independent indicators and biological data; the relative abundance index resulting from data collection by volunteers in **Paper III** was successfully included in the stock assessment of European lobster (Sundelöf et al., 2025). The LOBSERVE case illustrates how recreational fishers can be integrated into survey design *by design*, producing data directly usable in stock assessment, while also enabling geographical scaling of surveys that would otherwise be too resource-demanding (Fig. 9). The annual data collection expanded from a local scientific survey to coverage of most of the fished coastline. By scaling up a geographically limited scientific survey, LOBSERVE revealed spatial variation in both catchability and size distributions of European lobster, while substantially increasing the volume of biological data collected each year (**Paper III**).

There are many advantages and opportunities of participatory monitoring; it enables large-scale data collection at relatively low cost and provide access to otherwise small or unavailable fisheries, while increasing stakeholder

engagement and stewardship, improving communication as well as awareness of management measures, and paves the way for co-management frameworks. Moreover, programs can enhance trust, transparency and legitimacy in management (Bonney et al., 2021).

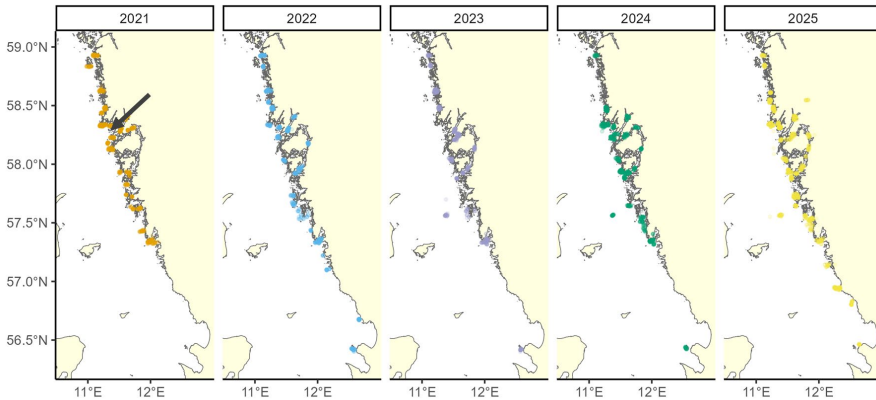


Figure 9 Geographical positions of pots hauled within the LOBSERVE program 2021 – 2025. The arrow in panel 2021 indicate the location of the scientific survey prior to the geographical expansion through LOBSERVE. Figure from **Paper III**.

Recreational fishers possess fisher ecological knowledge. They observe species, habitats and temporal change, and often possess local-scale insights difficult to obtain through conventional surveys. This has the potential to inform surveys, conservation, habitat mapping, and eventually management priorities. The inclusion of recreational fishers in the co-production of knowledge, where science and stakeholder experience are combined, represent an untapped potential (Arlinghaus et al., 2026; Evans et al., 2011).

However, some important limitations must be acknowledged. The users of a Danish smartphone app and website allowing anglers to report fishing trip data were often younger, more specialized and more avid than the general angler population (Gundelund et al., 2020). Catch rate and behaviour may therefore not be representative for all anglers. It is also difficult to retain users over longer time; after 90 days only 21% remained active in the Danish study above. Interestingly, while the users first signing up were younger, the users that were retained more than a year were significantly older, signalling different initial motivation and retention behaviour among groups of fishers.

A further limitation relates to the proliferation of digital platforms. The large number of recreational fishing apps fragments data collection across

platforms, making it difficult to obtain a comprehensive picture of recreational fishers from any single source. Users may distribute their activity across multiple apps or shift between platforms over time, reducing data continuity and completeness. For monitoring programs, this creates an additional challenge in both attracting participants and retaining them within a specific system designed for scientific purposes. As a result, even when participation rates are high at the aggregate level, data may remain siloed, or difficult to integrate across sources.

In contrast to opportunistic platforms, where retention is typically low and strongly linked to user motivation and engagement, LOBSERVE shows moderate but consistent year to year retention (40 – 52%, Fig. 10a, solid line). This level of retention is notable given the voluntary nature of the participation and the level of commitment required (e.g., use of own boat and gear, no gas-refund, all catch is released back into the ocean, and risk of gear loss without compensation). The number of unique exemptions per year varied between 23 and 60, showing high level of interest and engagement in the lobster fisher community (Fig. 10a, columns).

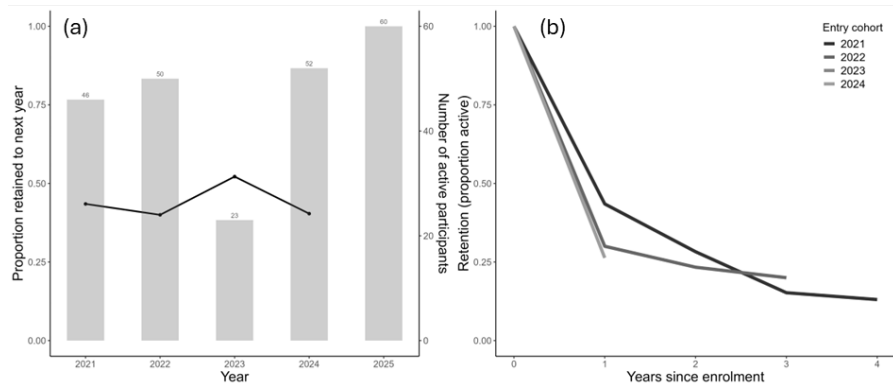


Figure 10 (a) Annual participation and retention in LOBSERVE. Solid line shows the proportion of participants retained to following year (left y-axis), while the columns show the total number of participants (exemptions) per year (right y-axis). (b) Cohort-specific retention curves showing the proportion of participants remaining active as a function of years since first participation (not showing 2025). Each line represents a cohort defined by the first year of participation. Based on data from **Paper III**.

The observed retention in LOBSERVE likely reflects several elements known to support sustained participation. First, participants are highly motivated and often strongly committed to the fishery itself, which aligns

with findings that more engaged or specialized individuals are more likely to remain active over time (Gundelund et al., 2020). Second, the project includes structured and recurring points of engagement: annual results presentations, pre-season methodological briefings, and a participant discussion group through a closed Facebook group. These elements reinforce transparency, clarify expectations, and maintain a sense of community – factors consistently linked to volunteer satisfaction and continued involvement (West and Pateman, 2016).

In addition, participants receive tangible recognition of their contributions, including annual gifts and project-specific clothing. While such incentives are not the primary driver of retention, they signal appreciation and strengthen volunteer identity within the project. While the highest risk of loss is after the initial participation year, once retained the volunteers tended to stay for multiple consecutive years (Fig. 10b). Together these features suggest that LOBSERVE benefits from a combination of good organisational practices, feedback mechanisms, and alignment between participant motivations and project design, all of which are known to promote sustained engagement in participatory monitoring programs (Beirne and Lambin, 2013; West and Pateman, 2016).

“I don’t really think lobster tastes that good, which is why I don’t go more often. There’s just something special about pot fishing that appeals to me, and it’s nice to contribute in some way” – Fredrik (born 1986)

## 6. Ecological Implications of Recreational Fisheries

Recreational fisheries can exert substantial and selective fishing pressure, contributing to ecological and life-history changes in exploited populations (Coleman et al., 2004; Cooke and Cowx, 2004; Flink et al., 2024; Hyder et al., 2018; Radford et al., 2018). As outlined in section 3.3, fishing mortality in this sector extends beyond retained catch to include mortality of released individuals, as well as behaviourally mediated selectivity, resulting in a spatially widespread and often poorly quantified component of total fishing pressure that can contribute to ecological and evolutionary responses in harvested populations.

In many systems, recreational fishing represents a non-negligible component of total fishing pressure. Prior to and during the stock collapse, recreational fisheries accounted for a considerable share of total removals of western Baltic cod (ICES, 2021), highlighting the need to include this sector when evaluating stock dynamics (Eero et al., 2015; ICES, 2021; Lewin et al., 2023). Although Swedish recreational cod catches in the Sound (ICES SD 23) were estimated to account for < 4.6% of the commercial landings in 2018, their impact may be disproportionate due to selective removal of specific components of the population.

Selective mortality is a key mechanism linking fishing pressure to biological change. Results from **Paper IV** demonstrate that both commercial and recreational fisheries disproportionately remove larger cod, with recreational fisheries additionally selecting individuals in better condition (Fig. 11a). Such patterns are associated with truncation of the population size structure, declines in length-at-age and body condition, and shifts towards earlier maturation (declines in L50 and A50, the length and age at which 50% are mature, Fig. 11b, based on data from **Paper. IV**) (Jørgensen et al., 2007; Liang et al., 2014). In addition, fishing mortality may be behaviourally selective, disproportionately removing more active or bold individuals, potentially altering behavioural traits and catchability within populations over time (Olsen et al., 2012). These responses occur in interaction with environmental conditions and resource availability, which may reinforce or constrain the effects of selective fishing pressure (Svedäng and Hornborg, 2014).

The LOBSERVE case (**Paper III**) provides another key example of how regulatory and behavioural selectivity interact to shape population structure. Following the opening of the seasonal fishery, selective removal of legal-sized males leads to a rapid shift in sex-specific size distributions, while protection of egg-bearing females results in differential survival among demographic groups (Fig. 4). Temporally concentrated fishing effort, such as during season openings, can lead to short-term but intense pulses of selective mortality, with potential consequences for reproductive dynamics.

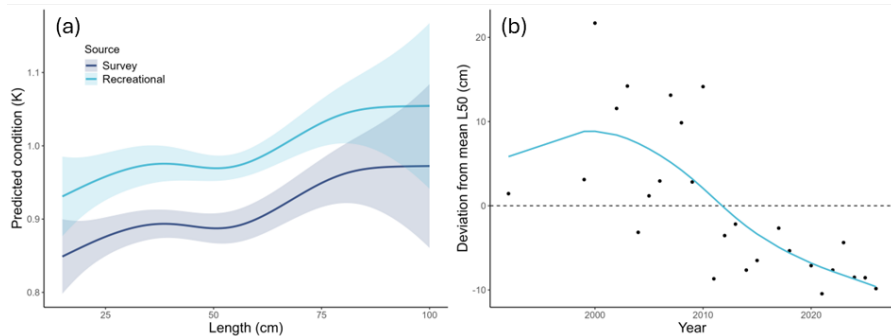


Figure 11 (a) Predicted condition (K) as a function of length for cod caught in 2019, estimated using a GAM, shown separately for survey and recreational fisheries, with shaded areas indicating uncertainty. (b) Annual deviations in L50 from the long-term mean over time. Points represent yearly estimates, the solid line shows a smoothed trend, and the dashed line indicates zero deviation (long-term mean). Based on data from **Paper IV**.

These processes represent life-history responses to sustained selective fishing pressure, with potential consequences for reproductive capacity, resilience, and recovery potential. Changes in size structure and selective removal of larger individuals may also have wider ecosystem implications, for example through altered trophic interactions or changes in the functional roles of large fish (Law et al. 2015).

Importantly, such dynamics are not fully captured by conventional assessment metrics such as Spawning Stock Biomass (SSB), which primarily reflect biomass rather than population structure or selective processes. Detecting and understanding these effects therefore require integrated monitoring approaches that combine fisheries-independent surveys with fisheries-dependent and participatory data sources. In this context, programs such as LOBSERVE (**Paper III**) provide critical resolution on otherwise

overlooked components of fishing mortality and selectivity, thereby strengthening the basis for ecosystem-informed and precautionary management. Translating these insights into effective regulation requires integrating ecological understanding of selectivity and population responses into management frameworks.

“A hearty breakfast and the picnic basket prepared. On goes the Grundéns over a warm base layer, and the red “lucky cap”. The line hauler and boathook are checked, and the baitbox set out. The measuring stick is ready, along with rubber bands for the claws, and repair gear for the pots in case something breaks. After hauling and resetting the pots, freshly brewed coffee and “fika” await before heading home. Any catch is either kept in the holding cage or enjoyed in the autumn darkness.” – Helena (born 1959)



## 7. From Monitoring to Management

Effective fisheries management depends on the availability of reliable data describing both total removals and the biological state of exploited populations. This includes estimates of catch and effort across sectors, as well as information on size structure, condition, maturation, and selectivity. While such data are routinely collected for commercial fisheries, recreational fisheries remain comparatively underrepresented in monitoring systems, despite evidence that they can contribute to total fishing mortality and may exert selective pressure on populations (Flink et al., 2024; Radford et al., 2018; Sutter et al., 2012). This mismatch between data availability and ecological relevance presents a key challenge for sustainable management.

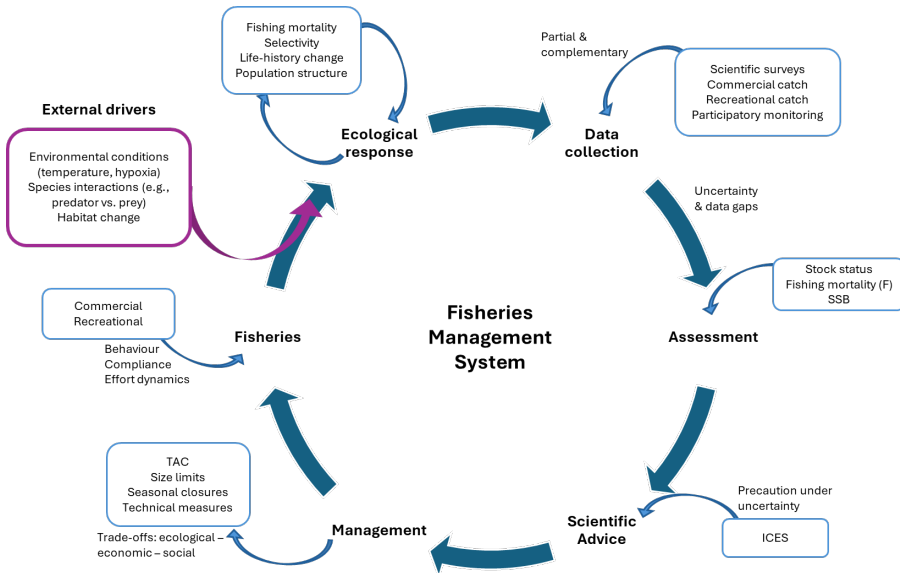


Figure 12 Conceptual overview of the fisheries management feedback loop linking data collection, stock assessment, scientific advice, and management measures with fishing activity and ecological responses. Multiple data sources, including scientific surveys, commercial and recreational fisheries, and participatory monitoring, inform stock assessment, which underpins advice and regulation. These, in turn, shape fishing behaviour and selectivity, influencing population structure and dynamics. External drivers such as environmental change, habitat conditions, and species interactions also affect ecological outcomes. Uncertainty and trade-offs are present throughout the system, influencing both the interpretation of data and the effectiveness of management actions. Illustration by Hege Sande.

More broadly, fisheries management operates as a feedback system in which data collection, stock assessment, scientific advice, and management measures interact with fishing activity and ecological responses (Fig. 12). Within this loop, uncertainties, trade-offs, and external drivers influence both the interpretation of data and the effectiveness of management actions.

Addressing this challenge requires the integration of multiple monitoring approaches. No single method can fully capture the complexities of recreational fisheries, which are characterized by diverse participants, dispersed activity, and variable catch processes. The work presented in this thesis demonstrates how different monitoring approaches provide complementary insights, while highlighting their respective limitations and trade-offs. On-site survey methods (**Paper I**) provide robust estimates of catch end effort in data-limited contexts, while the decision framework developed in **Paper II** highlights how survey design choices involve trade-offs between e.g., precision and coverage. Participatory monitoring approaches, such as the LOBSERVE program (**Paper III**), offer additional capacity to collect spatially and temporally resolved biological data. When integrated with scientific surveys and fisheries-dependent data, these approaches enable a more comprehensive understanding of both fishing pressure and its biological consequences (**Paper IV**).

Such integration is particularly important given the inherent trade-offs in monitoring-design. High-precision estimates often require substantial resources and well-defined sampling frames, which are frequently lacking in recreational fisheries. Conversely, more flexible or opportunistic approaches may increase spatial and temporal coverage but introduce biases that must be accounted for. The decision framework presented in **Paper II** provides a structured approach for navigating these trade-offs, emphasising that monitoring strategies should be tailored to specific management objectives and acceptable levels of uncertainty. In a management context, the key question is not only how to optimise survey design, but what level of information is sufficient to support robust decision-making.

Despite advances in monitoring, important data gaps and uncertainties remain. Recreational fishing effort and catch are often incompletely quantified, and selective fishing patterns may not be adequately captured by conventional data sources. These uncertainties propagate into stock assessment, leading to biased estimates of fishing mortality and stock status. Importantly, uncertainty does not imply negligible impact; rather it

highlights the risk of both underestimating and mischaracterising the role of recreational fisheries in population dynamics.

The implications for stock assessment and management are substantial. The combined catches of Swedish recreational tour boats (Sundelöf et al., 2020) and private boats (**Paper I**) in ICES SD 23 and 24 amounted to 177 t in 2018, which is just above 3% of the TAC and 4.6% of the commercial catches that year (ICES, 2018). While recreational fisheries may constitute a relatively small proportion of total removals at the stock scale, they can represent a non-negligible component of fishing mortality in specific areas and periods and should be considered alongside other pressures affecting the stock dynamics. As demonstrated in **Paper IV**, both commercial and recreational fisheries selectively remove larger individuals and those in better condition. Such selective harvesting contributes to truncation of size structure and shifts in life-history traits, processes that are not fully captured by conventional assessment metrics such as Spawning Stock Biomass. Incorporating recreational fisheries and their selectivity into stock assessments can therefore improve the representation of population structure and reduce the risk of misinterpreting biological signals. More broadly, stock dynamics are influenced by multiple interacting factors, including environmental change, habitat conditions, and species interaction, and fishing mortality represents only one component of this system (Hansson et al., 2018; Receveur et al., 2022).

Translating monitoring data into management action requires decision-making under uncertainty. Fisheries management must balance competing objectives, including exploitation, conservation, and stakeholder interests, often in absence of complete information. Recreational fisheries are not only a source of fishing mortality, but also provide substantial social, cultural, and economic benefits. They contribute to local and regional economies, in some cases generating greater economic value than commercial fisheries in the same area, and play an important role in cultural identity, food provisioning, and individual well-being (Griffiths et al., 2017; Pita et al., 2022). These dimensions must be considered alongside ecological objectives, as management measures affecting recreational fisheries can have direct consequences for livelihoods, social values, and public support for regulation.

Moreover, uncertainties in the magnitude and distribution of fishing mortality across sectors can lead to disproportional or misdirected

management responses. In situations where recreational fisheries are perceived to contribute substantially to total mortality, but remain poorly quantified, there is a risk that management actions are preferentially directed towards this sector due to its diffuse structure and comparable limited political influence. This phenomenon has been described as the Easy Restriction Syndrome (Cardinale et al., 2017), where regulations target stakeholders that are easier to control rather than those contributing most to total mortality. Such approaches may have limited effectiveness in reducing overall fishing pressure, while imposing unintended social and economic cost, with consequences extending well beyond the fishery itself.

In addition, disproportionate focus on recreational fisheries may create an unwarranted expectation of stock recovery if other, larger sources of mortality are not adequately addressed. These considerations highlight that uncertainty operates in both directions; it may obscure impacts, but also lead to management actions that are inefficient or misaligned with underlying drivers of population change.

In this context, precautionary approaches and the use of multiple, complimentary data sources are essential. Monitoring programs not only inform estimates of fishing mortality, but also enable evaluation of fisheries management measures, such as size limits and seasonal closures. The LOBSERVE case (**Paper III**) illustrates how regulations can shape selectivity patterns and population structure, highlighting the importance of considering behavioural and regulatory responses when designing management strategies.

Looking forward, sustainable management of recreational fisheries will depend on the development of integrated and adaptive monitoring systems. Combined survey-based approaches, participatory monitoring, and fisheries-dependent data can improve both the resolution and robustness of available information. At the same time, involving recreational fishers in data collection can enhance data availability, increase transparency, and strengthen legitimacy of management actions. In this context, recreational fishers are not only resource users, but also important contributors to knowledge generation and stewardship. Such approaches align with broader moves towards ecosystem-based and participatory management frameworks.

“I began fishing together with my father, who has experience dating back to the 1940s and grew up in an area where fishing was a primary livelihood. Over the past 15 years, I have fished together with my wife” – Roland (born 1959)



## 8. Future Directions: from Data to Governance

Recreational fisheries monitoring is undergoing a transition from fragmented, largely voluntary data collection towards more integrated and policy-driven systems. This shift is occurring in parallel with increasing ecological uncertainty, stock declines, and growing recognition of the role of recreational fisheries in stock dynamics. Together, these developments place new demands on how data are collected, integrated, and translated into management (Fig. 13).

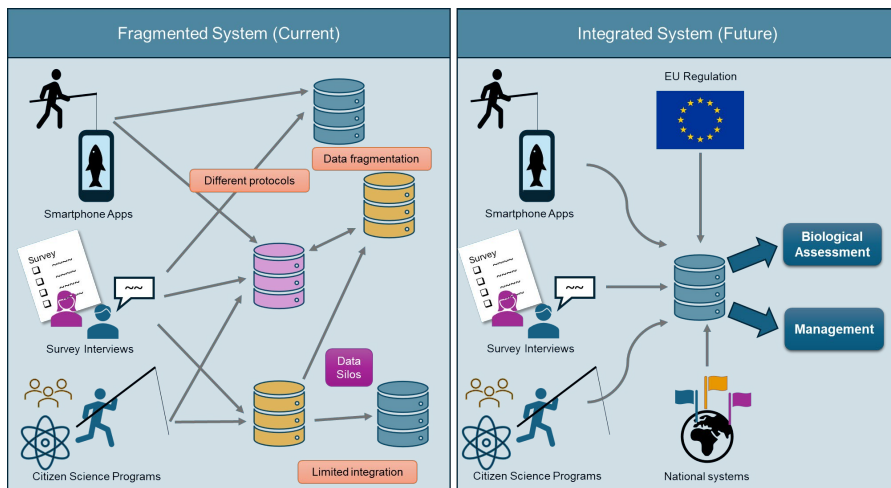


Figure 13 Conceptual illustration of the transition from fragmented, multi-sources recreational fisheries data collection towards integrated, policy-driven monitoring systems. In the current system (left), data are generated across multiple platforms and surveys but remain siloed and difficult to combine. In a future system (right), improved standardization and governance enable integration of diverse data sources into coherent information streams supporting stock assessment and management. Illustration by Hege Sande.

A key challenge moving forward is the integration of increasingly diverse data sources (Mather et al. 2021). As outlined in previous sections, recreational fisheries data are currently generated through a combination of surveys, digital platforms, and participatory monitoring programs. While the diversity provides opportunities for large-scale data collection, it also results

in fragmentation. Data are often siloed across platforms, collected under different protocols, and difficult to combine into coherent indicators at relevant spatial and temporal scales. Addressing this fragmentation will require greater standardisation, interoperability between systems, and coordination across national and institutional boundaries. Without such integration, the full potential of existing data sources is unlikely to be realised. However, it must be noted that integration alone does not guarantee improved inference, and future work must address how heterogeneous and potentially biased data sources can be combined within robust statistical frameworks.

At the same time, recreational fisheries monitoring is becoming increasingly institutionalised. Recent regulatory developments within the European Union, including the introduction of mandatory electronic reporting for certain species through systems such as RecFishing, represent a significant step toward incorporating recreational fisheries into formal data collection frameworks. These initiatives have the potential to improve data availability and comparability across member states, and to strengthen the role of recreational fisheries in stock assessment. However, their current design also highlights important limitations. Monitoring requirements are often introduced reactively, targeting stocks that are already under conservation measures, and may therefore contribute more to documenting decline than preventing it, reflecting the broader tendency for fisheries to be managed passively rather than through structured, proactive frameworks (Pereira and Hansen, 2003). In addition, the effectiveness of such systems will depend on user compliance, data quality, and the ability to integrate these data with existing monitoring programs.

Moreover, the implementation of such regulations may be complicated by mismatches between EU-level requirements and national legislation. For example, although reporting requirements are formally introduced at the EU level, the application depends on national legal frameworks, which may lag behind. This can result in periods where reporting systems are in place but not yet enforceable, creating uncertainty among fishers and limiting early data collection. This challenge is particularly evident in transboundary systems, where fish stocks and fishing effort span multiple jurisdictions, but monitoring frameworks and data standards remain nationally defined.

Practical challenges related to compliance and reporting behaviour may further affect data quality. In cases where fishing for certain species is

prohibited, but incidental catch must still be reported, accurate reporting relies on fishers both understanding and adhering to relatively complex regulations. This introduces potential biases through underreporting, misreporting, or selective participation, particularly if regulations are not clearly communicated or perceived as burdensome. As monitoring systems become more formalised, human dimensions – including trust, perceived legitimacy, and reporting burden – may become the true bottlenecks and primary constraints on data quality and system performance. In addition, the timeliness of data collection and analysis will become increasingly important, as delayed information may limit the ability of management systems to respond to rapid ecological change.

Alternative approaches highlight that different regulatory designs may address these challenges in various ways. For example, systems based on mandatory registration without continuous reporting can be used to establish sampling frames for probabilistic surveys, reducing the burden on participants while still enabling representative data collection (Marcussen et al., 2025). This suggests that the balance between mandatory reporting and survey-based approaches remains an open question in the design of future monitoring systems.

Sustained participation remains a central challenge across both voluntary and mandatory systems. As shown in participatory monitoring programs such as LOBSERVE, described in **Paper III**, long-term engagement depends on a combination of participant motivation, feedback mechanisms, and alignment between user interests and project objectives (Beirne and Lambin, 2013). Moving forward, this raises important questions about how participation will evolve as monitoring becomes more formalised and, in some cases, mandatory. Ensuring continued engagement will likely require balancing regulatory requirements with incentives, transparency, and clear communication of how data are used in management processes.

Finally, the future of recreational fisheries monitoring must be considered in the context of broader environmental and societal change. Many fish stocks are under increasing pressure from a combination of fishing, environmental change, and ecosystem shifts (Cardinale and Modin, 1999; Griffiths and Harrod, 2007; Kraus and Diekmann, 2018; Neuenfeldt et al., 2020). Climate-driven changes in species distribution, productivity, and accessibility are likely to alter both fishing patterns and stock dynamics, further complicating monitoring and assessment. At the same time,

recreational fisheries continue to grow in importance, both as a source of fishing mortality and as a socio-economic activity (Arlinghaus et al., 2015). These developments increase the need for monitoring systems that are not only robust and scalable, but also adaptive to changing conditions. Ultimately, the value of improved monitoring systems lies in their ability to detect biological change, rather than simply increasing data volume.

Together, these developments suggest that the future of recreational fisheries monitoring and science will depend not only on methodological advances, but more on the ability to connect existing approaches within coherent monitoring frameworks. This includes integrating multiple data sources, aligning stakeholder incentives, and embedding recreational fisheries more fully within governance and assessment processes. In this context, the challenge is no longer “just” how to collect data, but how to ensure that these data are sufficiently comprehensive, reliable, and timely to support sustainable management in a changing environment, where biological responses such as changes in growth, condition, and recruitment must be detected reliably, while also accounting for the human dimensions and governance structures that ultimately determine their use.

“Grew up with fishing, as my family are commercial fishers. Has fished every year since childhood” – Fredrik (born 1991)

## 9. Conclusions

In this thesis, I have examined recreational fisheries from multiple perspectives, including survey design, participatory monitoring, and biological change, to address a central challenge: how to generate reliable, management-relevant knowledge in systems characterised by incomplete data and complex human-ecological interactions. Across the papers, I have demonstrated both the potential and the limitations of current approaches, and highlighted the need for more integrated and adaptive frameworks.

Uncertainty remains a defining feature of recreational fisheries. As shown in **Paper I**, the absence of complete sampling frames complicates the design of representative surveys, while different monitoring approaches involve trade-offs between coverage and inference strength (**Paper II**). Simultaneously, **Paper III** illustrates that structured participatory monitoring can generate high-quality biological and fisheries-independent data, even at relatively large spatial scales. Taken together, the results suggest that no single method is sufficient, rather effective monitoring depends on combining complementary approaches within coherent frameworks.

The findings in this thesis do not suggest that recreational fisheries are the primary driver of stock declines. Rather, they highlight a broader challenge in fisheries management: decisions are often made under substantial uncertainty, with incomplete information on total removals and biological responses. This reinforces the need for precautionary approaches that account for uncertainty and integrate multiple data sources rather than relying on single-sector estimates.

In this context, recreational fisheries should not be viewed solely as an additional pressure to be quantified and controlled, but as a potential source of data and knowledge that can contribute to a more complete and precautionary management framework. Appropriately designed, participatory monitoring programs can contribute valuable data, while also fostering engagement and stewardship among fishers. This dual role positions recreational fishers as a key component of future monitoring and management systems.

The results further demonstrate that biological changes in fish populations – such as shifts in size, condition, and maturation patterns (**Paper IV**) – can occur over relatively short time scales. Detecting and

interpreting these changes requires monitoring systems that are not only spatially and temporally extensive, but also sufficiently robust to distinguish signal from noise. In this sense, the development of improved monitoring frameworks is not an end in itself, but a prerequisite for understanding and responding to biological processes.

Looking forward, the main challenge is not simply to collect more data, but to ensure that data are reliable, relevant, and purposeful, while being put to the best use. This requires moving beyond fragmented approaches towards shared frameworks that connect surveys, participatory monitoring, and administrative data. At the same time, human dimensions such as participation, compliance and trust must be considered as central to the success. Without sustained engagement from recreational fishers, even the most advanced technical solutions will fall short. However, improved data alone will not lead to better outcomes unless scientific advice is translated into management action. A key challenge moving forward is therefore to shift from reactive to precautionary and proactive decision-making, ensuring that available knowledge is effectively used in the management process.

Finally, recreational fisheries are deeply embedded in cultural traditions and provide significant social, economic, and health benefits. For many coastal communities, they represent an important connection to marine ecosystems. As such, management approaches should not only aim to quantify their impacts, but also recognise their broader societal value and engage fishers as active participants in knowledge production and stewardship. Integrating recreational and commercial fisheries within a shared monitoring and management framework may provide opportunities to improve both data quality and stakeholder legitimacy, supporting more adaptive and inclusive governance systems. We are currently managing a complex system with incomplete information. Recreational fisheries are part of that complexity – but also part of the solution.



Figure 14 Rod and line fishing outside the Stadt peninsula, Norway. Photo: Hege Sande

“It’s not the size that matters – it’s the story you tell afterwards” – unknown



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# Popular science summary

Recreational fishing is often seen as a small-scale activity, but in reality, millions of people fish every year and collectively catch vast numbers of fish. In some areas, recreational fishing can remove as many fish as commercial fisheries. Despite this, we still know surprisingly little about how much is caught, who is fishing, and how this affects fish populations.

This thesis focuses on improving how we measure and understand recreational fisheries, and what their impacts are on marine ecosystems. A key challenge is that recreational fishers are spread out over large areas, fish at different times, and are not routinely monitored. This makes it difficult to collect reliable data.

To address this, the first part of the thesis develops a new way to estimate how much recreational fishers catch, even when there is little existing information. By sampling fishers at access points using a carefully designed method, it was possible to produce the first reliable estimate of Swedish recreational cod catches of Western Baltic cod.

The thesis also presents a framework to help managers choose the best way to collect fisheries data. Different survey methods all have strengths and weaknesses, and this framework helps balance factors such as accuracy, timeliness, and usefulness for management.

Another part of the thesis explores whether fishers themselves can help collect scientific data. In a citizen science project on lobster fishing, experienced fishers followed a strict sampling protocol and collected data on their catches. The results showed that this approach can produce data comparable to traditional scientific surveys, while covering much larger areas.

Finally, the thesis investigates the life-history characteristics of a heavily fished stock. By analysing long-term data on cod, clear changes were detected: fish are becoming smaller, in poorer condition, and are maturing earlier. Both commercial and recreational fisheries tend to catch the largest fish, and recreational fishers also tend to catch fish in better condition. These patterns indicate selective removal, which can influence the structure and health of fish populations over time.

Overall, this thesis shows that recreational fishing is one component of a complex system that is still poorly understood. Improved data collection can help reduce uncertainty, but no single data source is sufficient on its own.

Reliable understanding depends on combining information across sectors and approaches. Ultimately, better data will only lead to improved outcomes if it is effectively used in management.

# Populärvetenskaplig sammanfattning

Fritidsfiske betraktas ofta som en småskalig aktivitet, men i verkligheten fiskar miljontals människor varje år och fångar tillsammans mycket stora mängder fisk. I vissa områden kan fritidsfisket ta upp lika mycket fisk som det kommersiella fisket. Trots detta vet vi fortfarande förvånansvärt lite om hur mycket som fångas, vem som fiskar och hur detta påverkar fiskbestånden.

Denna avhandling fokuserar på att förbättra hur vi mäter och förstår fritidsfisket och dess betydelse för marina ekosystem. En central utmaning är att fritidsfiskare är spridda över stora områden, fiskar vid olika tidpunkter och sällan ingår i systematiska datainsamlingar. Detta gör det svårt att samla in tillförlitliga data.

För att hantera detta utvecklar den första delen av avhandlingen en metod för att uppskatta fritidsfiskets fångster även när det finns begränsad förhandsinformation. Genom att provta fiskare vid åtkomstpunkter med en noggrant utformad metod kunde den första tillförlitliga skattningen av svenska fritidsfångster av torsk i västra östersjön tas fram.

Avhandlingen presenterar även ett ramverk som kan hjälpa beslutsfattare att välja lämpliga metoder för datainsamling. Tillgängliga undersökningsmetoder har olika styrkor och svagheter, och ramverket bidrar till att balansera faktorer som noggrannhet, aktualitet och relevans för förvaltning.

En annan del av avhandlingen undersöker om fiskare själva kan bidra till datainsamling. I ett medborgarforskningsprojekt om hummerfiske följde erfarna fiskare ett standardiserat protokoll och samlade in data om sina fångster. Resultaten visar att denna metod kan ge data jämförbara med traditionella undersökningar, samtidigt som den täcker betydligt större områden.

Slutligen analyseras livshistoriska egenskaper hos ett hårt fiskat bestånd. Genom långa tidsserier på torsk identifierades tydliga förändringar: fiskarna blir mindre, har sämre kondition och mognar tidigare. Både kommersiellt fiske och fritidsfiske fångar i högre grad större individer, och fritidsfisket tenderar även att fånga fisk i bättre kondition. Dessa mönster tyder på selektivt uttag, vilket kan påverka beståndens struktur och dynamik över tid.

Sammanfattningsvis visar avhandlingen att fritidsfiske är en del av ett komplext system som vi fortfarande förstår dåligt. Förbättrad datainsamling

kan minska osäkerheten, men ingen enskild datakälla är tillräcklig. En tillförlitlig förståelse kräver att information kombineras över sektorer och metoder. I slutändan leder bättre data endast till bättre beslut om de också används effektivt i förvaltningen.

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Kärlek.

"There's a fine line between fishing and just standing on the shore looking like an idiot." —Mark Twain.



# Appendix







# Frameless—finding and refining a sampling frame for surveying recreational fisheries: lessons from estimating Swedish harvest of western Baltic cod

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To achieve sustainable fisheries, advice to management should be based on reliable science and unbiased data. Attaining quality data (i.e. precise and unbiased) on recreational fishing can be challenging, particularly when prior knowledge of the sector is limited and a proper sample frame of recreational fishers or vessels does not exist. In this study, a registry of access points was constructed for the Swedish south–west coast and used as a spatial sample frame in determining both effort and catches of the private boat fishery. Sampling dates, times for sampling, and access points visited were selected using probabilistic methods, ensuring unbiased results. The final multi-stage sampling design involved multiple strata, clusters, and probability selection methods and enabled first-time estimation of Swedish recreational landings of western Baltic cod by private boats to be used in stock assessment. Concurrent data collection covering aspects such as boat counts at access points, provided additional information on e.g. activity patterns. That additional information opens possibilities to refine the design of the original survey and optimize the sampling effort towards different goals, such as other fished resources. In this paper, we reflect on the challenges that limitations in initial information poses to the design and deployment of a new recreational fisheries survey. We suggest ways, whereby indirect sampling frames can be developed from initially incomplete or limited information to access the fishers and their catch. Our experience shows that, despite initial frame and knowledge limitations, full probabilistic methods are worth considering in data limited scenarios and that the design-based point estimates and variances they provide on recreational fishing effort and catches are useful in guiding initial management and the next steps of survey improvement.

**Keywords:** multi-stage sampling, on-site survey, probability sampling, recreational fisheries, western Baltic cod.

## Introduction

To achieve sustainable fisheries, advice to management should be based on reliable science supported by unbiased data. Accomplishing such evidence-based management involves identifying the different types of fisheries that exert fishing pressure on the stocks and obtaining “good enough” data ahead of advice to management and management actions. Commercial fisheries have traditionally been treated as having great impact on the stock status, and commercial landings have long been used as the basis for stock assessment and management (Ricker, 1954; Beverton and Holt, 1957). In recent years, other components of fishing mortality have been increasingly considered, such as the additional mortality caused by discards (Aarts and Poos, 2009; Fernandez *et al.*, 2010).

In total, one fishing sector that exerts relevant pressure on many fished stocks is recreational fishing, with an estimated total global catch (retained and landed) of 900 000 t/year from marine waters (Freire *et al.*, 2020). Estimates from recreational fisheries are increasingly being included in stock assessments worldwide (Radford *et al.*, 2018), and the catches have in many cases been shown to be substantial (Hyder *et al.*, 2018; Radford *et al.*, 2018; Freire *et al.*, 2020). In the United States, the recreational catches dominate over

commercial catches in several fisheries, such as the fishery for red drum (*Sciaenops ocellatus*), spotted sea trout (*Cynoscion nebulosus*), and striped bass (*Morone saxatilis*; NAS, 2017; Shertzer *et al.*, 2019). In Europe, however, marine recreational fisheries remain largely unquantified and only a few stock assessments have, thus far included marine recreational fisheries in their inputs: European sea bass (*Dicentrarchus labrax*), Atlantic salmon (*Salmo salar*), sea trout (*Salmo trutta*), and western Baltic cod (WBC; *Gadus morhua*; Radford *et al.*, 2018). Although there are indications of substantial recreational catches in other stocks, recreational catch reporting has only recently been introduced in the EU Data Collection Framework (EU, 2016), and for a limited number of species. As such, for most stocks, recreational catches remain largely unknown and their impacts are still to be quantified.

Attaining high quality (i.e. precise and unbiased) data on catch, effort and biology of a fishery and its target stocks can be challenging, especially where prior knowledge of the sector is limited, and a sampling frame of fishers or vessels involved in the fishery does not exist. For most commercial fisheries of the International Council for the Exploration of the Sea (ICES) European areas, census data collected under fishery control regulations are available that, alongside good direct

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sampling frames (e.g. registers of licensed vessels), can be used to plan the sampling of landings, discards, and biological data. This situation vastly contrasts that of the recreational counterparts, where census data and control are infrequent and sampling plans scarce. For the latter, the essential first step required ahead of any sample planning then becomes establishing the importance and localization of the fishery itself, i.e. the catches and effort exerted by the different recreational components; only after that is it possible to proceed towards a characterization of length, age, and other biological properties of the catches.

Estimates of catch and effort generally require a probabilistic approach and the use of survey sampling methodologies that allow inference about the target population with measurable sampling error (Maiti, 2021). Registries of fishing license holders or boat owners are examples of sample frames from which samples of recreational fishers can be drawn (Pollock *et al.*, 1994), allowing, e.g. a combination between off-site mail surveys and license sales for effort estimation, with on-site methods for catch rate and biology (i.e. Strehlow *et al.*, 2012). However, in many recreational fisheries a complete record of fishers or fishing vessels is not available and an indirect sampling frame must be used to access the fishers and their catch. In some cases, lists of coastal households exist that can be sampled with off-site questionnaires to provide catch and effort estimates (NRC, 2006). Such off-site surveys are then complemented with on-site surveys that gather catch per unit effort (CPUE) and biological data. Still, in many recreational cases such frame information does not exist at all or is deemed poor in quality. In such situations, a possible sampling frame can consist of a list of access points from which randomized selections can be drawn for the purpose of on-site, simultaneous, data collection on catches, effort, and fish biology by means of interviews to fishers and analyses of their catches.

In Sweden, marine recreational fisheries are to a large extent open access and have been for a long time. The fish resources are perceived by the general public as openly available for harvest for private consumption and there has been societal reluctance to the setting of mandatory registration of fishers, fishing activities, or catches. Routine off-site questionnaire surveys and available knowledge on coastline property regimes, indicates fishing is ongoing during all seasons (HaV, 2019), and that the Swedish marine recreational fisheries consists of three main fishing “modes”: fishing from shoreline (with rods), fishing from private boats (with rods, nets, or pots), and fishing from for-profit tour boats run by local enterprises (with rods). In southern Sweden, tour boat fishing is recognized as a non-negligible source of fishing mortality on some stocks (ICES, 2020), but thus far catches and effort exerted by private boat and shoreline fishing have not been quantified. Besides the lack of a direct frame of registered fishers or boats, one of the main difficulties involved in the quantification of these fisheries has remained the limited knowledge at hand on access point's location, size, and composition. National and local legislation effectuates that nearly all coastline, marinas, and piers are public access. The ports and marinas vary a lot in size and fleet composition (proportion of fishing boats vs. other boats such as sailboats), and a few beaches exist where both private boats and shoreline fishers can also, at least potentially, be found.

In this study, we report on the development of an indirect frame for data collection on catch, effort, and biology of the private boat fishery operating in south-west Sweden,

on the subsequent implementation of the sampling design, and on the estimates it generated, namely with regards to WBC stock, an important EU/management concern. Due to the lack of a registry or mandatory reporting of recreational catches as well as the heterogeneous nature of the recreational fishery, novel methods were warranted to construct a sample frame and obtain data on the effort (number of trips), catch (number of landed and returned fish), and catch composition (sizes of landed and returned fish). A list of access points was constructed and used as a spatial sample frame. Probabilistic methods were used to allocate samples in space and time. Our approach, inspired by the bus route approach (Robson and Jones, 1989; Pollock *et al.*, 1994), made it possible to obtain catch and effort estimates even when starting from an originally frameless situation, where information available was limited and no sampling frame existed of fishers or vessels that could be contacted. In doing this, we demonstrate the impacts that initial assumptions on the fishery, frequently left unchecked in these types of data-limited situations, may have for recreational data collection. Our results are of general interest to researchers responsible for setting up surveys of recreational fisheries in similarly data-limited and frame-limited situations, but also to those specifically involved in the research and management of WBC fisheries.

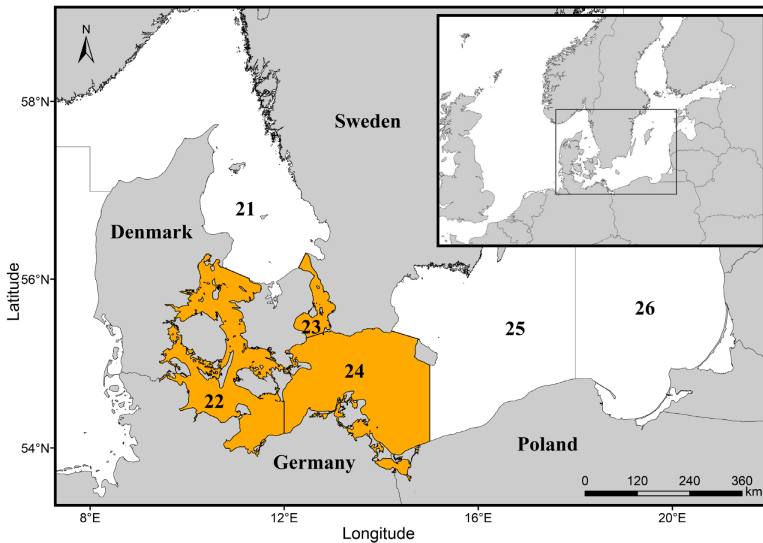
## Methods

### Study area

The study area was defined as the Swedish mainland coastline bordering ICES Subdivisions (SDs) 23 and 24 (Figure 1). The coastline extends roughly for 340 km and includes several large cities (e.g. Malmö and Helsingborg) as well as many small villages and towns, with the total population in the coastal municipalities approaching 1 million. The area is located between 55° and 56°N, characterized by mild summers with ca. 17 h of daylight per day and moderately cold winters with ca. 7 h of daylight per day. Oceanography is highly varying due to the outflowing brackish Baltic Sea water and the high saline inflow along the bottom, with key habitats such as vast sandy banks, rocky reefs, mussel beds, seagrass beds, and kelp forests (Højgård Petersen *et al.*, 2018). There is seldom ice coverage on the coastal waters so recreational fishing activity is possible year-round but expected to be highly modulated by temperature, wind, and daylight conditions.

### WBC stock

In the area defined by ICES SDs 22–24, there is an active recreational fishery that targets several species but that is mainly driven by the aggregations of large cod in SD 23 (Sundelöf *et al.*, 2013) (Figure 1). The cod stock in this area is the WBC stock and its recreational catches are included in the list of recreationally fished stocks on which EU member states are obliged to estimate catches and gather biological data (EU, 2016). The WBC is a shared stock between Germany, Denmark, and Sweden, is considered biologically distinct from the eastern Baltic cod (SDs 24–32) and Kattegat cod (SD 21), and is managed as a separate stock (ICES, 1974). The western Baltic stock is known to be heavily targeted by recreational fishers in at least some of its distribution areas (Eero *et al.*, 2014), and that motivated the integration of its recreational catches in the stock assessment in 2013 (ICES, 2019). In fact, German recreational catches have been estimated to



**Figure 1.** Map of the WBC stock distribution (orange) and the study area. Numbers indicate ICES SDs.

**Table 1.** Sampling design in the SLU Marine Recreational Fisheries Survey. The temporal sampling stages are marked with prime (') to distinguish them from spatial sampling stages. <sup>a</sup>Day = a 24-hour period between 06 a.m. and 06 a.m. the following day.

Stage	Sampling frame	Sampling unit	Sampling method
I	List of municipalities	Municipality	Simple random sampling with replacement (SIR).
II	List of access points within municipality	Access point	Stratified simple random sampling without replacement (STSI), with stratification by geographical proximity.
I'	List of days <sup>a</sup>	Day <sup>a</sup>	Stratified systematic sampling (STSY), with stratification by quarter.
II'	List of work shifts	Work shift	Probability proportional-to-size sampling with replacement (pps), using the size measure “expected effort” where size is expected effort.
II*II'	Scheduling of observation of selected access points within selected day and work shift.		

constitute ca. one-third of total known catches of the stock, thus constituting a non-negligible part of total fishing mortality (Strehlow *et al.*, 2012). This situation largely motivated the need to estimate the Swedish and Danish recreational catches of the stock (ICES, 2019). The WBC fishery by Swedish tour boats has been monitored *via* voluntary catch journals for quite some time (Lovén *et al.*, 2017), but the private boat and shoreline fishery have remained, thus far unquantified.

**On-site survey design**

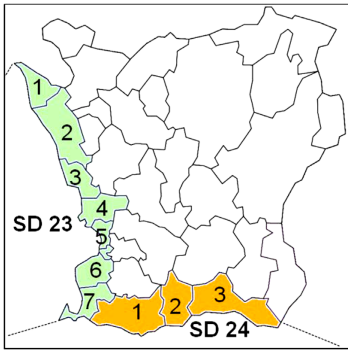
The on-site survey was designed as a multi-stage cluster sampling program (Table 1). The use of stratification within clusters allowed for optimization of travelling times and increased observation time while keeping the design probabilistic and the number of observers required at acceptable levels.

**Sampling frames**

Probability sampling and well-defined sampling frames are two corner stones of statistical survey theory and a necessary requirement for high quality (i.e. precise and unbiased) survey estimates (Quinn and Keough, 2002). There is no registry of recreational fishers or private boats in Sweden, nor are there mandatory licenses for marine recreational fishing.

As such, a list frame was lacking at the start of this study. Additionally, there was limited knowledge on the spatial, seasonal, and diel activity patterns of the private boat fishery. Some recreational fishing clubs and angler associations exist in the area, but it was unknown how representative their registries were in terms of anglers targeting cod. Hence, there was no available sampling frame of anglers from which one could draw a random sample to gather information on effort and catches of the private boat fishery catching cod. Under such circumstances, sample designers are frequently confronted with a dilemma: should they aim at a design involving a non-probabilistic method that makes use of partial (and potentially biased) readily available information (such as assumed fishing activity related to size of marinas or population size) to achieve some degree of efficiency but produces biased estimates? Or should they aim at a probabilistic design that albeit suboptimal in terms of efficiency, still provides unbiased estimates from the fishery? The option taken in this study was the latter.

A possible solution to implement a probabilistic approach in sampling of frameless recreational fisheries, is meeting anglers and their boats directly at the places and times where they are most likely to be found and concentrate. Natural candidates, when the spatial distribution of an off-shore fishery is



**Figure 2.** The main survey area corresponds to all municipalities with coastline bordering ICES SDs 23 and 24. The first border municipalities (SDs 21 and 25) were also included in the survey during 2017.

unknown, are local harbours from where boats depart and return daily to/from the fishing grounds. When designing such a survey, one needs to do it in a probabilistic way, securing that all possible harbours and times are included in the frame at the beginning of the study so that all, or nearly all, yet-unknown anglers and boats participating in the fishery have a positive and known chance of being interviewed, and that later decision-making on efficiency improvements to data collection can be *de facto* evidence-based.

The knowledge of the spatial and temporal distribution of the private boat cod fishery and its harbours and landing sites available at the start of the present study was limited or outdated. Since this was a first-time characterization of this fishery, we found it important to use a full frame of spatial and temporal aspects and avoid the impacts that possibly strong erroneous assumptions on harbour importance or diel activity could have on study results and perception of the fishery. As an example, it was unknown whether larger or smaller marinas accounted for most of the fishing activity, since the largest marinas are also known to be prime sailboat spots. Accordingly, a stratified multi-stage cluster sampling survey was designed with the aim of collecting data on angler's effort and catches directly at the places and times of their return from the fishery, i.e. the access points of private boats in southern Sweden, namely marinas, piers, small beaches (< 1 km), and camping sites.

#### Main spatial sampling frame

In the first spatial sampling stage, municipalities (considered as clusters of access points) were stratified on SD (Figure 2). In each SD, the nearest neighbouring municipality outside of the survey area (in SDs 21 and 25, termed “fringe municipalities”) was initially included in the sample frame to examine the chance of “spill-over effort,” i.e. boats originating in neighbouring areas fishing inside the survey area waters and returning to those initial places. Municipality was selected by random sampling with replacement, with unequal probability (see Table 1 for a simplified sampling design). All municipalities, where trips aiming at SDs 23 and 24 could depart from were, therefore, included in the study. The main municipalities, i.e. those bordering on SDs 23 or 24, were assigned a selection probability of 0.9, while “fringe municipalities” were

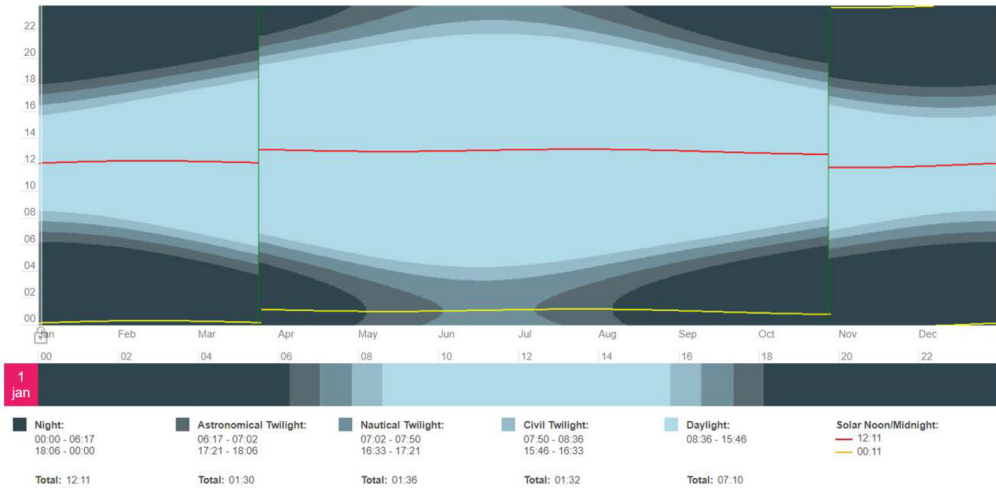
assigned the probability 0.1. More sampling effort was allocated to the stratum SD 23 where an existing national survey indicate most catches to be concentrated (HaV, 2019).

In the second spatial sampling stage, a stratified random sample of access points was selected without replacement. A registry of access points was created during field trips to the area in late 2016, starting from information available from scientific and technical SLU personnel with *a priori* knowledge of the area. The list was then both validated and slightly augmented using present and historical Google Earth satellite images. In the end, a list of 84 access points was built that included all access points in the study area from which private boats could initiate a fishing trip. The access points ranged in size from marinas accommodating just a few boats to several hundred boats, with variable proportions of boat types (fishing, sailing, and so on) and sites such as beaches or camping sites. Access points were clustered in municipalities and further stratified within municipalities according to the geographical proximity to facilitate the logistics of data collection. Within each municipality, between one and three strata of access points were determined. The R package “ggmap” (Kahle and Wickham, 2013) was used to determine the travel time between access points within municipalities, and a cluster analysis was then used to identify access points with a driving distance of less than 20 min within strata and 30 min between strata (R Core Team, 2013).

#### Main temporal sampling frame

In the first temporal sampling stage, days of the year (here defined as the time spanning between 06 a.m. of one day and 06 a.m. the next day) were stratified into quarters. Days to sample each quarter were selected systematically with a random start. During the first year (2017), planned sampling effort was initially set to 18 days per quarter (Quarter 1 (Q1) and Q2) and then increased to 30 days per quarter during Q3 and Q4. In 2018, planned sampling effort was lower in Q1 and Q4 (15 days per quarter) and higher during Q2 and Q3 (30 days per quarter). Since only one municipality could be sampled each day, days where SDs 23 and 24 would be sampled were grouped in sampling “waves” to optimize the staff travelling time to the area during the multiple sampling occasions undertaken each quarter. Within each quarter a predetermined number of sampling waves were planned, spaced 15 days apart. This design implicitly ensures the proportional coverage of both weekdays and weekends throughout a quarter.

In the second temporal sampling stage, one work shift was selected for each day and municipality. Partitioning the day into work shifts was necessary to comply with Swedish working-hours regulations, which stipulate a max number of working hours in regular days. At the start in 2017, the work shifts were 06:00–14:00, 14:00–22:00, or 22:00–06:00. Unequal probabilities (0.4, 0.4, and 0.2, respectively) were used to accommodate probabilistically the expectation of lower activity during the 22:00–06:00 shift while maintaining its coverage (Diogo and Pereira, 2016). In the Northern Hemisphere, light conditions vary substantially between seasons, increasing from about 7 h daylight during winter solstice to 17.5 h at summer solstice (Figure 3). The combination of a partition of days into daily shifts and full coverage of all periods of the day enabled the comparability of estimates across quarters.



**Figure 3.** 2017 Sun graph for Malmö. “Night” occurs when the sun is more than 18° below the horizon. Red and yellow lines indicate solar noon and midnight. Daylight varies between ~7 h at winter solstice (December 21) and 17.5 h at summer solstice (June 21). Copied with permission from <https://www.timeanddate.com> (Copyright © Time and Date AS 1995-2022. All rights reserved). Accessed and retrieved on 3rd March 2021.

**Combination of spatial and temporal frames**

One sampling day consisted of a calendar day, a municipality, and a work shift (06–14; 14–22; and 22–06). For each municipality, public access points to visit and their order was set randomly within each stratum, and the starting time and duration of each access point visit was allocated via an R script. The design ensured randomized geographical and temporal coverage of the coast. For further details on the survey design see supplementary material SM1–3.

**On-site sampling procedure**

Upon arriving at an access point, observers took position on pre-selected look-out points with a clear view of the entrance to the access point and easy access to the docking places where incoming boats would anchor. Contact was also made with the marina personnel or equivalent, informing them about the observer presence and the purpose of the survey. The observers worked in pairs, and followed strict protocol on task partitioning. While one observer kept the entrance in sight at all times to observe, count, and classify incoming traffic, the other observer carried out interviews, and counted and classified the boats currently located in the access point. When access points were beaches or camping sites, sampling procedures were maintained with only minor adaptations needed to meet the specifics of each place. Communication between observers by walkie-talkie and the use of a bike ensured the possibility of reaching the incoming boats for interviews even when anchoring places were more distant or the incoming activity high.

The sampling procedure was divided in two main components:

I) Boat activity in access points.

During designated access point visit times, all vessels arriving to the access point were counted, separating recreational fishing boats from other boats based on

external characteristics. Incoming boats were approached for an interview about their trip and potential catches were inspected. Information obtained about the trip was collected, including the fishing mode and gear used, targeted species, area fished and time spent fishing there, the number of fishers in the boat, and whether more fishing trips were planned that day. The fishers were also asked to recall the total number of fishing trips of that fishing mode completed in the last quarter, and demographics such as gender, age, and postal code were noted (for complete interview form see supplementary material SM4). Participation in the survey was voluntary.

II) Catch.

At the start of the interview the fishers were asked about their catches, namely numbers or weight retained and released per species. The retained catch was then identified at the species level by the observer, individual fish were measured and weighed (when possible), and otoliths removed for age determination. When catches had been processed at sea (e.g. gutted, cleaned, and/or filleted), weights were not obtained. The observer counted the fish, or provided an estimated count of individuals landed per species (based on filets). The number of released fish per species was estimated by the fisher.

**Adjustments to the sampling frame in 2018**

With the information and knowledge gathered during 2017, some adjustments to the sampling frame, focused on increasing precision, optimizing observer field time, and improving work conditions of observers while increasing the likelihood of interviews, were introduced in 2018. Available evidence from data collected during the first year of the survey indicated that recreational fishing vessel arrivals were rare during the dark hours, irrespective of the time of the day, and that cod fisheries during such dark periods were negligible.

Consequently, the shift 22:00–06:00 was dropped in Q1 and Q4 2018 and, within the 06:00–14:00 and 14:00–22:00 shifts only ports selected for sampling during “light hours” (defined as the part of the day between nautical dawn and nautical dusk + 2 h; Figure 3) were surveyed, the ports in the shifts to be visited during dark hours being assumed to have registered zero activity during their scheduled “dark hour” visit. The spatial sampling frame was also adjusted by removing the two “fringe municipalities” that in 2017 revealed negligible contribution to SDs 23 and 24 fishing effort, the merging of two adjacent municipalities (4 and 5 in Figure 2) and the merging of two access points in municipality 7, which experience revealed could be surveyed simultaneously. Alongside a range of other minor changes, including some within municipality re-stratification to optimize travel times, the adjustments allowed for a significant increase in observation time in the most active times of the day and areas of the coast, and an overall increase in the probability of selection in the stage I of the design that could, as results demonstrate, be used to provide observers with a much needed 30 min resting break in each shift, with only a slight reduction in average observation time (< 5 min, see results).

**Auxiliary data collection**

With the aim of better characterizing the study area and facilitating the future improvement and optimization of the sampling scheme, observers were requested to count all vessels present at the access points. These counts took place in all visits to access points and made use of the available time (e.g. before the start of the observation time or during periods of low incoming trip activity), involving the classification of moored vessels into categories chosen to indicate the likelihood of the boat in question to contribute to recreational fishing effort: (1) *private boats—non-fishing* (e.g. sailboats and large yachts), (2) *private boats—fishing*, and (3) *commercial fishing vessels* (district code on hull). This classification of boat-type was developed and refined as experience was gathered, and in 2018 category 2 was further separated into (a) *private boats—fishing* (smaller yachts), and (b) *engaged fishing* (boats with clear signs of being used actively for fishing such as rod holders, nets, rods, fishing baskets, or gillnet flags inside or near the boat). Inter-calibration among the field observers (using a photo library) was performed to minimize bias in individual category identification.

**Data analysis**

**Design-based estimation of retained catch**

From our sample survey, we mainly wanted to estimate one finite population total: the total number of cod landed by recreational fishing from private boats in a given geographical area during a year. Because we used a multi-stage sampling design, this unknown total is expressed as a sum over the sampling stages. The primary sampling units in our multi-stage design were municipalities. We denote a set of all municipalities of interest by  $U_I$  of size  $N_I$ . The secondary sampling units were access points. We denote a set of all access points in municipality  $i \in U_I$  by  $U_{IIi}$  of size  $N_{IIi}$ ,  $i = 1, \dots, N_I$ . To take the extension of our population over time into account, we first introduce a set of all days of interest. This population is denoted by  $U_{II'}$  of size  $N_{II'}$ . The set of all (three) work shifts in day  $d \in U_{II'}$  is denoted  $U_{III'd}$  of size  $N_{III'd}$ . Now, the population

total we wanted to estimate is given by

$$t_y = \sum_{U_I} \sum_{U_{IIi}} \sum_{U_{II'd}} \sum_{U_{III'kd}} y_{q,k},$$

where  $y_{q,k}$  is the number of cod caught by all recreational fishers arriving with a private boat to access point  $q$  during work shift  $k$ . This equation denotes an unknown quantity that must be estimated.

Before we proceed to the estimation of  $t_y$ , let us recapitulate the sampling design and at the same time introduce some more notation. To simplify, in this section, we ignore the stratification in stage I and  $II'$ —in other words, we consider only one municipality stratum and one quarter. Expansion to all strata is straightforward, but requires more notation. Another more important simplification is that we do not take the use of “waves” or travel routes into account, but treat all sampling in time (of days and work shifts) as completely random.

**Stage I.** By use of simple random sampling with replacement, we made  $m_I$  draws of municipalities from  $U_I$ . The draws of municipalities resulted in an ordered sample  $os_I = (i_1, \dots, i_v, \dots, i_{m_I})$ , where  $i_v$  denotes the municipality selected in the  $v$ th draw,  $v = 1, \dots, m_I$ . In each draw, the probability of selecting municipality  $i \in U_I$  was  $p_{Ii} = 1/N_I$ .

**Stage II.** For every municipality drawing  $i_v$  in  $os_I$ , we independently selected a simple random sample without replacement of access points. The sample from municipality drawing  $i_v$  is denoted  $s_{IIi_v}$  of size  $n_{IIi_v}$ . The conditional probability (conditional on the drawing of municipality  $i$ ) for access point  $q \in U_{IIi}$  to be included in  $s_{IIi_v}$  was given by  $\pi_{IIq|i_v} = n_{IIi_v}/N_{IIi}$ .

**Stage II'.** For every municipality drawing  $i_v$  in  $os_I$ , we independently and randomly selected 1 day during the quarter. The conditional probability (conditional on the drawing of municipality  $i$ ) for day  $d \in U_{II'}$  to be selected was given by  $\pi_{II'd|i_v} = 1/N_{II'}$ . The selected day for municipality drawing  $i$  applied to all selected access points in this municipality drawing.

**Stage III'.** For every combination  $(q, d)$  of access point and day selected in the preceding stages, we independently and randomly selected one 8-hour work shift with unequal probability. The conditional probability (conditional on the drawing of municipality  $i$  and day  $d$ ) for work shift  $k \in U_{III'd}$  to be selected is denoted by  $\pi_{III'k|i_v, d}$ .

In each selected combination  $(q, k)$  of access point and work shift, we made observations for  $T_{q,k}$  minutes. Let  $y_{q(obs),k}$  denote the observed number of cod caught by all recreational fishers arriving with a private boat to access point  $q$  during the observed part of work shift  $k$ . The total length of the work shift was  $T_k$  minutes. Consider the observed minutes as a random sample from all minutes during the work shift. Under this assumption,  $\hat{y}_{q,k} = (T_k/T_{q,k}) y_{q(obs),k}$  is an unbiased estimator of  $y_{q,k}$ .

Estimation of the total landings of cod,  $t_y$ , was much simplified by the fact that sampling was done with replacement in Stage I. Then, from Särndal et al. (1992, Result 4.5.1), an unbiased point estimator of  $t_y$  is given by

$$\hat{t}_y = \frac{1}{m_I} \sum_{v=1}^{m_I} \frac{\hat{t}_{i_v}}{p_{Ii_v}} = \frac{1}{m_I} \sum_{v=1}^{m_I} N_I \hat{t}_{i_v},$$

where

$$\hat{t}_{i_v} = \sum_{s_{IIq|i_v}} \frac{\hat{y}_{q,k}}{\pi_{IIq|i_v} \pi_{II'd|i_v} \pi_{III'k|i_v, d}},$$

**Table 2.** Summary of sampling effort and observed activity of fishing during the survey years 2017 and 2018. AP = access point.

	2017	2018	Total
Sampling days ( <i>n</i> )	95	88	183
Observation time (h)	593 h 16 m	483 h 14 m	1 076 h 30 m
Daylight observation (h)	387 h 41 m	441 h 11 m	828 h 52 m
% daylight observation	65.1	87.0	75.1
Effective observation time/sampling day (h)	06 h 16 m	05 h 30 m	05 h 53 m
Unique access points ( <i>n</i> )	83	68	88
Visits to access points ( <i>n</i> )	533	487	1 020
Visits to access points/sampling day	5.61	5.53	5.57
Average time in AP (h)	01 h 7 m	0 h 59 m	01 h 3 m
Incoming boats—observed	173	272	445
Incoming boats class rec fishing	34	46	80
Interviews			
Incoming fishing	31	34	65
– With fish landed	20	28	48
– With cod landed	10	16	26
Number of cod landed	35	57	92

and an unbiased estimator of the variance of  $\hat{t}_y$  is given by

$$\hat{V}(\hat{t}_y) = \frac{1}{m_I(m_I - 1)} \sum_{i=1}^{m_I} \left( \frac{\hat{t}_{i_{iv}}}{p_{I_{i_{iv}}}} - \hat{t}_y \right)^2$$

If instead we want to estimate the total number of recreational fishing trips, let  $y_{q(obs), k}$  in the above estimation procedure denote the observed number of incoming private boat “fishing” to access point *q* during the observed part of work shift *k*.

Calculations were made using R version 4.0.3 (R Core Team, 2013, 10-10-2020, RStudio Team, 2021).

## Results

The total sampling effort of the 2017 and 2018 surveys amounted to 183 days and over 1000 h spent at access points. A total of 83 unique access points were visited in the first year. During this survey, 445 private boats were observed returning to an access point and approached for an interview. A total of 80 of these were classified as a recreational fishing vessels by the observers, i.e. only 18% of all private boats arriving to the access points displayed signs of routine involvement in recreational fishing. Interviews confirmed 65 (14.6% of all traffic) were actual fishing trips (Table 2).

### Effort and catch

#### Fishing effort

The number of observed incoming boats (completed “trips”) was generally higher during Q2 and Q3 compared to Q1 and Q4 when all boat-types are considered. The number of boats returning after a completed fishing trip, private boats landing fish, and private boats landing cod (all confirmed by interview) varied somewhat between quarters (Figure 4). Of all the observed incoming boats, 20% and 17% were classified as recreational fishing boats by observers in 2017 and 2018, respectively, while interviews confirmed that 18% (2017) and 12.5% (2018) had actually been fishing (Table 2).

The number of completed fishing trips is estimated by quarter and SD for 2017 and 2018 (Figure 4 and Table 3). A total of 27 000 fishing trips is estimated to have taken place in 2017, increasing to 36 000 in 2018. It is noticeable that the increase can almost alone be justified by the contribution of Q4. In 2018 the good weather conditions that occurred

during Q2 and Q3 and also during much of Q4 (Supplementary material SM5) have been the likely main driver of the increase in point estimates and variance in 2018 relative to 2017.

#### Catch composition

The survey design covered all recreational fishing trips returning to access points in the survey area, regardless of target or bycatch species in the catch. Interviews in access points revealed a large number of species caught (*n* = 20; Figure 5) but also large variability on what was kept and released. Cod was the most common target species by far, with more than half of the interviewed boat fishing parties stating this to be their primary target species (Supplementary material SM6). The second largest group (8% of the interviewed) had no particular target species in mind, while mackerel or herring were targeted by 6% of the interviewed fishers. In 2017 and 2018, respectively, about 63% and 82% of those interviewed who had been fishing actually landed fish. In total, 27% of the interviewed fishers returned without any catch (Table 2).

#### Catch estimates—the case of WBC

About 11% of all observed incoming boats landed fish (Table 2 and Figure 4). A total of 32 % (2017) and 47% (2018) of the completed fishing trips (as confirmed by interview) resulted in landed cod. In total, we observed 445 incoming private boats, and less than 6% of them landed cod. The total number of cod caught and retained estimated by ICES SD and quarter is displayed in Table 3, along with confidence intervals.

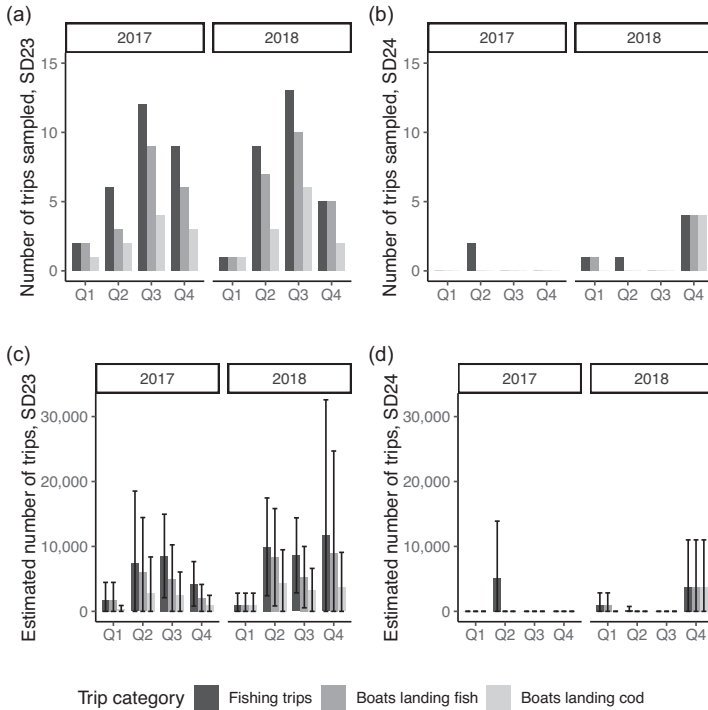
### Spatial and temporal distribution of the fisheries

#### Diel pattern

Trips categorized as recreationally fishing were observed returning to access points throughout the day (Figure 6), being registered between 06:00 and 16:00 during Q1 and Q4, and between 06:00 and 20:00 during Q2 and Q3 (Figure 6). Such extension of arrival times in Q2 and Q3 corresponds well with the extended daylight duration of Swedish summer (Figure 3).

#### Fishing trips returning to fringe municipalities

The two “fringe” municipalities, Simrishamn (SD 25) and Ängelholm (SD 21), were sampled on 12 days during 2017,



**Figure 4.** Observed and estimated boat trips. (a) and (b): observations of boats returning after a completed fishing trip by year, quarter and SD (a—SD 23, b—SD 24, raw data). (Note: in 2017, sampling effort was higher during Q3 and Q4 in comparison to Q1 and Q2. In 2018, sampling effort was highest during Q2 and Q3). (c) and (d): design-based estimates of fishing effort, boats landing fish, and boats landing cod, with 95% CIs (c—SD 23, d—SD 24). All boats classified as “private boats” were approached for an interview and asked whether they had been fishing. The interview was carried out if the incoming vessel had been fishing.

totaling 72 h and 80 access point visits. Access points were visited 32 times in Simrishamn, and 48 times in Ängelholm. The number of incoming trips amounted to 20, all in Q2 and Q3, of which only two were classified as recreational fishing-type. None had been fishing in SDs 23 or 24, which was the area of interest, and none had any catch. For 2018, these municipalities were excluded from the survey, allowing more days to be spent in the target area.

**Sampling considerations and adaptation**

The interview form remained similar, with minor updates to accommodate ease of the observers. During 2017 and 2018, no fisher refused to participate in the interview.

In 2017, the 22:00–06:00 shift was performed throughout the year, amounting to a total of 75 visits to access points and ca. 71.6 h of observation. In this time, no incoming trips were observed in Q1 or Q4 (51.9% of observed time). Access points were observed on an average of 66.8 min per visit in 2017, and the observation time spent in daylight (after sunrise and before sunset) amounted to 65%.

Updates to the design done in early 2018 led to less time observed and fewer visits to access points, but increased records of number of incoming vessels, including those fishing cod (Table 2). From the start of 2018, the sampling of the

22:00–06:00 shift could be conservatively restricted to Q2 and Q3 as effort had been proved lower in Q1 and Q4. This option was further corroborated by the 2018 data that indicated that in over 52.7 h of observation in this shift (during Q2 and Q3) only one boat was seen arriving, and it was not fishing (Figure 6). The assumption made in 2018 that arrivals during dark hours would be null (restricting sampling to the period between nautical dawn and nautical dusk + 2 h) only affected 6% of the access point visits during the year and can, therefore, be considered to have negligible impacts in final estimates. After the 2018 elimination of fringe municipalities, updates to the design and introduction of a 30-minutes lunch break in each shift, access points were observed, on average, 59.5 min per visit, and the number of unique access points visited was reduced to 68. More time was spent sampling in daylight, particularly during Q1 and Q4, following the implementation of changes to the survey design in 2018. The observation time spent in daylight (after sunrise and before sunset) was increased to 87% in 2018 (Table 2).

**Auxiliary data**

The number of boats present at access points showed large variability when counted on multiple occasions, quite pronounced between hours of the day, but also quarter of the

**Table 3.** Fishing effort as number of trips and retained catch estimates in total numbers of cod landed, by quarter and SD. Upper and lower bond of the confidence interval are shown in brackets. For indicative purposes only, an approximation of landed catch in Kg is also provided (assuming an average weight of 1.8 kg derived from a parallel study of four boats operating in SD 23).

Year	Subdiv	Quarter	Fishing trips	Cod landed	Catch (kg)
2017	SD 23	Q1	1 704 (+/- 2 755)	913 (+/- 1 790)	1 643
		Q2	7 386 (+/- 11 140)	4 247 (+/- 8 323)	7 644
		Q3	8 530 (+/- 6 430)	7 587 (+/- 13 718)	13 656
		Q4	4 239 (+/- 3 425)	5 911 (+/- 7 890)	10 640
	SD 23	Total	21 858 (+/- 13 593)	18 657 (+/- 17 971)	33 583
	SD 24	Q1	0	0	0
		Q2	5 139 (+/- 8 760)	0	0
		Q3	0	0	0
		Q4	0	0	0
	SD 24	Total	5 139 (+/- 8 760)	0	0
2017			26 997 (+/- 16 172)	18 657 (+/- 17 971)	33 583
2018	SD 23	Q1	947 (+/- 1 857)	4 737 (+/- 9 284)	8 526
		Q2	9 939 (+/- 7 529)	9 804 (+/- 14 442)	17 648
		Q3	8 626 (+/- 5 778)	15 397 (+/- 25 523)	27 715
		Q4	11 691 (+/- 20 896)	5 634 (+/- 7 455)	10 140
SD 23	Total	31 204 (+/- 23 025)	35 572 (+/- 31 651)	64 030	
SD 24	Q1	960 (+/- 1 882)	0	0	
	Q2	254 (+/- 498)	0	0	
	Q3	0	0	0	
	Q4	3 719 (+/- 7 288)	11 156 (+/- 21 866)	20 081	
SD 24	Total	4 933 (+/- 7 544)	11 156 (+/- 21 866)	20 081	
2018			36 137 (+/- 24 229)	46 728 (+/- 38 470)	84 111

year (Supplementary material SM 7). Some access points were completely closed off during winter, with all boats, and sometimes also the jetties, hauled on land. Since each access point was visited on multiple occasions (mean 10, median 8 times), the maximum boat counts were used to check the validity of boat counts as auxiliary data for future sampling allocation proportional to size (Figure 7). Based on such counts we estimate at least 9000 vessels could have been harboured in the study area in periods of high activity, 12% of them displaying signs of fishing activity.

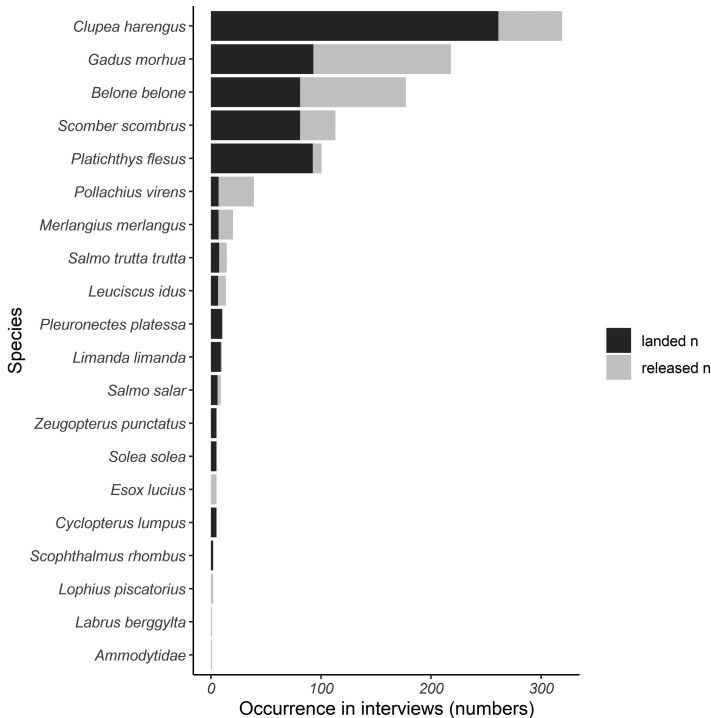
In the 14 largest access points, i.e. the access points with the highest number of private boats, relatively few landings of cod were observed ( $n = 23$ , from a survey total of  $n = 92$ ; Figure 7, Supplementary material SM 8). A substantially higher amount of cod landings were observed in the 14 access points with highest numbers of private boats with signs of fishing ( $n = 77$ ) and private fishing boats ( $n = 80$ ). These results indicate that some improvement to cod estimates may be attained in the future by adjusting the sampling design towards increased sampling of access points with large number of vessels with signs of fishing, but not necessarily so by a design that just increases sampling on the largest access points.

## Discussion

Our multi-stage random sampling program enabled the quantification of the recreational cod fishery along the Swedish coast of the western Baltic Sea and revealed recreational catches that consist of a wide range of species. Herring, mackerel, cod, garfish, and flounder were the main species caught, but also a variety of other marine, brackish, and freshwater species were caught in this coastal area. Although cod was the focus of this study, and cod catch expectations drove

initial sampling effort allocation across strata (higher in SD 23, where the cod fishery was expected to be more prevalent), that objective did not constrain the survey design itself. Accordingly, the initially little informed randomized sampling design not only allowed the estimation of recreational effort and cod landings (present study), but will also enable the future estimation of the total catch of the entire range of species as well as the provision of extensive information about the distribution in time and place of the fishery.

The randomized setup of the survey allowed the identification of the main spatial and temporal patterns in fishing activities. The survey confirmed recreational fishing to be more popular during spring and summer (Q2 and Q3) and occurring mostly in daylight or twilight. The assumption that fishing takes place mostly during daylight/normal-working hours is commonly made in recreational fisheries studies, many of which schedule similar work-shifts all year round (Pollock *et al.*, 1994; Lai *et al.*, 2019). In the case of higher latitudes, however, large differences in daylight/dark periods occur and normal working hours do not necessarily cover all non-negligible fishing activity. The initial decision made in 2017 to sample between 22 o'clock and 06 o'clock all year, irrespective of light conditions, was deliberate and a necessary one to validate the assumptions made in 2018 of not sampling specific times of the day in specific times of the year. We recommend this procedure to all studies where it can be implemented, particularly in areas of medium/high latitude, but not only, since fishing outside working hours or even at night has been found common in many fisheries and countries where that possibility was evaluated (Diogo and Pereira, 2016; Taylor *et al.*, 2018). Night fishing or dark-fishing ended up not being common in southern Sweden during Q1 and Q4, and because we sampled probabilistically in 2017, we are confident that was also



**Figure 5.** Fish species (targeted and non-targeted) retained (dark) and released (light) by intercepted and interviewed returning fishing trip parties sampled in southern Sweden during 2017–2018. Bar length indicates the number of fish by species caught. *Clupea harengus*—Atlantic herring, *Belone belone*—Garfish, *Scomber scombrus*—Atlantic mackerel, *Platichthys flesus*—European flounder, *Pollachius virens*—Saithe, *Merlangius merlangus*—Whiting, *S. trutta trutta*—Sea trout, *Leuciscus idus*—ide, *Pleuronectes platessa*—European plaice, *Limanda limanda*—common dab, *S. salar*—Atlantic salmon, *Zeugopterus punctatus*—common topknot, *Solea solea*—Common sole, *Esox lucius*—Northern pike, *Cyclopterus lumpus*—Lumpfish, *Scophthalmus rhombus*—Brill, *Lophius piscatorius*—European angler, *Labrus bergyllta*—Ballan wrasse, and Ammodytidae—Sandlance.

true in 2018. However, as daylight lasts longer in Q2 and Q3, fishing activity also extends past working hours well into the evening (Figure 6). In summer, when dusk sets late if at all, light conditions would not necessarily be a limiting factor for fishing trips to take place, yet no fishing activity was found after 23:00 during any month in the present survey, and no fishing trips were observed during or after dusk (astronomical twilight).

Our survey design makes a clear distinction between strata (that we used for sampling) and domains (where we aimed to obtain our estimates). As such, the spatial strata of the initial survey design (2017) included access points from “fringe municipalities”, located outside the target area to account for the possibility of boats returning there after having fished in the target areas SDs 23 and 24. A substantial sampling effort was made and no completed fishing trips in the target area were observed at these access points, so the municipalities were removed from the survey design in 2018. If there was any fishing in the target area departing from the “fringe” municipalities, its contribution to the total catches is now known to be null or very small and, thus, negligible. Defining a target area and a corresponding list of access points for a survey is not always straightforward and will largely depend on the spatial

scale of management and the need for data. International, national, or regional delimitations have often been used, particularly when these correspond well with fish stock management units (NRC, 2006), as was the case in the present survey. Spatial strata might also be shaped by natural geographical delimitations or by empirical knowledge of particular fisheries (Herfaut *et al.*, 2013). At finer management scales, such as is the case for the WBC, the cost of achieving adequate precision of the estimates is high, and a continuous evaluation of the survey design and the sampling frame will be beneficial for such on-site surveys. We recommend the inclusion of ports that are outside the target area in initial stages of the design. These ports may harbour vessels that fish in the target area, and the decision on whether or not they are maintained in a second stage will be evidence-based. Assigning a lower, but non-negligible, probability to fringe ports or municipalities should, in general, be enough to allow for such evidence gathering without jeopardizing the core part of estimates, naturally expected to come from the main ports or municipalities, nor sacrificing the overall statistical quality of the study.

The Swedish recreational WBC landings from private boats in 2017 and 2018 were small compared to those of neighbouring countries fishing in the same area (the total recreational

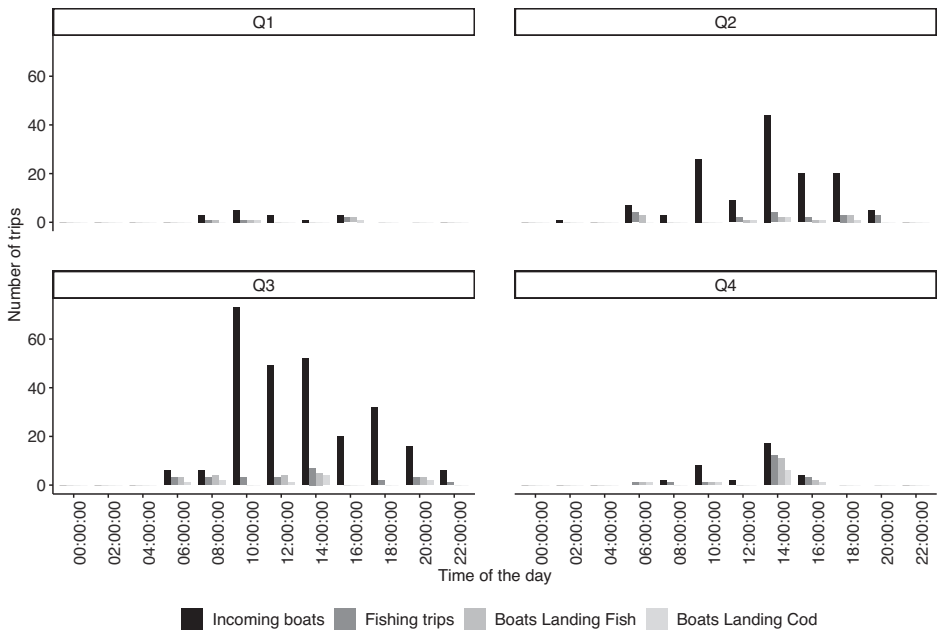


Figure 6. Number of trips sampled according to trip category and time of day shown by quarter.

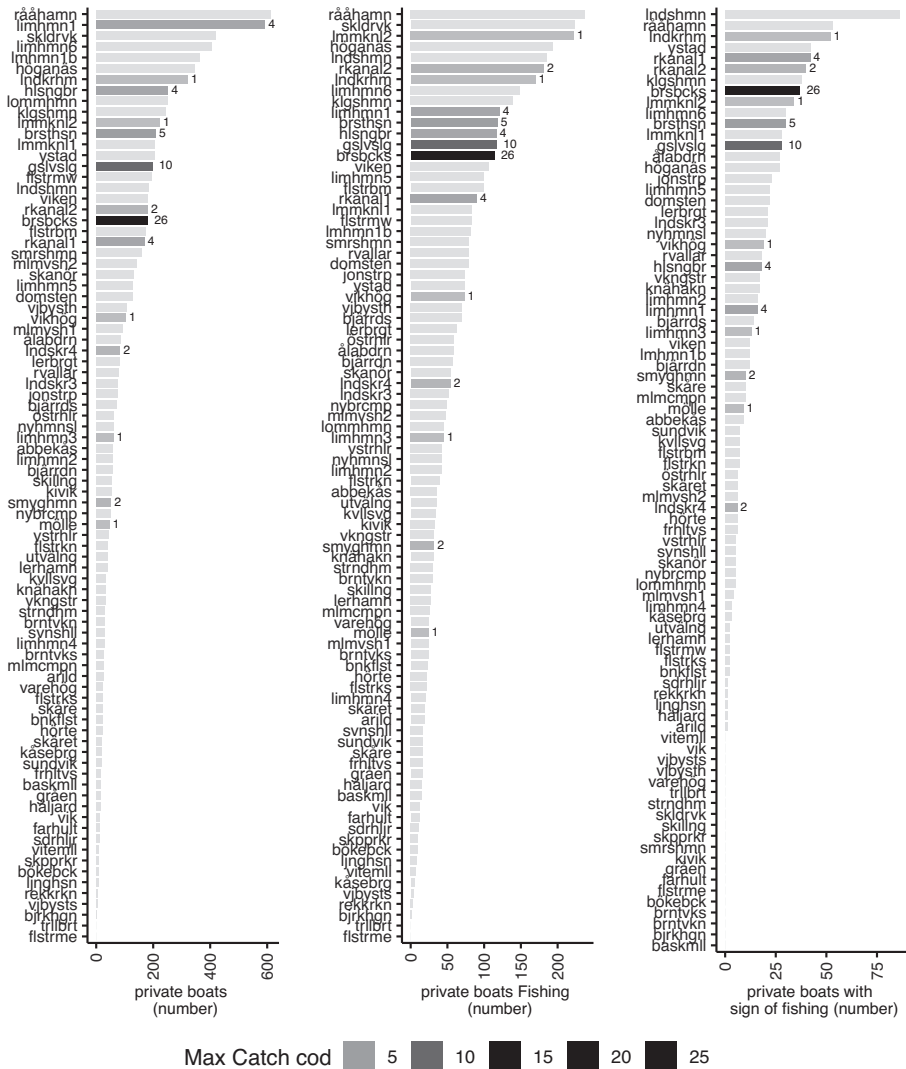
catches of WBC, dominated by German and Danish catches, was estimated at 1315 and 1600 t in the 2017 and 2018 stock assessments; ICES, 2021). Swedish recreational landings were small, also when compared to the total commercial cod landings of the WBC stock (3861 t and 3555 t, respectively; ICES, 2021), and will, thus have had little impact *per se* on the stock assessment of the WBC. However, the most recent stock assessment estimates for the WBC stock depicted a stock below  $B_{lim}$  since 2016 (ICES, 2021). In addition, the stock recruitment has been very low in recent years. This has resulted in the advice for landings in 2022 to be severely reduced, at less than 12% of the advice for 2021. The resulting advised Total Allowable Catch is, hence, below the estimated recreational catches of WBC, and not much higher than the Swedish recreational landings of WBC registered during 2017 and 2018. Moreover, restrictions on recreational anglers have tightened in 2022, with a daily bag limit of 1 cod per angler between April and January and a complete ban during spawning season (EU, 2021). As greater constraints are put on the fishery, recreational catches may not only come to represent a significant part of the total mortality of this stock, but also enter in direct conflicts with the commercial fishery over a limited resource.

Most of the Swedish recreational cod catches are caught in the Sound between Denmark and Sweden (ICES SD 23), where there is evidence of locally spawning cod populations (Svedäng *et al.*, 2010a). A strong population with a healthy size structure has been found in this geographical area (Svedäng *et al.*, 2002, 2010b; Lindegren *et al.*, 2013; Sundelöf *et al.*, 2013), in contrast to deteriorated cod populations in adjacent waters (Jonzén *et al.*, 2002; Eero *et al.*, 2015).

Recently Wenne *et al.* (2020) demonstrated genetic differentiation within the WBC stock, indicating a need for sub-stock consideration in the management process. In lieu of this, the Swedish recreational catches of cod might very well be significant on a local (SD 23) level, and thus impact this sub-stock in question more severely than previously assumed. Many of the recreationally caught species seen in this survey are also targeted by commercial fisheries, and hence recreational fisheries add to the total mortality of commercially fished stocks, possibly impacting the stock assessment and contributing to declines in fish stocks (Post *et al.*, 2002; Coleman *et al.*, 2004; Smith and Zeller, 2016; Freire *et al.*, 2020).

The funding for the current survey was grounded on the need for recreational fisheries data of one particular stock, the WBC stock. The data quality required for assessment is high, and on-site surveys, while expensive, can provide this level of quality, if well-designed. However, such a survey is spatially and temporally complex, and usually cannot give accurate information on the fishery beyond the defined spatial and temporal sampling frame.

There is no “one fits all” template for recreational fisheries assessments, and survey designs must accommodate needs for data based on continuously changing policies and management strategies while being adapted to local circumstances. Designing an on-site angler survey is challenging for extensive coastlines with many access points. Applying a typical access point survey, where each site is chosen independently and randomly, requires substantial observer effort and significant travelling, rendering that type of survey an often expensive option. The bus route design, on the other hand, minimizes the number of observers and travelling time by grouping nearby



**Figure 7.** Boat counts (maximum) in the access points, (left) the total number of boats, i.e. size of marina, (middle) the number of boats classified as recreational fishing boats, (right) the number of boats classified as “engaged fishing,” i.e. private boats with signs of fishing. Signs included rod holders, nets, pots, fishing gear, and so on. The access point bars are coloured according to the maximum number of cod that were observed landed there in one sampling occasion during the survey, and the maximum number of cod is shown in text to the right of the bar (Note the different range on the x-axis).

sites within a route that is then surveyed as a unit (Robson and Jones, 1989; Lai et al., 2019). In the current survey, a stratified multi-stage cluster sampling design was used. The design is inspired by the bus route method but has significant modifications. In the bus route design, every site is sampled in the course of the day on the route that is selected, but in this study, since the number of sites and the distances were too large to be covered in a single route we divided the area into clusters (coastal municipalities). Each day, we randomly sampled

one cluster. When the number of ports within clusters were large, geographical stratification of ports and/or their subsampling along the route was used. This approach draws on the strengths of both the bus route method and the access point method, and allowed us to avoid large travelling times, and thus increase observation time while maintaining the number of observers needed at adequate levels. Cluster sampling allowed sampling efficiency to be increased, and therefore, costs to be reduced, while no assumptions were made on the

relative level of activity emanating from differently sized access points. This design enabled a general mapping of the recreational fisheries taking place in the study region, laying the foundation for multi-species recreational fisheries surveys and catch estimation.

In a situation where prior knowledge about the fishery is poor, it is important to sample in a randomized manner and avoid biases caused by unverified assumptions. Doing so necessarily leads to observational time being spent in access points that have low or negligible activity, increasing the final variance of the design-based estimates (see results). However, the data collected probabilistically, alongside the auxiliary data also collected (which benefits from the same underlying statistical randomization as the main data) are invaluable for assumption checking, safe later reduction of costs and improvements of accuracy of global effort and catch estimates or their redirection towards more specific objectives (e.g. the estimation of catch and effort targeting a specific resource or taking place in a specific area). It can also support evidence-based shifts towards other types of more efficient sampling methods such as those that involve separate sampling for effort and CPUE. In fact, auxiliary data can be attained by traffic counts at boat ramps (Steffe *et al.*, 2008; van Poorten and Brydle, 2018) or digital camera monitoring (Hartill *et al.*, 2020). This type of data collection can facilitate accurately quantifying fishing effort at the access points. Auxiliary data can also be used to inform data collection and sampling design. It is necessary to verify auxiliary data, so as not to leave bias unknown (Steffe *et al.*, 2008). In this survey, while probabilistic sampling took place, an effort matrix was also constructed with moored boat counts of all access points, with details of boat category based on likelihood of the boat to be contributing to the fishing activity. This revealed that fishing activity was not proportional to the size of the access point (a likely erroneous assumption that could have been made to save costs at survey start), and hence, a proportional inclusion probability for access points based on size alone would likely have led to less precise estimates of both effort and catch (since the target variable does not correlate well with port size) or even erroneous ones (if ports with smaller size had been left out of the sampling frame). The effort matrix (i.e. boat counts) also showed a strong seasonal variation in occupancy at certain access points, some being completely closed off during parts of the year. It is, however, necessary to determine the underlying cause of the variation in counts of occupied boat slots. In some locations, winter storage in dry docks might be common, while in others empty slots are equivalent to the boats being out fishing. This issue can be overcome in several ways, e.g. by considering only occupancy counts done at night, in bad weather, or using the max count when repeated counts are performed. In this survey, counts were carried out at every visit to an access point, and importantly, access points were visited also at times when sampling could be assumed inefficient, rendering “max counts” a good measure of access point occupancy. This type of auxiliary knowledge, when linked to fishing activity, allows future optimization with regards to the temporal and spatial strata, where sampling effort can be allocated proportional to empirical knowledge on the probability of fishing taking place. By separating the sampling for catch rate and the sampling for effort determination, more sampling effort can be concentrated at the sites and times of high activity. Coupled with, e.g. unequal probabilities based on likelihood of fishing taking place,

it is possible to maintain full coverage of the population while making sampling more efficient. There are several examples of large-scale recreational fisheries survey, where catch rate and effort sampling are separated (NRC, 2006; NAS, 2017), and different methods on how to assess these components exist.

A prerequisite for probabilistic sampling is knowing the characteristics of the target population to be sampled. The more one knows about the target population and the better delimited it is, the more efficient the sampling design can be and the more precise estimates one can expect to obtain. A good sampling frame covers all the units in the target population, whether it be a list frame (boat owners, license registries) used for off-site surveys or a spatiotemporal frame (access points) used for on-site surveys (NRC, 1998). To sample recreational fisheries, the most efficient frame is a list of all those participating in the fishery, but where that is not available, indirect list frames such as national registries, address lists or lists of access points (as in our study) can be also be used. Such indirect frames can be sampled probabilistically. However, where participation rate in fisheries is not very high (NRC, 1998; our results: only 6% of boat arrivals had been fishing) and estimates are needed for smaller geographical areas (like SDs 23 or 24), they are usually burdened with lack of precision.

Attempting to cover all fishing modes, access points, and fished species in a recreational fisheries survey leads to complex and extensive surveys that come with a high cost. Making some assumptions about, e.g. angler behaviour might ameliorate this, but such assumptions can be hard, or impossible, to verify, and when taken too early and without evidence, based on expert judgement only, may be the cause of significant bias in the estimates that will later be derived. Constructing a proper indirect sample frame can be a resource demanding task, yet it might be worthwhile considering those alternatives against, i.e. unknown bias and a failure to correctly represent the target population or producing very variable estimates. As we have shown, where good direct frames are not available, the inefficiency of a randomized design and an indirect frame (largely evident in the present study in the low number of encounters of cod fishers) provide the necessary framework for obtaining a first set of estimates, with known variance, and a path to the future optimization of the efficiency of surveys and its estimates. Their apparent inefficiency (evident in the less precise estimates) is easily counterbalanced by the unbiased characteristics of the estimates obtained from them, the extensive additional information and characterization they render possible, and the forward opportunities they offer to evidence-based evolution and optimization of the sample design in the medium-long term. Nevertheless, the underlying assumptions, although evidence-based, might change over time, and should, therefore, be checked regularly, e.g. every 5–10 years.

## Supplementary data

Supplementary material is available at the *ICESJMS* online version of the manuscript:

SM 1) Cluster dendrogram showing stratification of municipality Helsingborg; SM 2) Selection probabilities of a) municipalities and b) work shifts; SM 3) Sampling allocation in number of days by quarter and subdivision; SM 4) The interview form (english); SM 5) Weather data and analysis

excluding sampling effects of weather on the results; SM 6) Primary target species as percentage of all interviews; SM 7) The counts of moored boats shown by quarter for a) private boats fishing and b) private boats with signs of fishing; SM 8) The number of landed cod for the 14 largest access points according to the three main boat categories.

## Authors' contributions

HS: conceptualization, data collection, data curation, formal analysis, visualization, and writing—original draft (lead). NP: conceptualization, design and methodology of the survey, and the analysis, data curation, formal analysis, and writing—original draft. AdG: formal analysis and writing—original draft. MC: conceptualization, funding acquisition, supervision, discussion of results, and writing—review and editing. CJ: supervision, discussion of results and methodology, and writing—review and editing. AS: conceptualization, funding acquisition, project administration, methodology, resources, data collection, supervision, and writing—review and editing.

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## Competing interest statement

The authors have no conflict of interest to declare.

## Data availability statement

The data underlying this article may be shared on request to the corresponding author.

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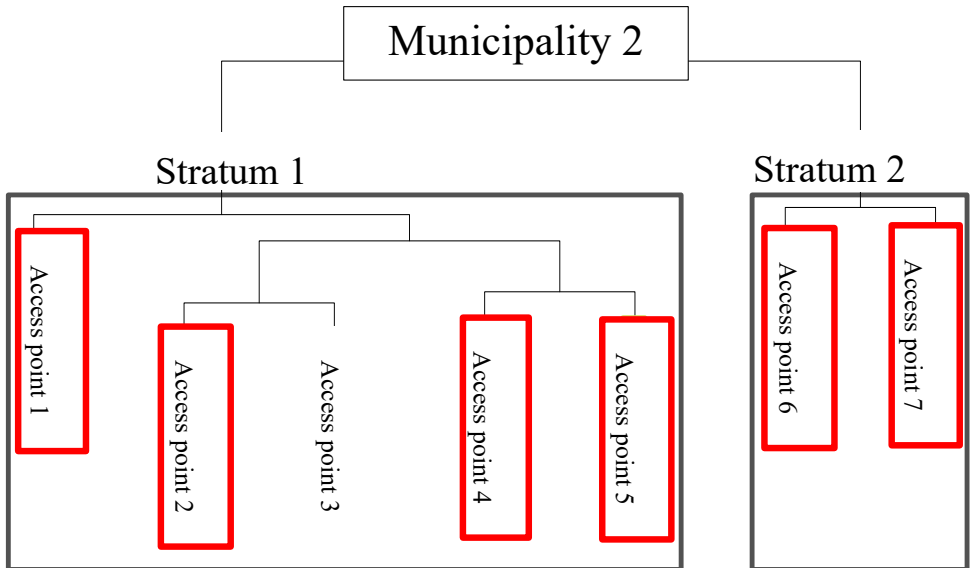
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# Supplementary Material

SM1

A cluster dendrogram showing the stratification of Helsingborg municipality into 2 strata. When this cluster was selected, four out of five access points in stratum 1 were sampled, and two out of two access points in stratum 2. This ensured observation time of 5.5 hours in an 8-hour work shift, minimizing time lost to travel.



## SM2 Selection probabilities

### a) The municipality selection probabilities.

	<b>2017</b>	<b>2018</b>
Helsingborg	0.128571	0.166667
Höganäs	0.128571	NA
Höganäs-Domsten	NA	0.166667
Kävlinge	0.128571	NA
Kävlinge-Lomma	NA	0.166667
Landskrona	0.128571	0.166667
Lomma	0.128571	NA
Malmö	0.128571	0.166667
Simrishamn	0.1	NA
Skurup	0.3	0.333333
Trelleborg	0.3	0.333333
Vellinge	0.128571	0.166667
Ystad	0.3	0.333333
Ängelholm	0.1	NA

### b) Selection probabilities for the possible work shifts, with slight changes between 2017 and 2018.

<b>2017/2018</b>	<b>Q1</b>	<b>Q2</b>	<b>Q3</b>	<b>Q4</b>
06 – 14	0,4/0,5	0,4/0,4	0,4/0,4	0,4/0,5
14 – 22	0,4/0,5	0,4/0,4	0,4/0,4	0,4/0,5
22 – 06	0,2/-	0,2/0,2	0,2/0,2	0,2/-

### SM3 Sampling allocation by SD

*Table 1 Number of planned sampling days by quarter (Q) and sub-division in 2017 and 2018. Sub-division 23 include sampling events taking place in access points bordering SD 21, while for SD 24 also SD 25 is included. The realized sampling events are shown in brackets if different from planned.*

Year	Sub-division	Q1	Q2	Q3	Q4	Sum
2017	23 + 21	12	12	24	24	72
	24 + 25	6 (5)	6	6	6	24 (23)
	sum	18 (17)	18	30	30	96 (95)
2018	23	12	24 (22)	24	12	72 (70)
	24	3	6	6	3	18
	Sum	15	30	30	15	90 (88)
Total		32 (31)	48 (46)	60	45	186 (183)

SM4 Interview form

Questionnaire for on site recreational fisheries data collection

Date	<input type="text"/>	ResID	<input type="text"/>	Observer	<input type="text"/>
		ICES SD	<input type="text"/>	Time of interview:	<input type="text"/>
Port of departure	<input type="text"/>	Port of arrival	<input type="text"/>	Boat type (1,2a,2b,4)	<input type="text"/>
Quality of answer (1,2,3)	<input type="text"/>	Fishing mode (1,2,3,4)	<input type="text"/>	1=non-fishing	2a=Fishing
1=complete answer 3=Refusal (non-response)		1=tour boat	3=private	2b=signs of fishing	4= other
2=partly answered		2=charter	4=land		

1. Did you fish in the ocean today?  YES  NO

2. When did you leave the port today?

3. Tavel time today (to fishing spot, hh:mm)?

4. In which direction did you travel? (N, W, E, S):

Comment:

5. Did you fish closer to Denmark or Sweden today? (Private boat)  SWEDEN  DENMARK  DO NOT KNOW

6. What was your target species today?

Species 1	Species 2	Species 3
<input type="text"/>	<input type="text"/>	<input type="text"/>

7. How many were fishing onboard the boat?  N

8. How much cod have you been fishing today (entire boat)?  N  kg

9. How much cod have you released today?  N  kg

10. How many fish of other species have you caught today?  N  kg  Comments/species

11. How many fish of other species have you released today?  N  kg

12. What gear did you fish with today?

GEAR	Net	Longline	Angling	Jig	trolling	Spinning/fly fishing
Number/length/mesh size	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>
Start time	<input type="text"/>					
Stop time	<input type="text"/>					

13. How long (hh:mm) are you planning to continue fishing today (Shoreline)?

14. Will you go for more fishing trips today? (Private boat)  YES  NO

15. How many days have you fished the last 4 months, in this area (including today)?

	Tourboat	Charter	Private boat	Shoreline
Number of days	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>

Socioeconomic data

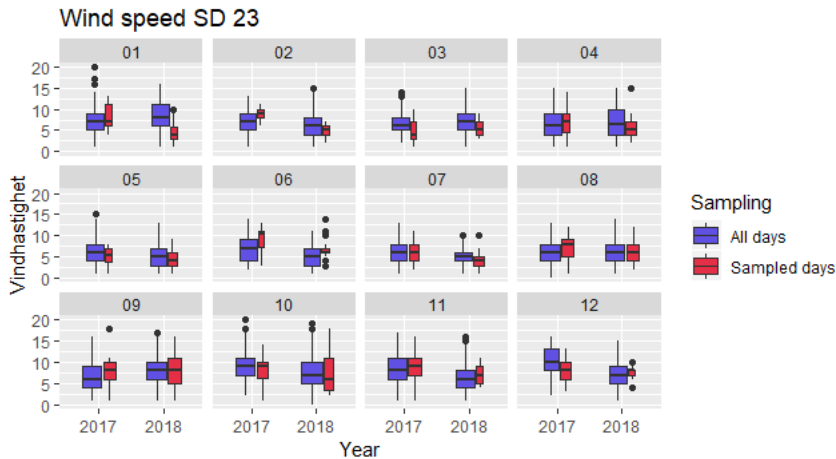
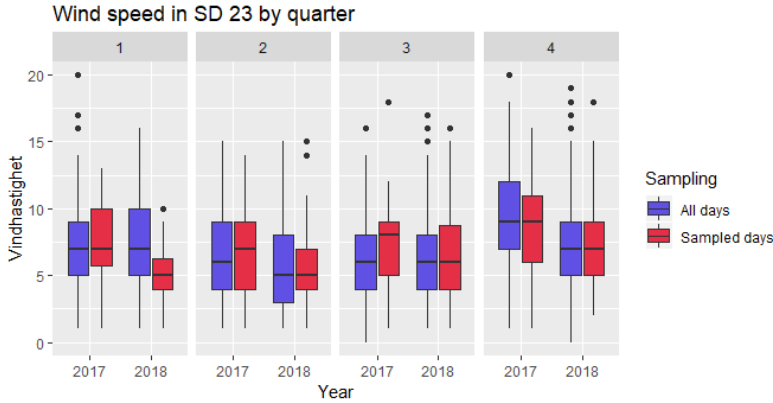
Age  Gender  Postal code

Nationality  Country of birth



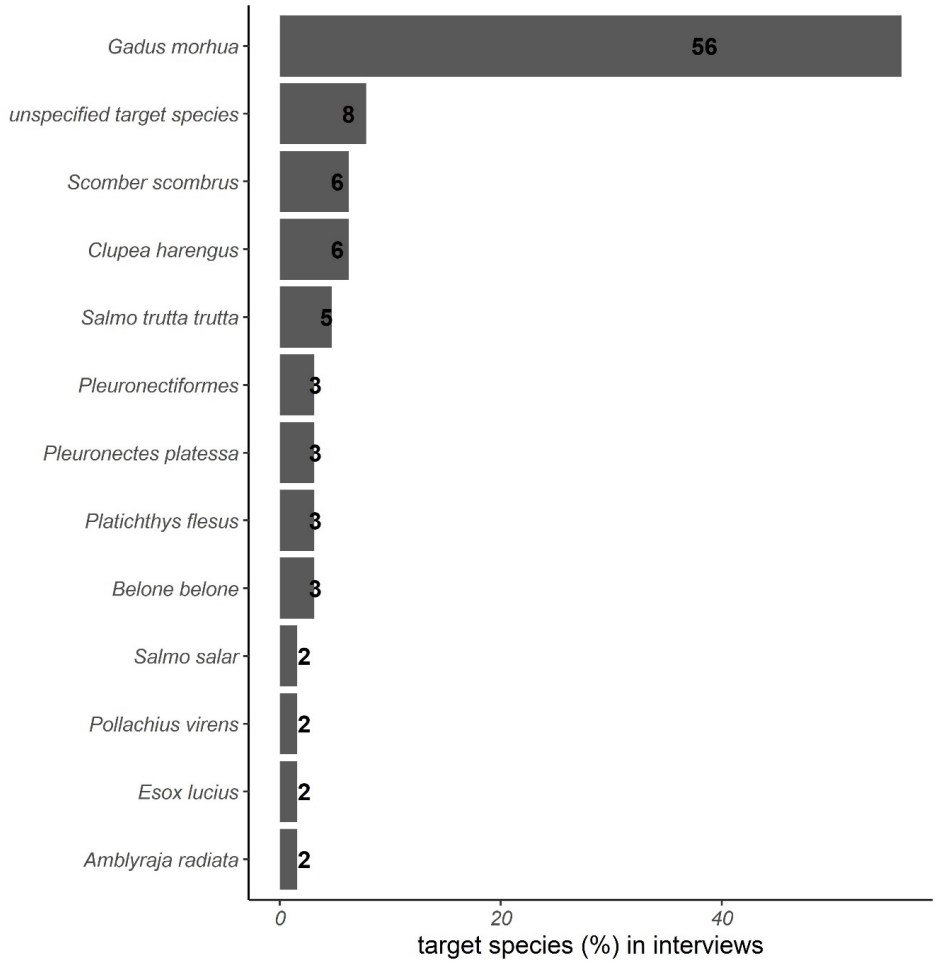
## SM5 Weather data and analysis

Wind speed data was obtained from a permanent SMHI weather station located at the southwestern tip of Skåne (Falsterbo). The data is provided as mean wind speed over 10 minutes every 3<sup>rd</sup> hour. (Not 21, 00, 03 during dec and jan – jul 20). Weather data (wind speed m/s) show that sampling weather did not differ considerably from the mean weather, excluding sampling effects of weather on the results. Any resulting difference in fishing activity connected to weather can hence be interpreted as actual effort changes as opposed to a sampling effect.



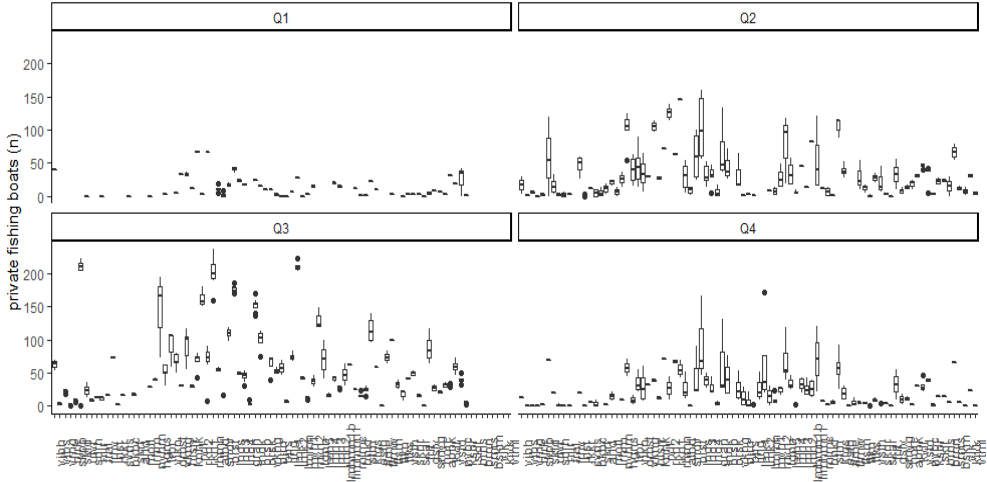
SM6

The primary target species as a percentage of all interviews. A majority of interviewed claimed to target cod (56%).

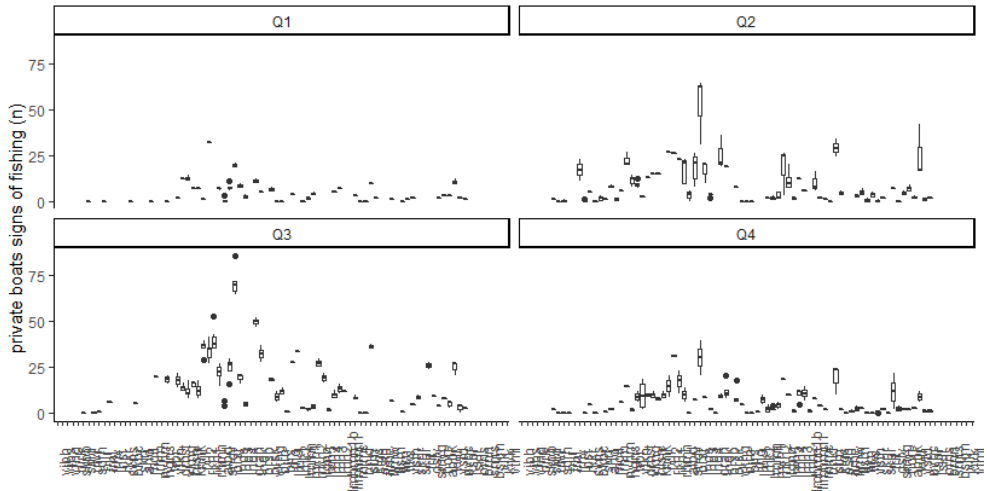


SM7 The effort matrix

- a) Moored boat counts by quarter, showing the boats classified as "private boat fishing". Access points are listed from north-west to south-east



- b) Moored boat counts by quarter, boats classified as "private boats with signs of fishing". (Note the difference in scale):



## SM 8

*The number of landed cod for the fourteen largest access points with regards to the three main categories used for boat counts; private boats, private boats fishing, and private boats with signs of fishing.*

Access Point	Maximum moored private boats #	Cod landed (sum)	Access Point	Maximum moored private boats fishing #	Cod landed (sum)	Access Point	Maximum moored private boats with signs of fishing #	Cod landed (sum)
råå hamn	611	0	råå hamn	237	0	lindeshamn	86	0
limhamn 1a	593	4	skälderviken	223	0	råå hamn	53	0
skälderviken	418	0	lomma kanal 2	222	1	lundåkrahamnen	52	1
limhamn 6	404	0	höganäs	194	0	råå kanal 1	42	5
limhamn 1b	362	0	lindeshamn	185	0	ystad	42	0
höganäs	344	0	råå kanal 2	181	3	råå kanal 2	40	3
lundåkrahamnen	321	1	lundåkrahamnen	170	1	klagshamn	38	0
helsingborg	252	4	limhamn 6	149	0	barsebäckshamn	37	44
lomma hamn	250	0	klagshamn	139	0	lomma kanal 2	34	1
klagshamn	243	0	limhamn 1a	121	4	borstahusen	30	13
lomma kanal 2	223	1	borstahusen	118	13	limhamn 6	30	0
borstahusen	209	13	gislövsläge	117	10	gislövsläge	28	10
lomma kanal 1	207	0	helsingborg	117	4	lomma kanal 1	28	0
Ystad	206	0	Barsebäckshamn	114	44	Höganäs	27	0
		23			80			77



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Recreational fisheries are widespread but poorly quantified, limiting their integration into fisheries science and management. This thesis advances understanding through methodological and empirical contributions, including improved survey design, a Total Survey Quality–based decision framework, and evaluation of citizen science. Results show that recreational fisheries contribute to fishing mortality and selective pressures, alongside pronounced life-history changes in Western Baltic cod. Integrating complementary data sources is essential for reducing uncertainty and supporting precautionary, inclusive fisheries management.

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SLU generates knowledge for the sustainable use of biological natural resources. Research, education, extension, as well as environmental monitoring and assessment are used to achieve this goal.

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