How to estimate the unknown:

THE STATISTICAL CHALLENGES OF QUANTIFYING IIU FISHING

Outline

- What is IUU fishing exactly?
- Challenges of quantifying IUU fishing

What is IUU fishing exactly?

- Illegal
  - There has to be laws or regulations to break
  - by national or international vessels
  - In areas under national jurisdiction
  - or regional fisheries management organization (RFMO) conservation and management measures

What is IUU fishing exactly?

- Unreported
  - Non-reporting,
  - Underreporting
  - Misreporting
  - of any information related to the fishing activity

What is IUU fishing exactly?

- Unregulated
  - The lack of fisheries governance framework
  - An issue of governance failure

Challenges of quantifying IUU fishing

- For statistical analyses, we like the data to be
  - A lot
  - Good coverage (i.e. spatially, temporally)
  - Unbiasedly sampled

The IUU fishing data often don't look like that

Challenges of quantifying IUU fishing

- Defining what to estimate in specific contexts.
- The lack of data by nature.
- Gathering data from sources with varying uncertainty.
- Sampling issue: non-randomness and bias within available datasets.

Challenges of quantifying IUU fishing

- Defining what to estimate in specific contexts.
  - Back to *what is IUU fishing* question.
  - What should we focus on?
    - IUU fishing efforts?
    - IUU catches?
    - Ecological impacts?
    - Socioeconomic impacts?

Challenges of quantifying IUU fishing

- Defining what to estimate in specific contexts.
  - Resources and time are finite.
    - We have to choose what to look for
    - AND how to look for it.

Challenges of quantifying IUU fishing

- The lack of data by nature.
  - Fishers hiding their IUU activities (obviously)
  - Not enough routine monitoring coverage
  - Not knowing how to get the data

Challenges of quantifying IUU fishing

- Gathering data from sources with varying uncertainty.
  - Patrol sighting
  - Satellite imagery
  - Ariel survey
  - Onboard observers
  - Landing inspection
  - Market survey
  - Differences of methodology among literatures

Challenges of quantifying IUU fishing

- Sampling issue: non-randomness and bias within available datasets.
  - IUU activities are often encountered without scientific sampling design.
  - Targeted monitoring efforts over specific area or time.

Challenges of quantifying IUU fishing

- Double counting data
  - A single unit of IUU product might be counted for more than one activities.
    - Fishing
    - Transhipment
    - Sale
  - Overlapping between different studies

Challenges of quantifying IUU fishing

- Statistically, what could those challenges look like?

> In 1990, illegal catches of shark in the Gulf of Carpentaria were believed to be only around 10 per cent of the legal Australian catch. By 2005, illegal catches of shark were believed to be at least equivalent to those caught legally by Australian fishers.

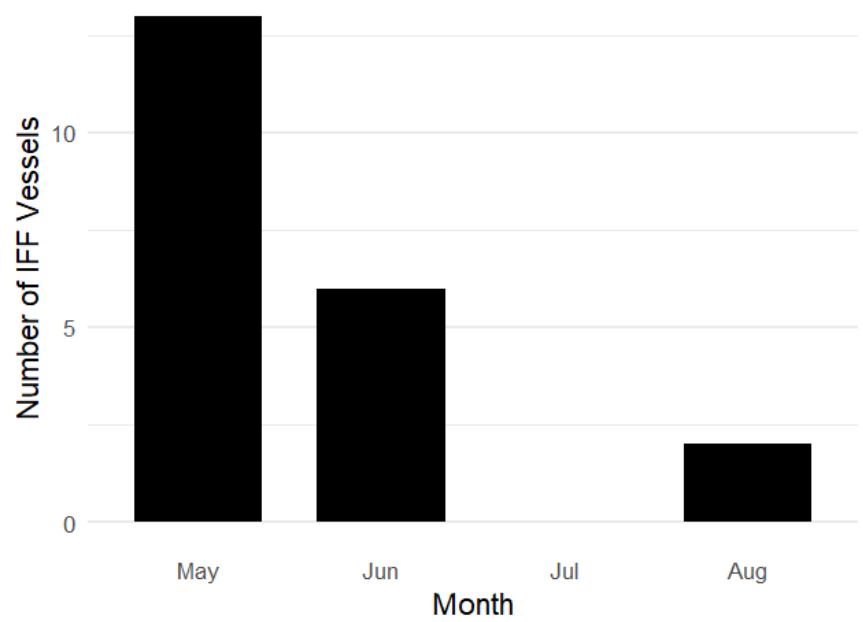
Pascoe *et.al*. 2008

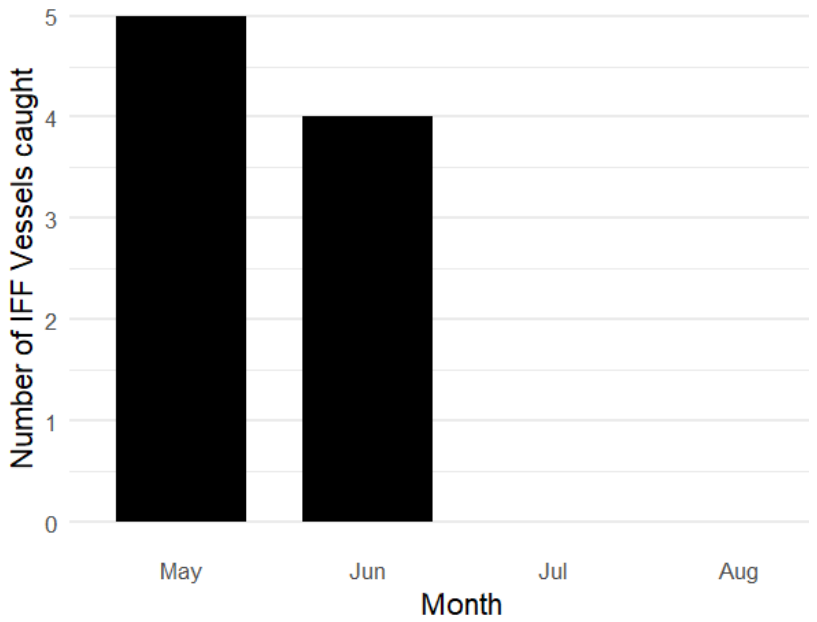
Economic and ecosystem impacts of illegal, unregulated and unreported (IUU) fishing in Northern Australia

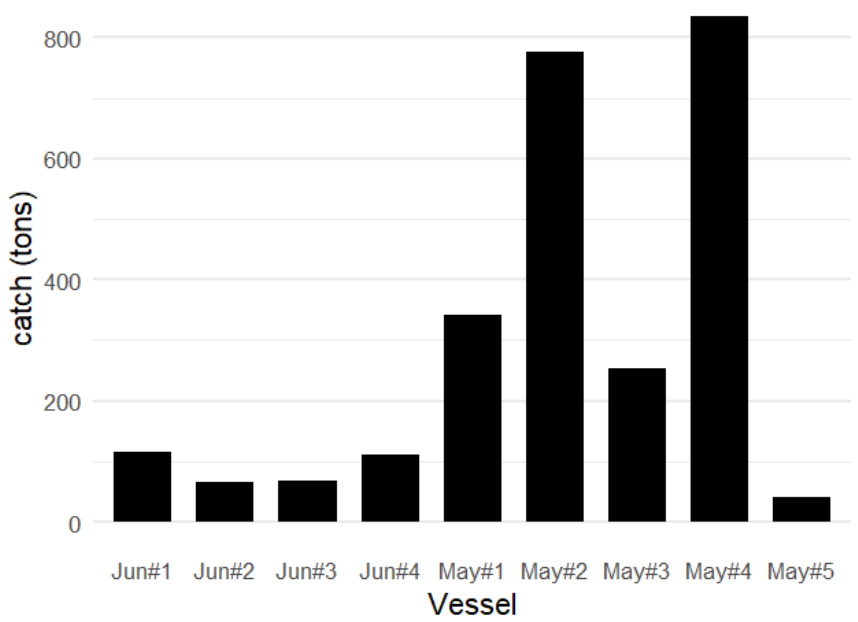
Challenges of quantifying IUU fishing

- Statistically, what could those challenges look like?
  - Example1 Scenario 1

We monitor only the *season we know* IUU by illegal foreign fishing (IFF) would take place, and we found this:







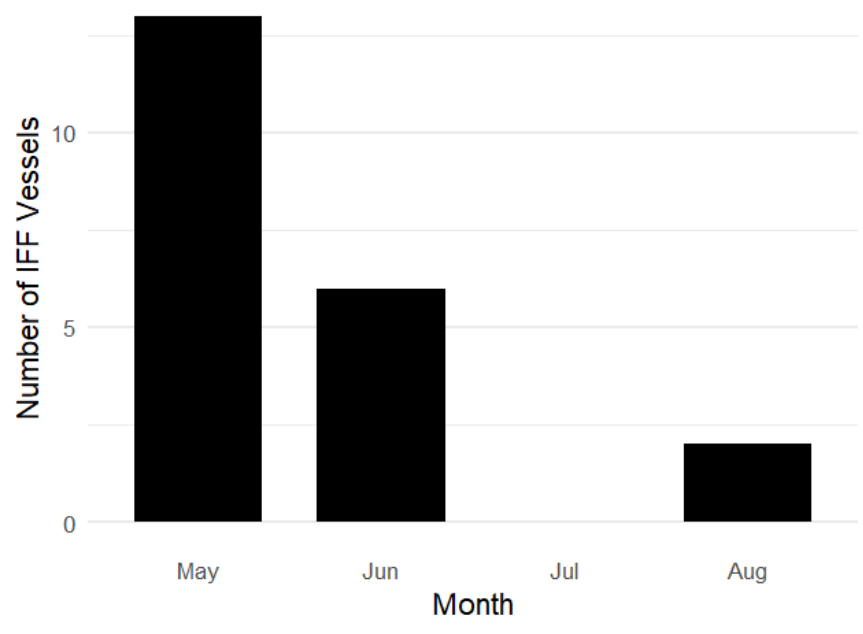
Challenges of quantifying IUU fishing

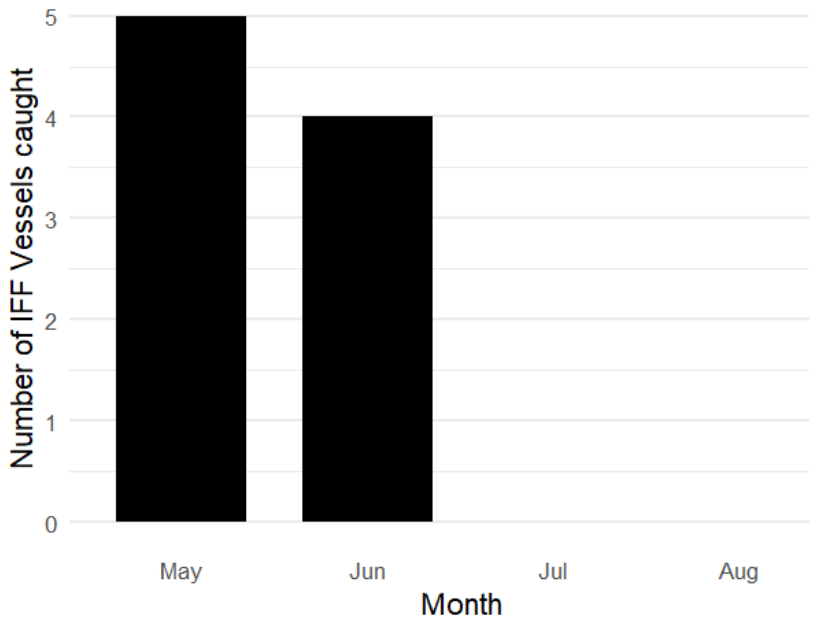
- Statistically, what could those challenges look like?
  - Example1 Scenario 1

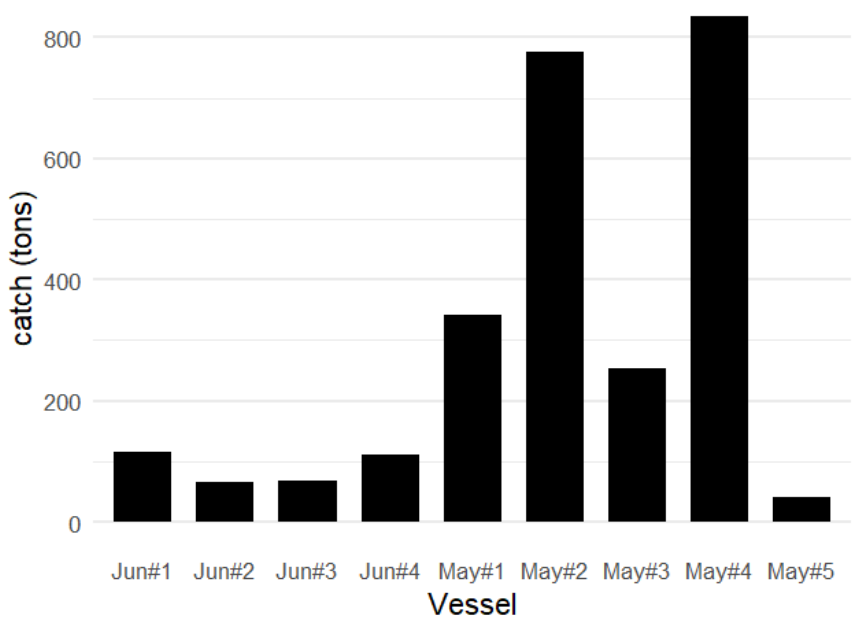
Number of vessels observed in 4 months = 13+6+0+2 = 21

Averaged to 21/4 = 5.25 boats/month

Average catch = 290.23 tons/boat





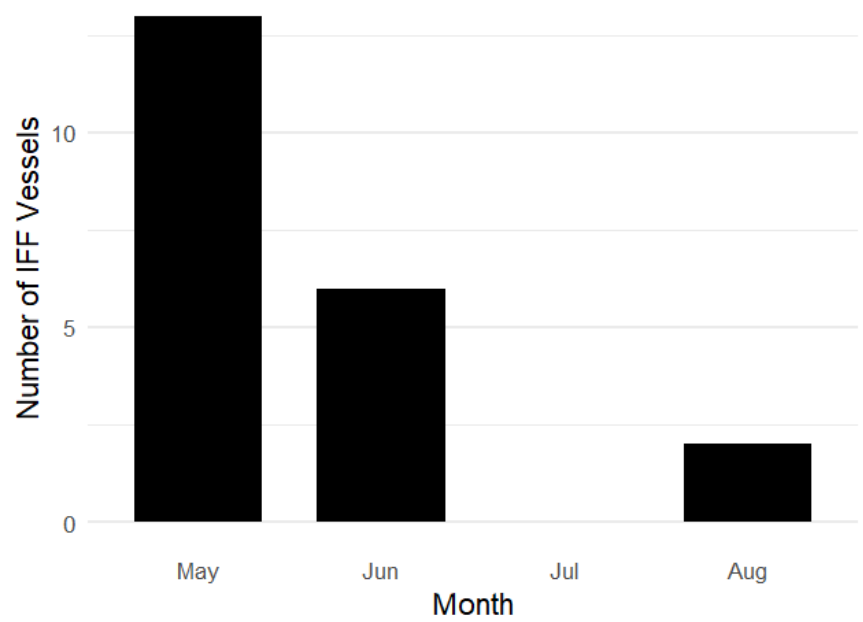


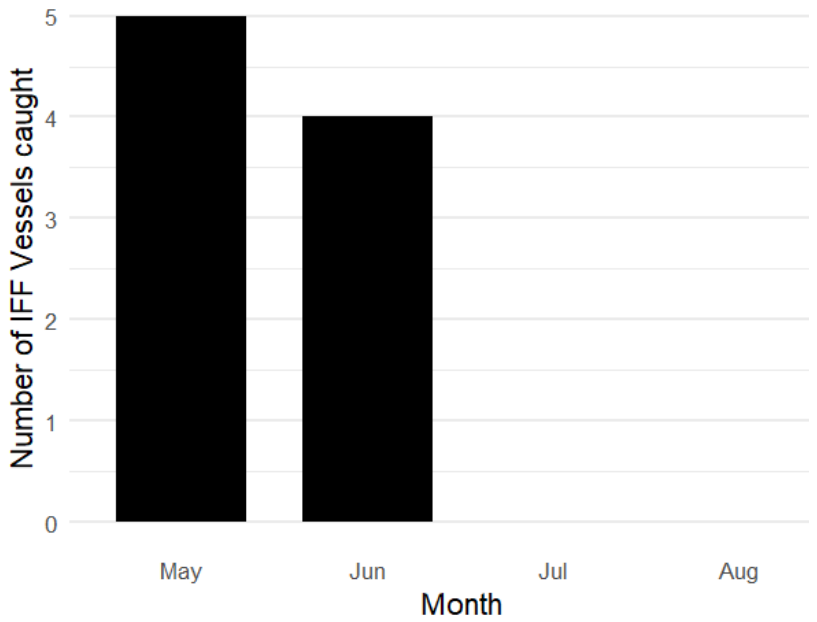
Challenges of quantifying IUU fishing

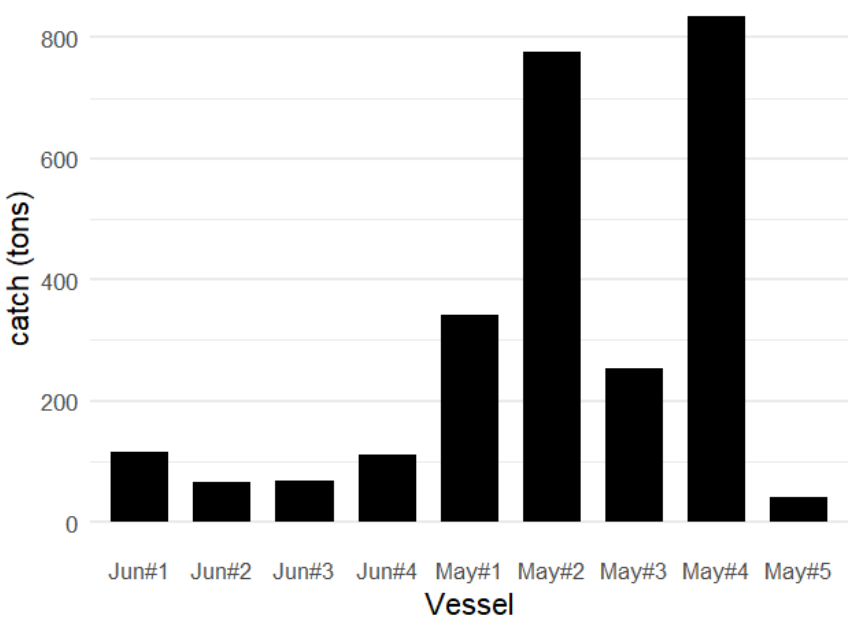
- Statistically, what could those challenges look like?
  - Example1 Scenario 1

Annual total catch = 290.23*5.25*12 = 18284.49 tons/year

What are the problems with this estimation?????



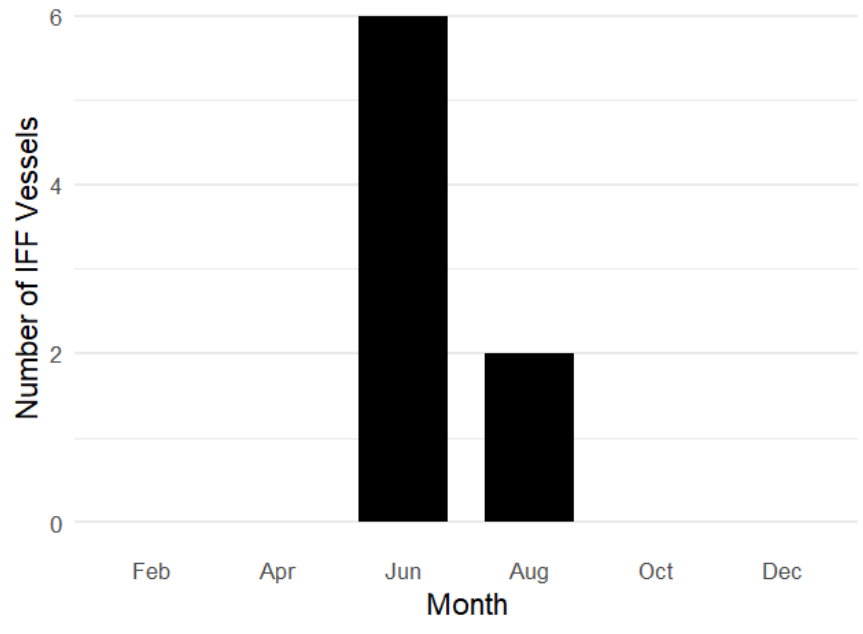


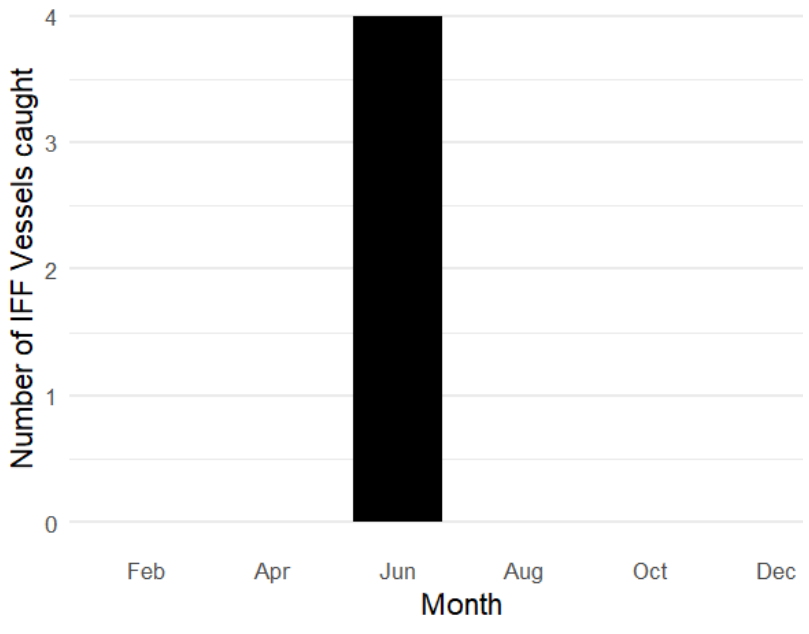


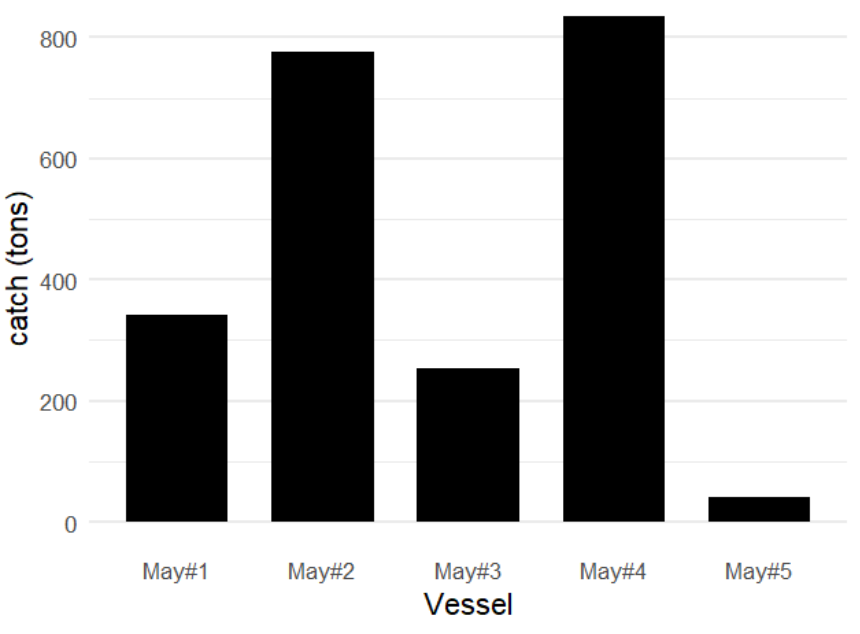
Challenges of quantifying IUU fishing

- Statistically, what could those challenges look like?
  - Example1 Scenario 2

We monitor *every other month* for IUU by illegal foreign fishing (IFF), and we found this:







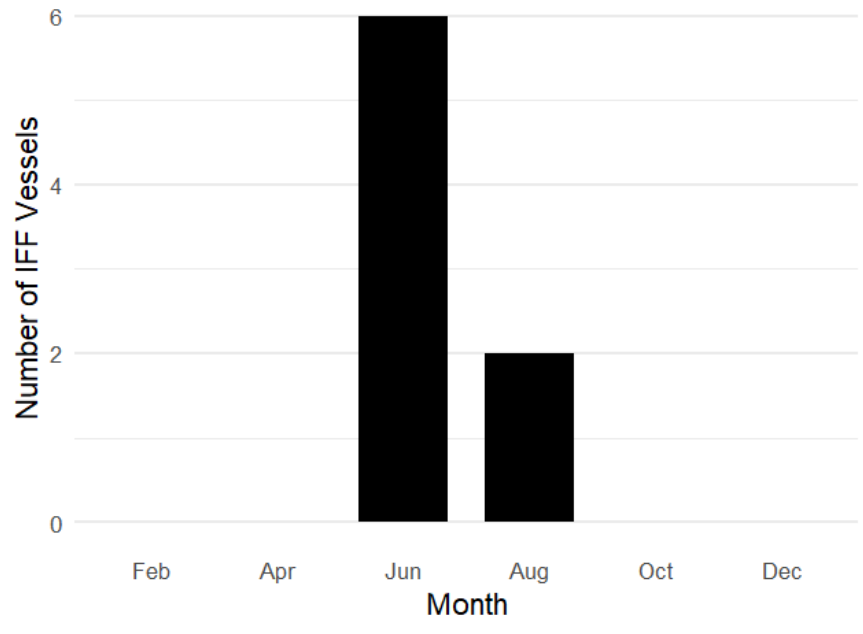
Challenges of quantifying IUU fishing

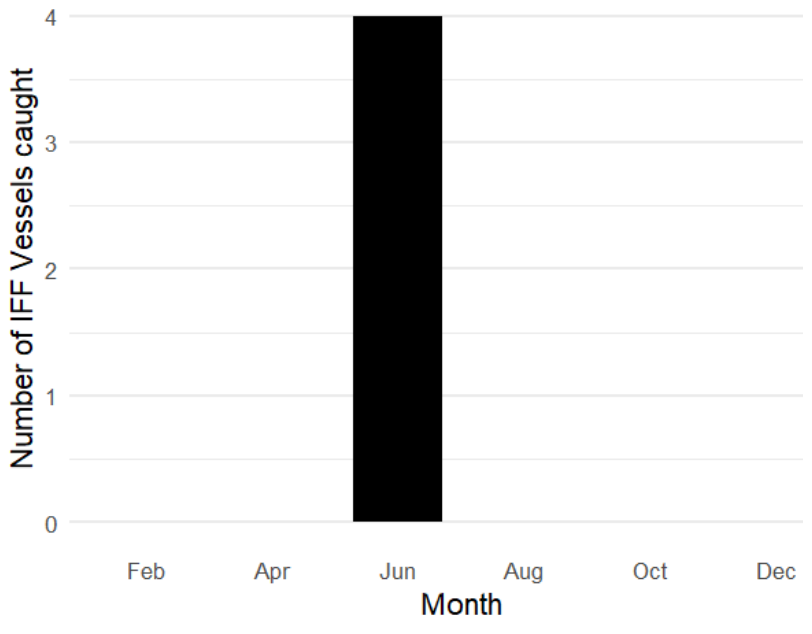
- Statistically, what could those challenges look like?
  - Example1 Scenario 2

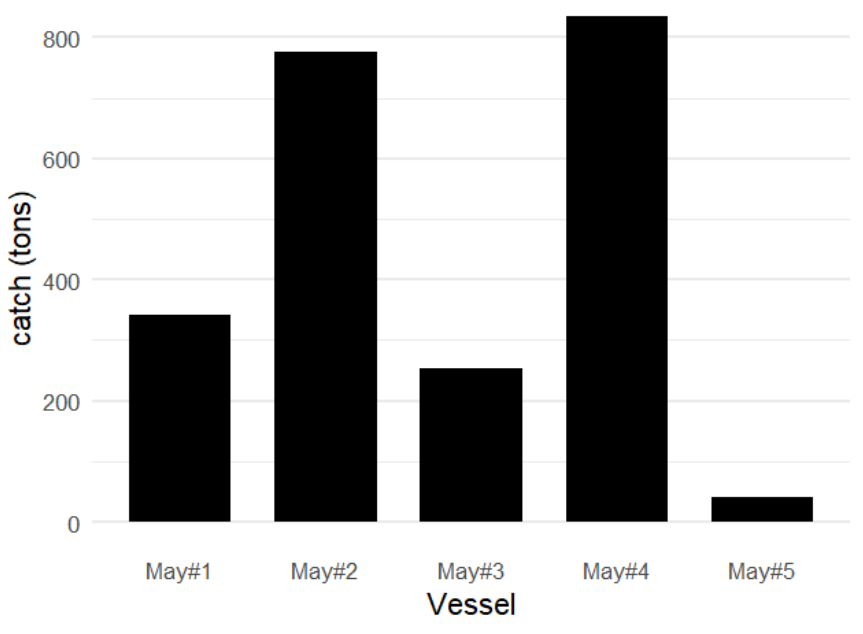
Number of vessels observed in 6 months = 0+3+13+0+0+0 = 16

Averaged to 16/4 = 4 boats/month

Average catch = 449.94 tons/boat





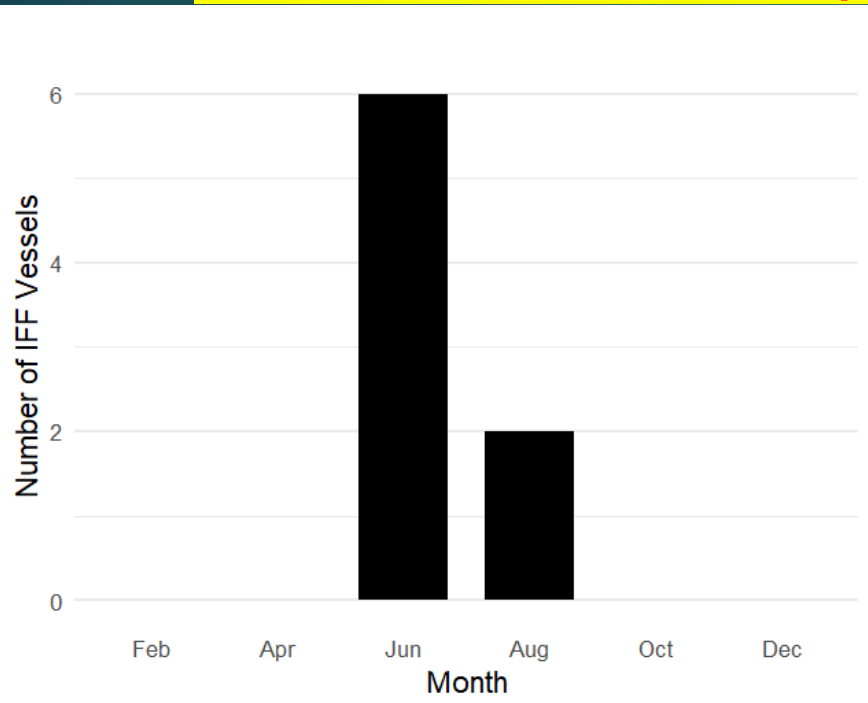


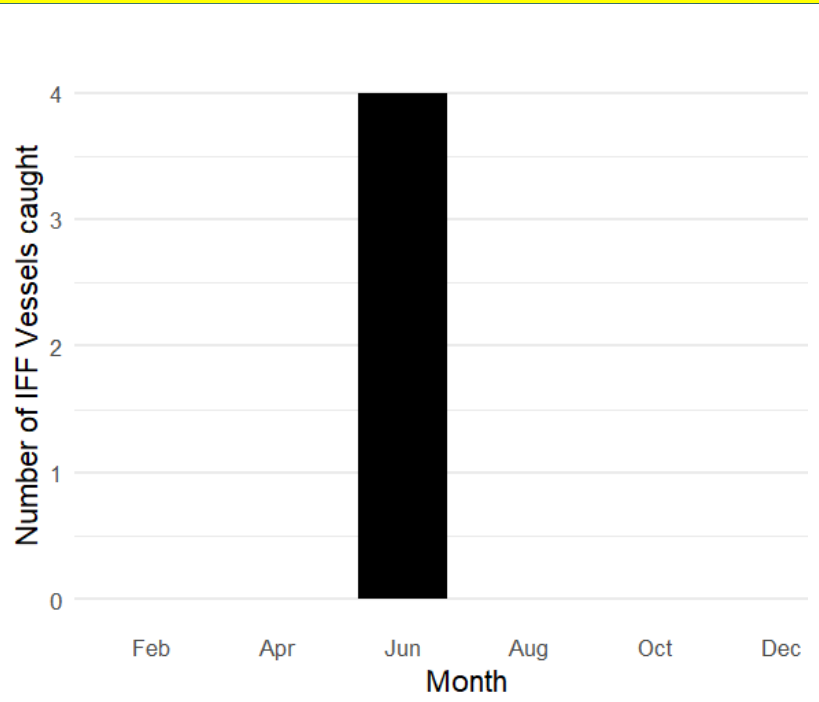
Challenges of quantifying IUU fishing

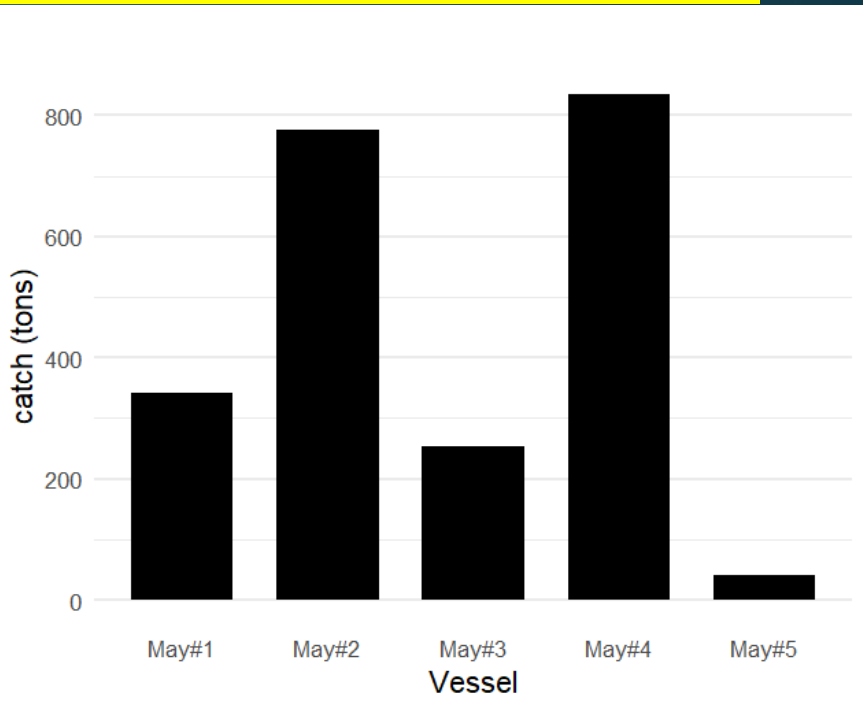
- Statistically, what could those challenges look like?
  - Example1 Scenario 2

Annual total catch = 449.94*4+12 = 14398.02 tons/year

What are the problems with this estimation?????



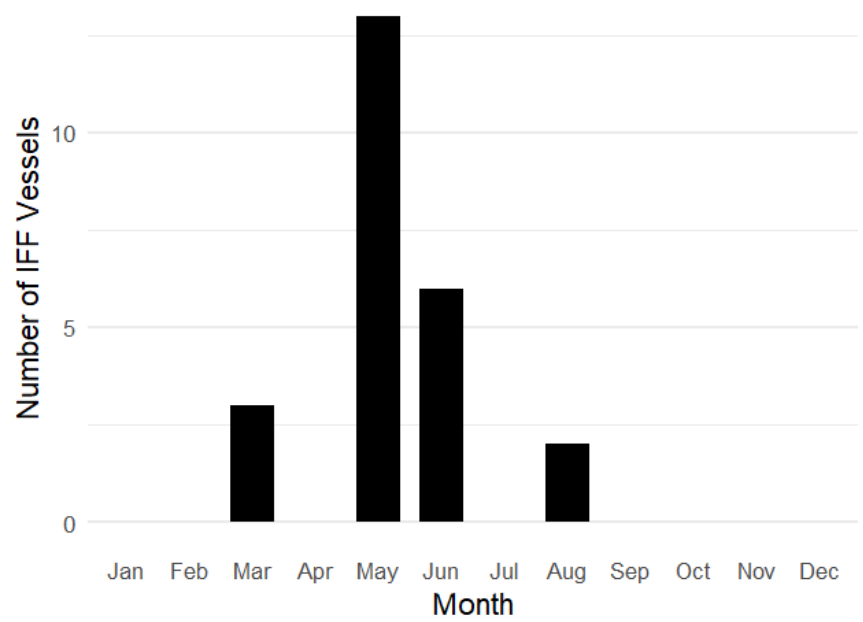


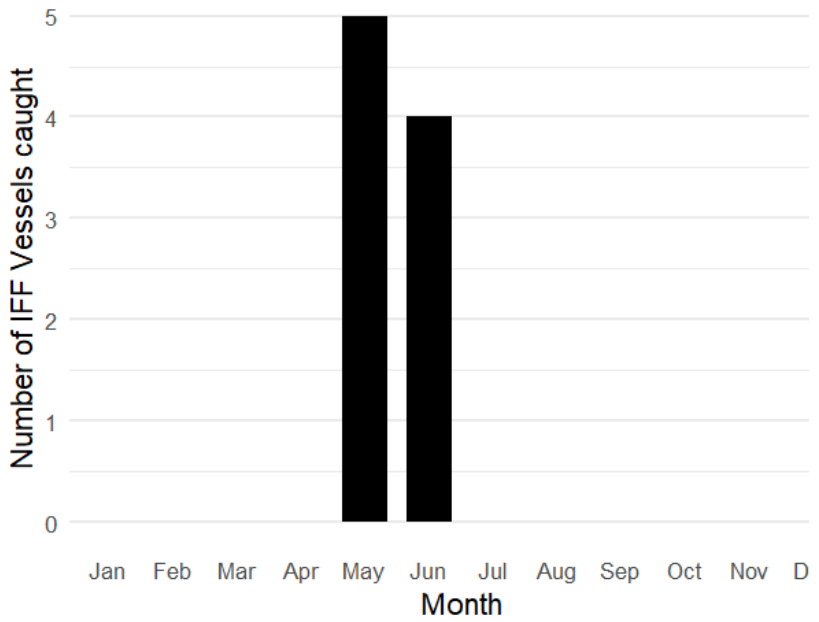


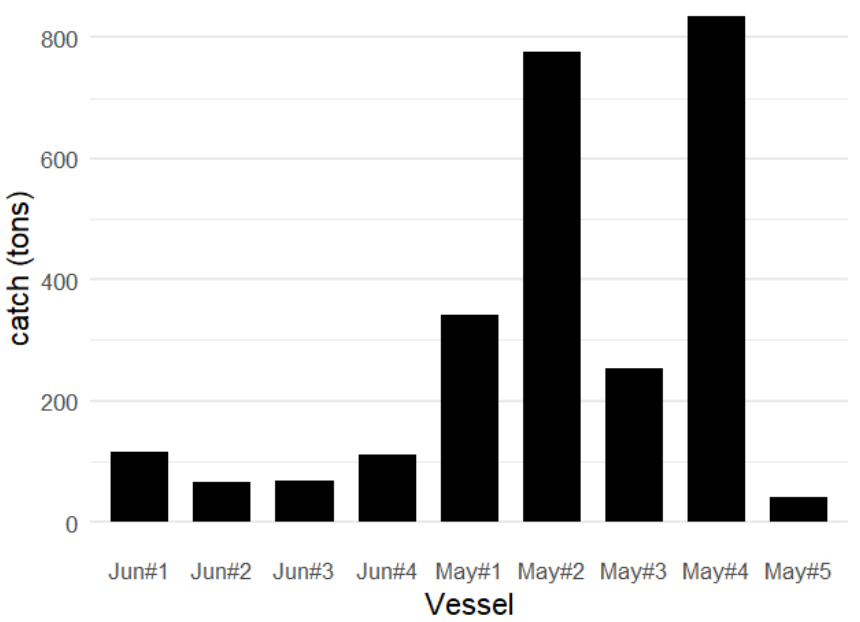
Challenges of quantifying IUU fishing

- Statistically, what could those challenges look like?
  - Example1 Scenario 3

We monitor *every month* for IUU by illegal foreign fishing (IFF), and we found this:







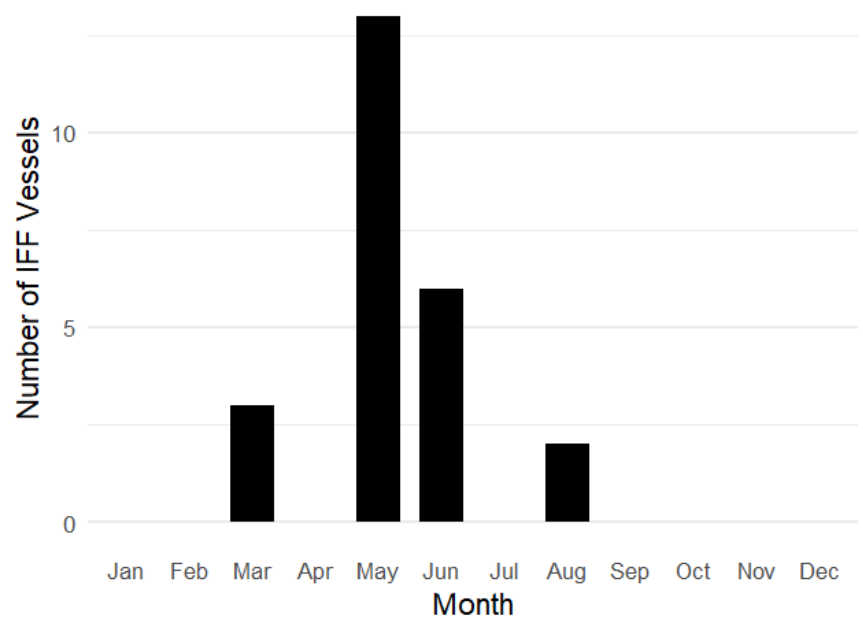
Challenges of quantifying IUU fishing

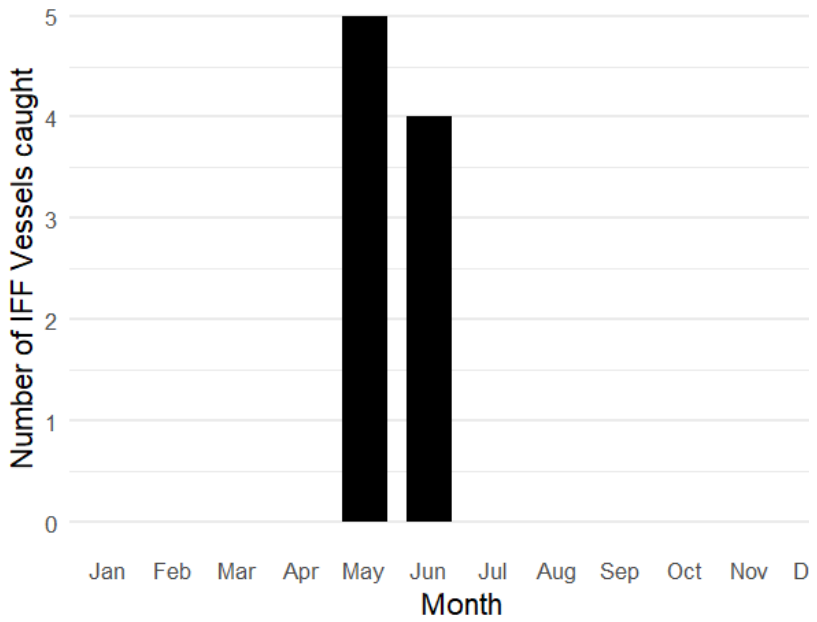
- Statistically, what could those challenges look like?
  - Example1 Scenario 3

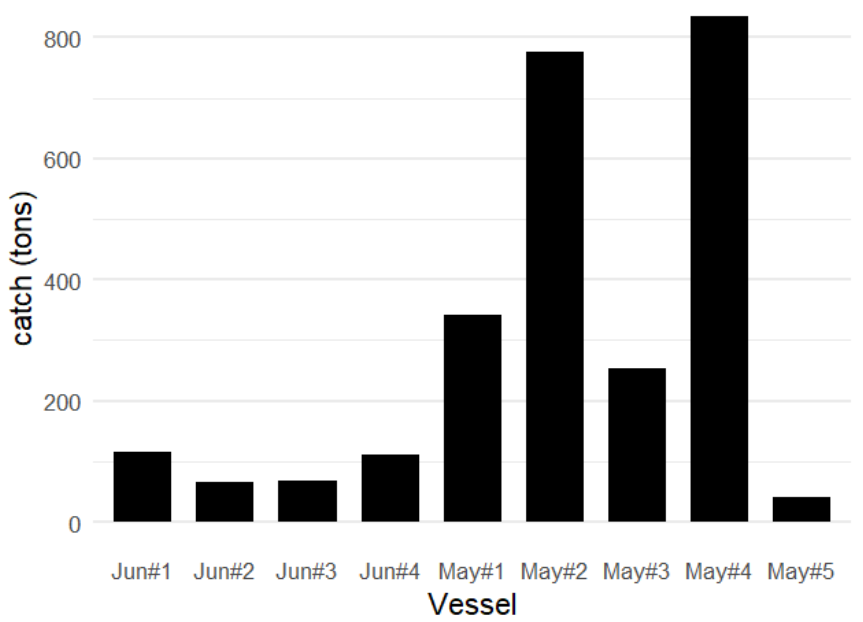
Number of vessels observed in 12 months = 0+0+3+0+13+6+0+2+0+0+0+0 = 24

Averaged to 24/12 = 2 boats/month

Average catch = 290.23 tons/boat





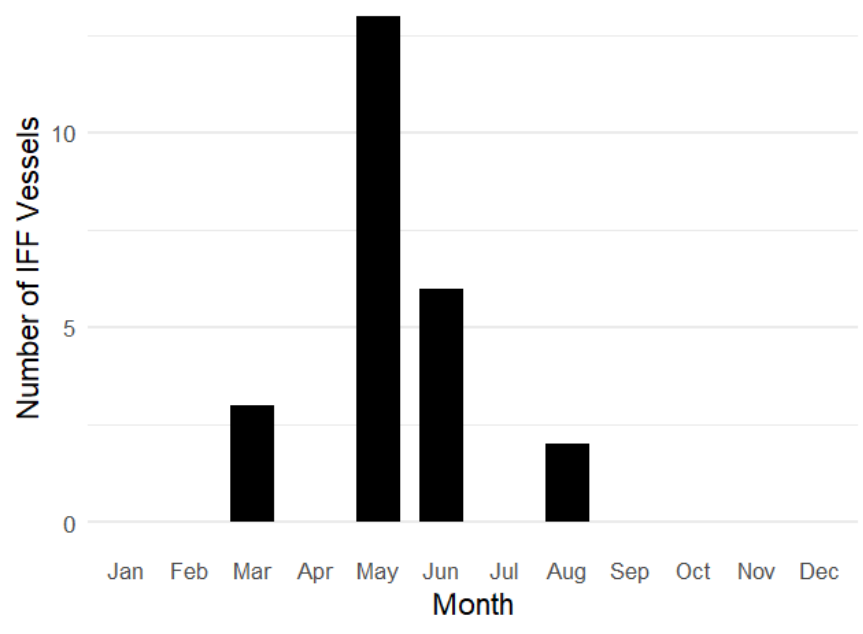


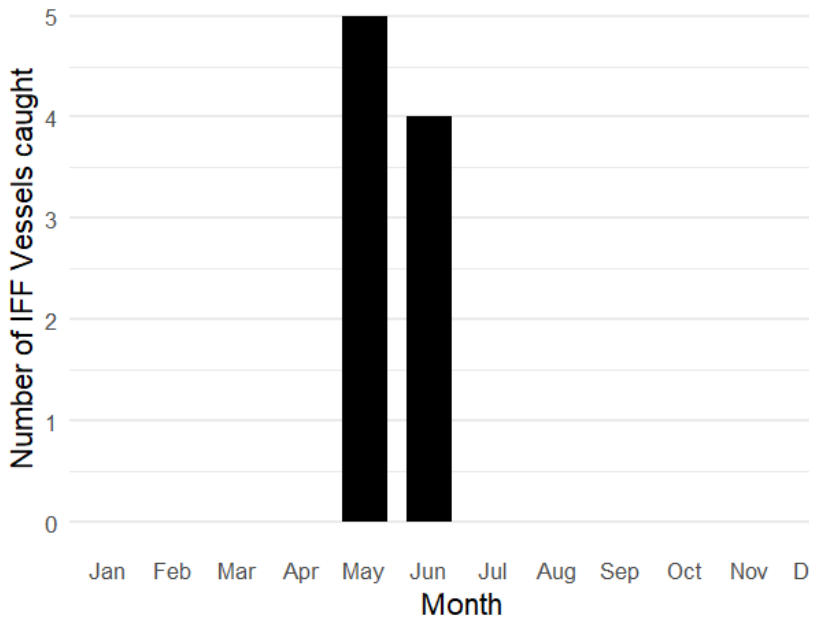
Challenges of quantifying IUU fishing

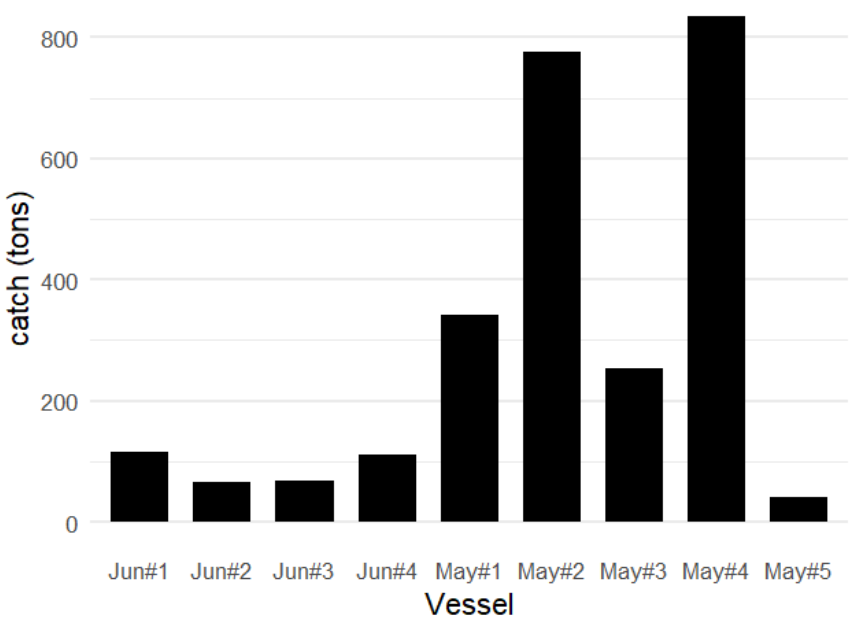
- Statistically, what could those challenges look like?
  - Example1 Scenario 3

Annual total catch = 290.23*2*12 = 6965.49 tons/year

What are the problems with this estimation?????

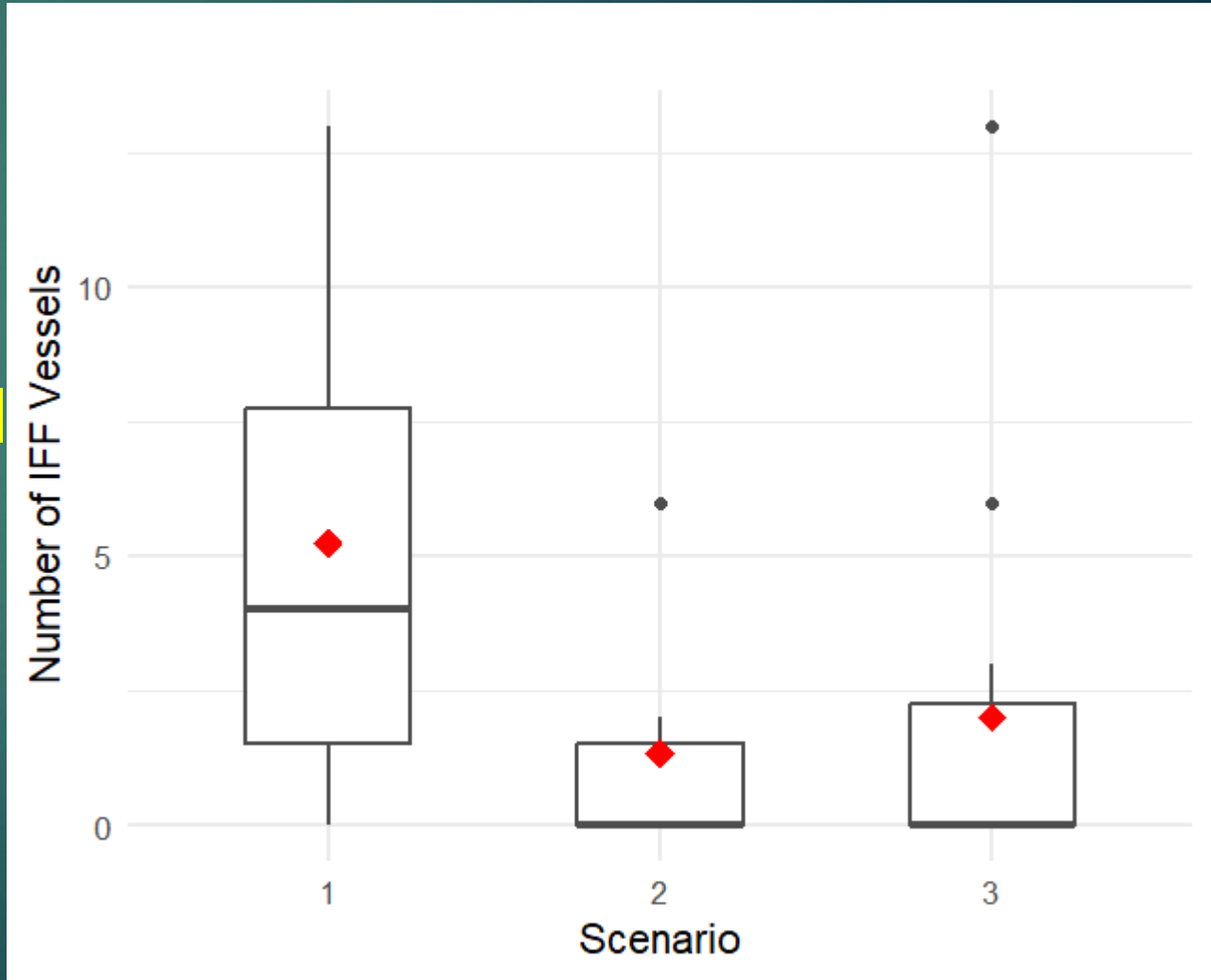






Challenges of quantifying IUU fishing

- From the 3 scenarios:
  - Is the number of samples enough?
  - Does using average make sense?
  - Is temporal coverage enough?
    - Did we talk about observation days?
  - Have we look at spatial coverage?????



Challenges of quantifying IUU fishing

- Example 2

  Shark fin market survey from 2 years, 62 days each year

year	n	mean	sd	se	median	Q1	Q3	IQR	min	max	sum
1	62	251.	92.0	11.7	238.	180.	329.	148.	105	400	15537
2	62	280.	74.2	9.42	283	227.	346	119.	152	402	17346

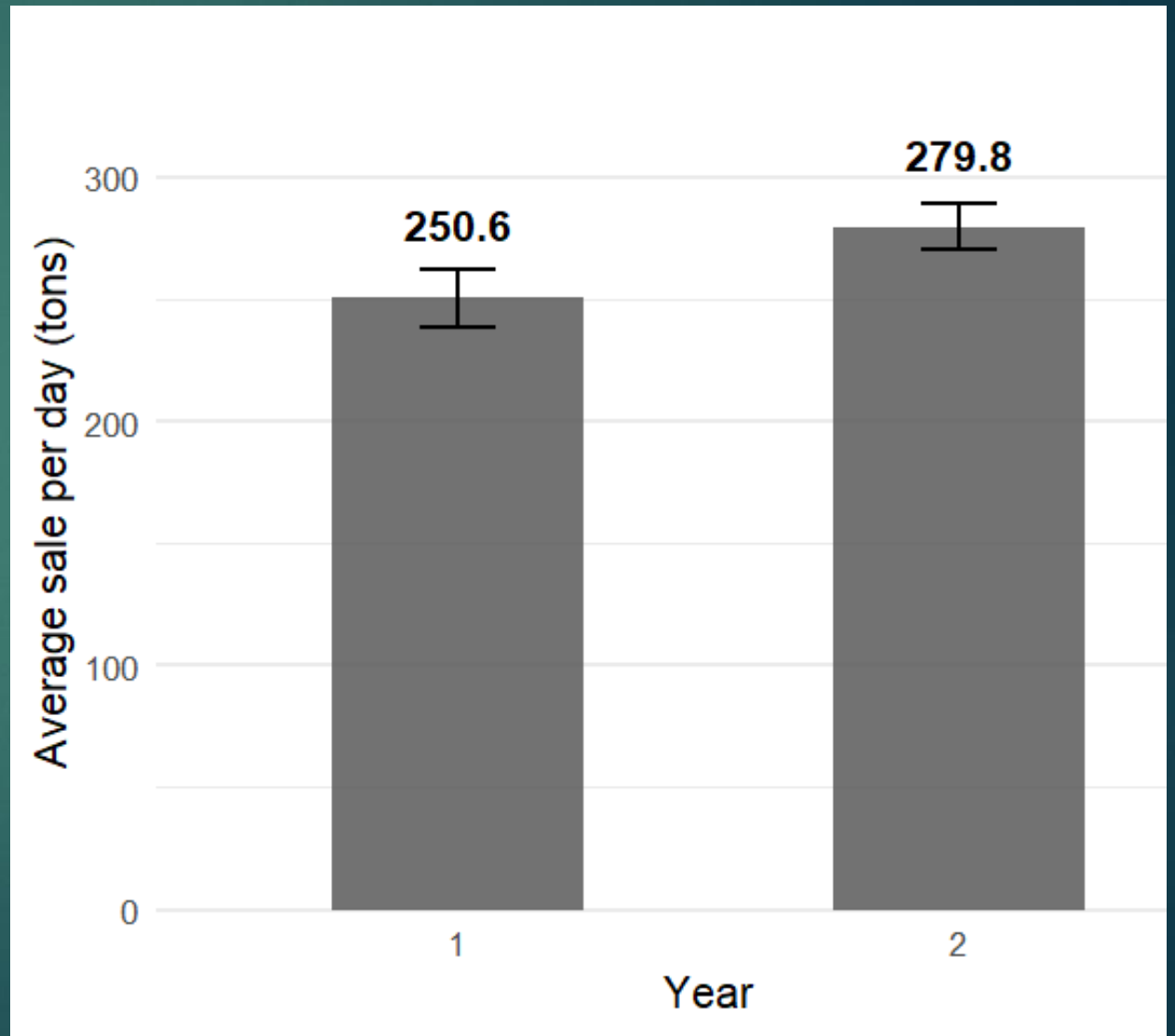
Did the sale increase?

Challenges of quantifying IUU fishing

- Example 2

  Shark fin market survey from 2 years, 62 days each year

Did the sale increase?

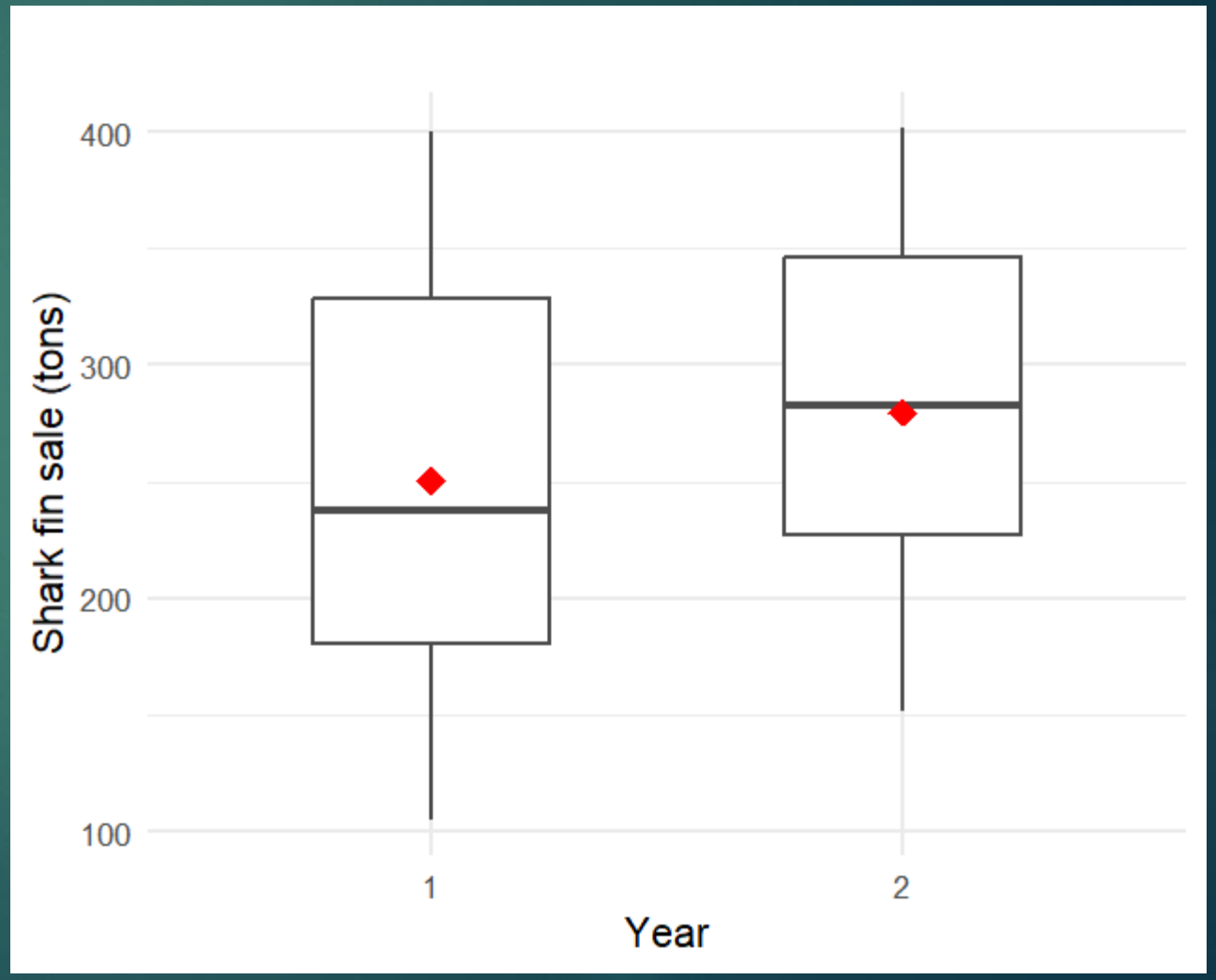


Challenges of quantifying IUU fishing

- Example 2

  Shark fin market survey from 2 years, 62 days each year

Did the sale increase?



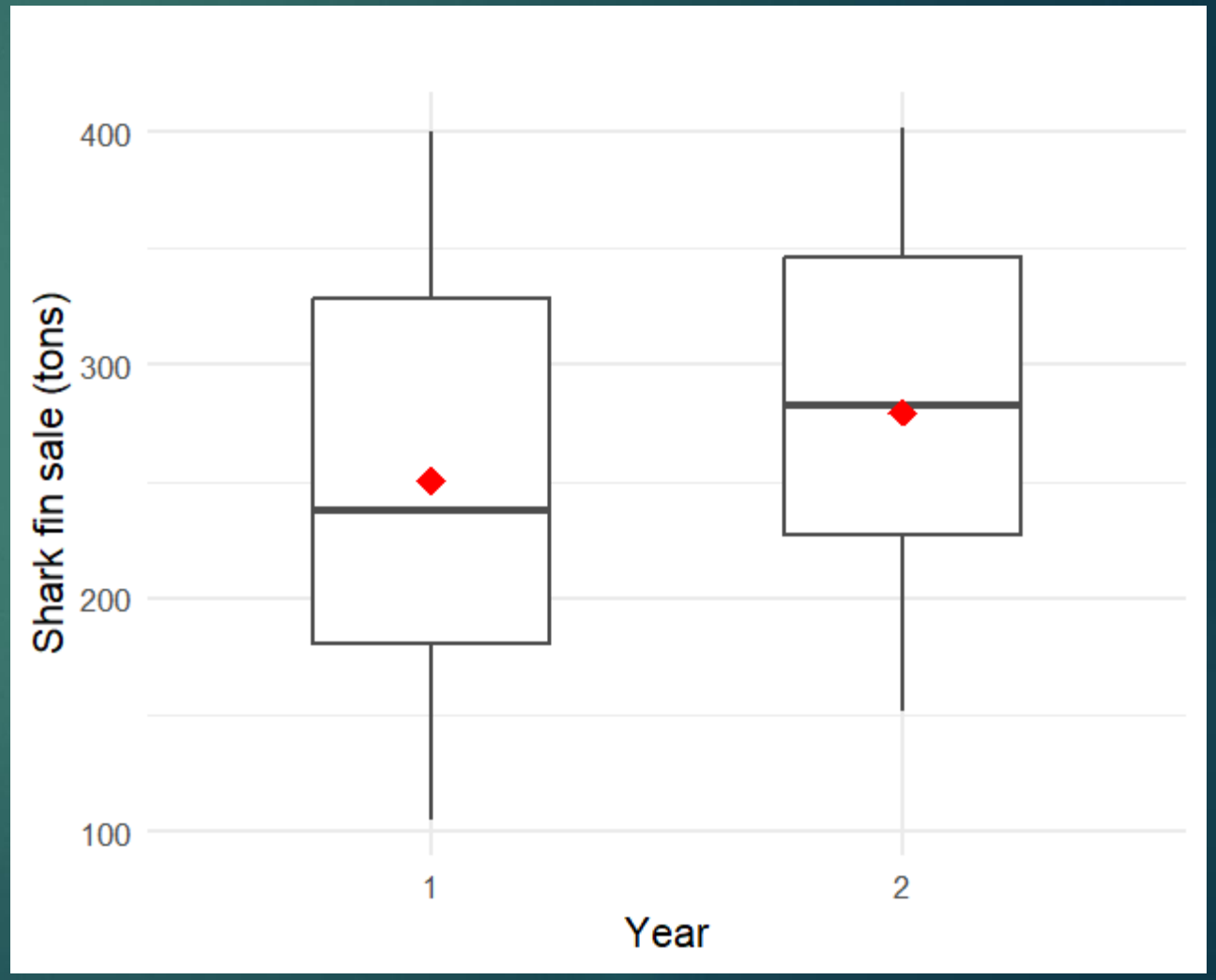
Challenges of quantifying IUU fishing

- Example 2

  Shark fin market survey from 2 years, 62 days each year

Did the sale increase?

- Before we answer this, what should we ask about the data?

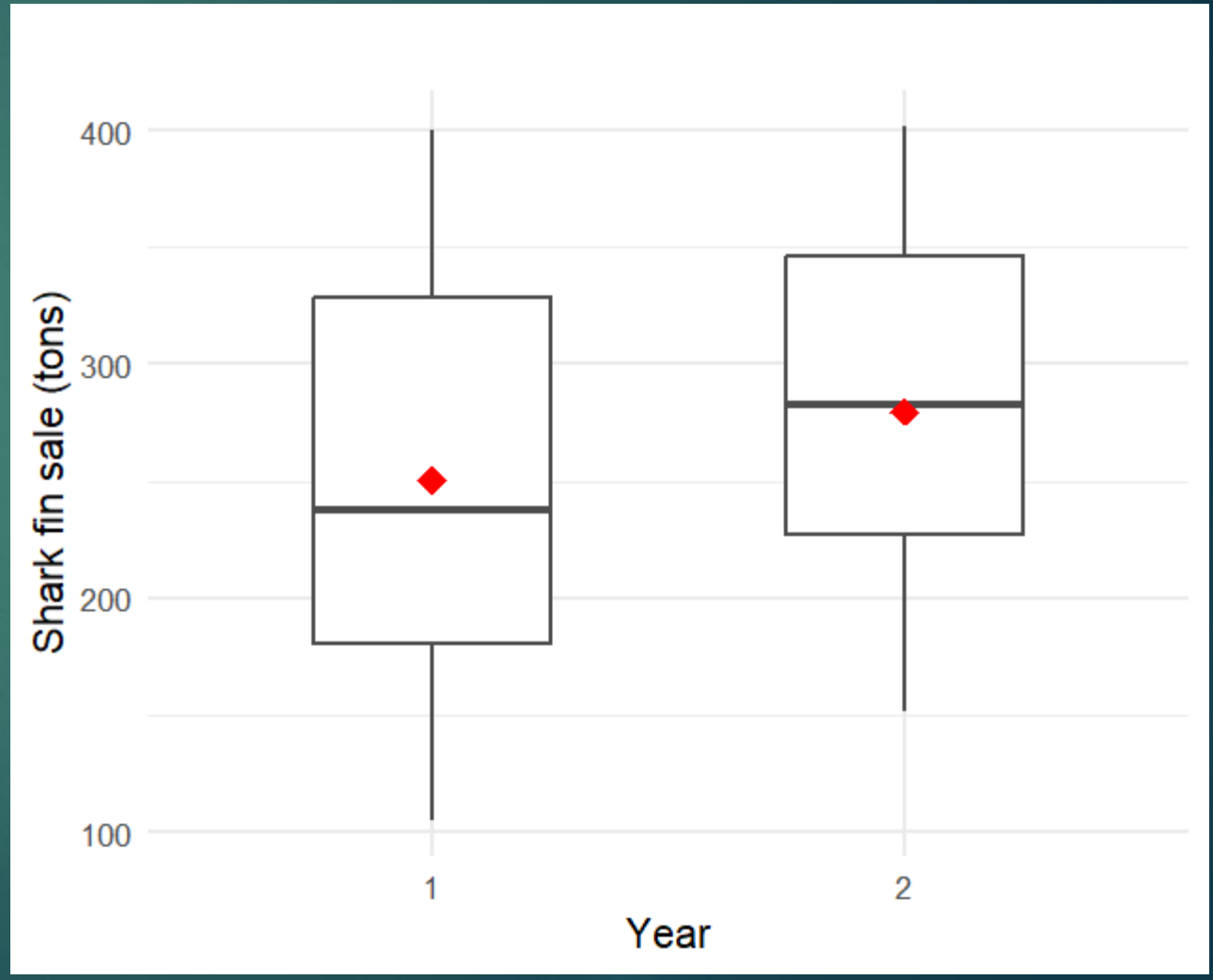


Challenges of quantifying IUU fishing

- Example 2

  Shark fin market survey from 2 years, 62 days each year

Can we make extrapolation to biomass loss?



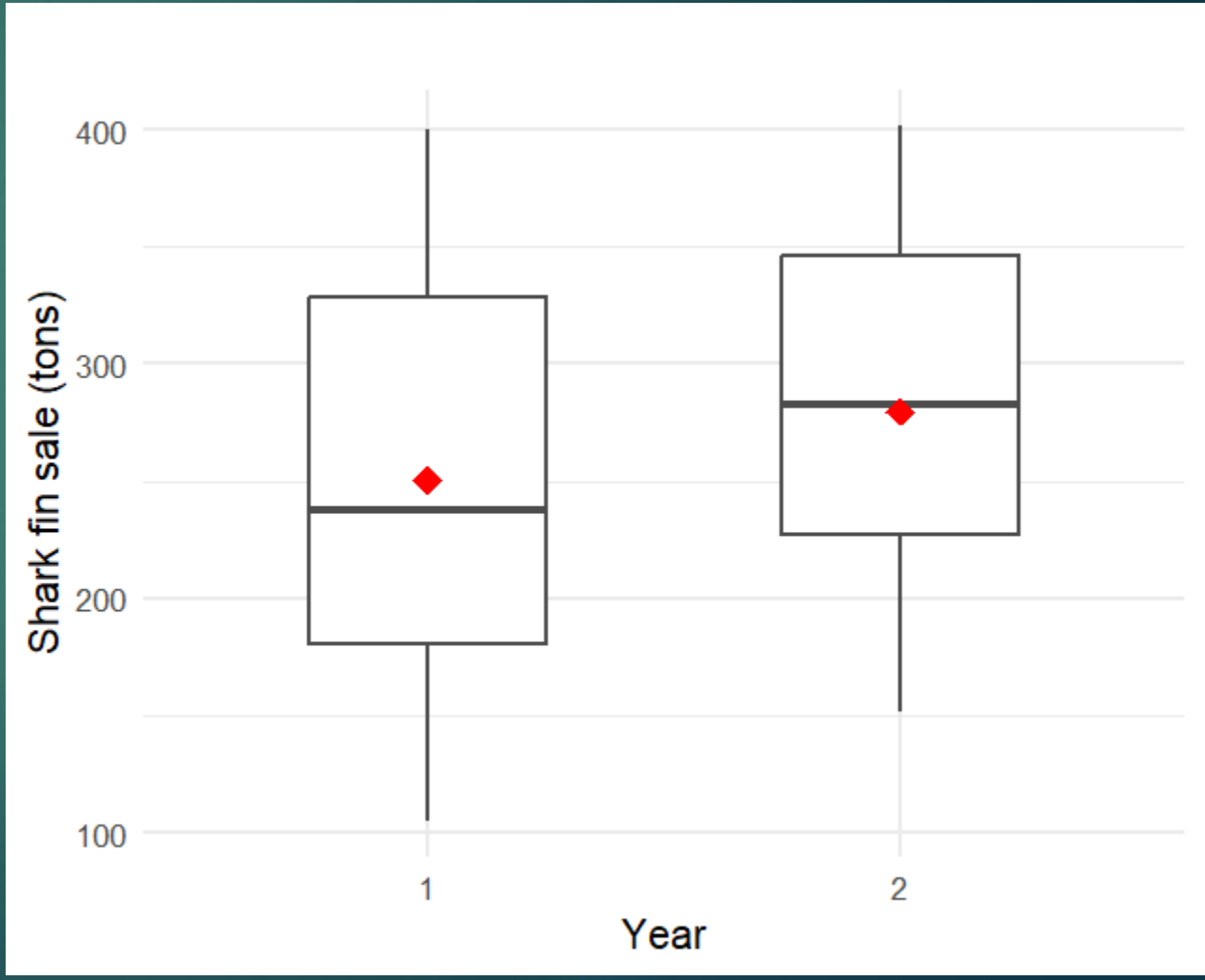
Challenges of quantifying IUU fishing

- Example 2

  Shark fin market survey from 2 years, 62 days each year

We have to make many assumptions for biomass loss extrapolation.

- The sampling period represents the temporal variations.
- The sampled market represents the entire trade.
- The dried fins are from certain areas.



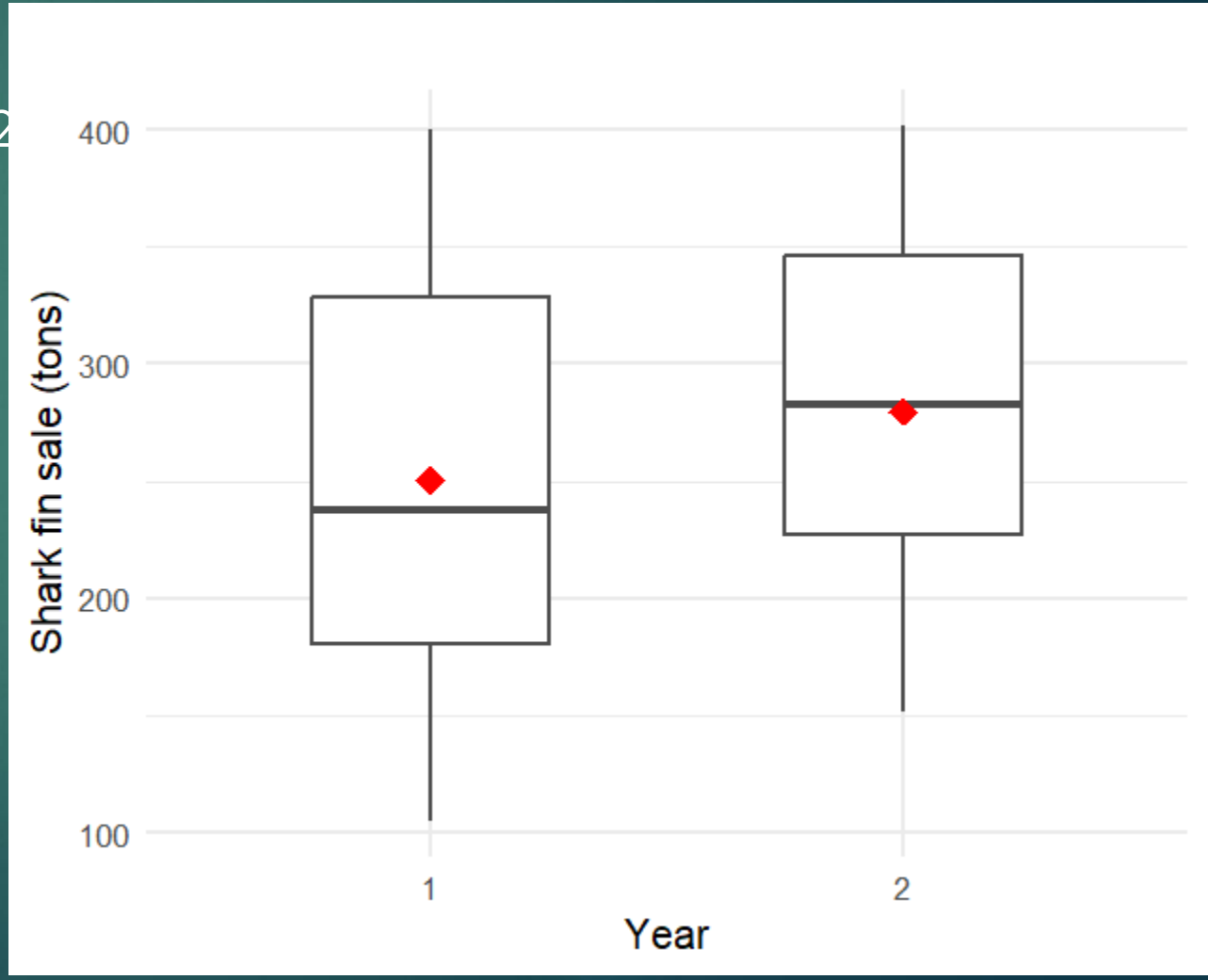
Challenges of quantifying IUU fishing

- Example 2

Shark fin market survey from 2 years, 62 days each year

We have to make many assumptions for biomass loss extrapolation.

- The dried fins are from certain species composition
- The proportion of dried fin weight to wet whole fish weight.



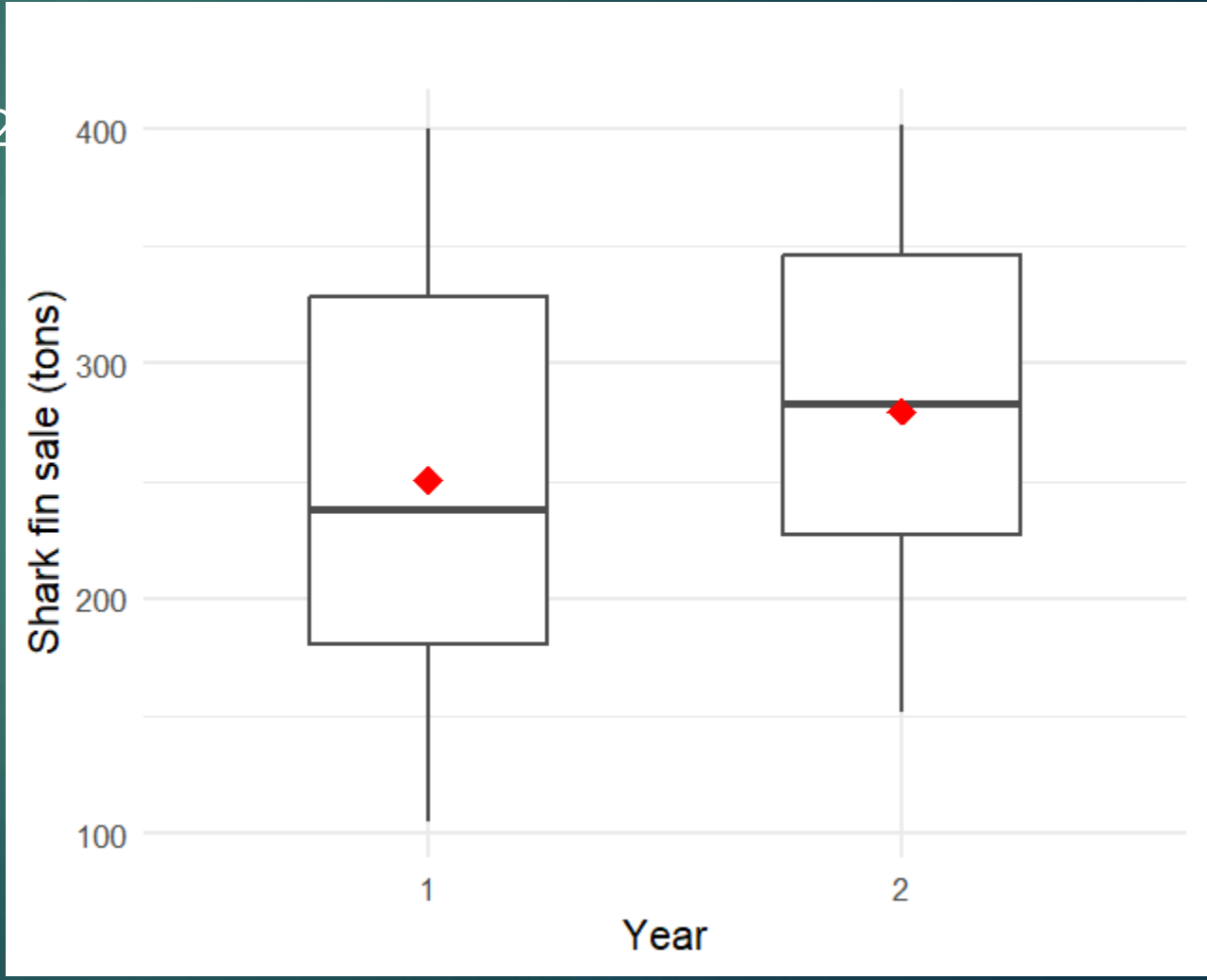
Challenges of quantifying IUU fishing

- Example 2

Shark fin market survey from 2 years, 62 days each year

We have to make many assumptions for biomass loss extrapolation.

Every factor in multiplication carries its own range of uncertainty.



Challenges of quantifying IUU fishing

- Example 3: a real world unreported tuna estimation

1) Only a fraction of the frozen wild whole tuna sold in Japan actually goes through these wholesale markets. There are direct sales of tuna, longline caught and farmed, that by-pass the wholesale market system (e.g. bulk purchases by super-market chains).
2) The complex distribution and market systems result in some tuna being included in the sales statistics for more than one wholesale market (i.e. double counting exists in the simple sum of the total SBT sold across all markets).
3) A fraction of the wild caught frozen imported longline catches from other countries (e.g. Korea and Taiwan) are also sold in the wholesale markets.
4) A large fraction of the farmed SBT caught by the Australian surface fishery are frozen and a portion of these are sold in the wholesale market auctions.
5) There can be a substantial time lag between when an SBT was caught and when it is actually sold at Japanese markets, as a result of the duration of longline cruises and because tuna can be held in frozen storage for extended periods (often several years). This time lag is also likely to have varied over time with changes in technology, fleet operations and market practices.
6) Each of the above factors is likely to have varied over the last 20 years in response to changes in the nature of the fishery and the markets.

CCSBT 2006

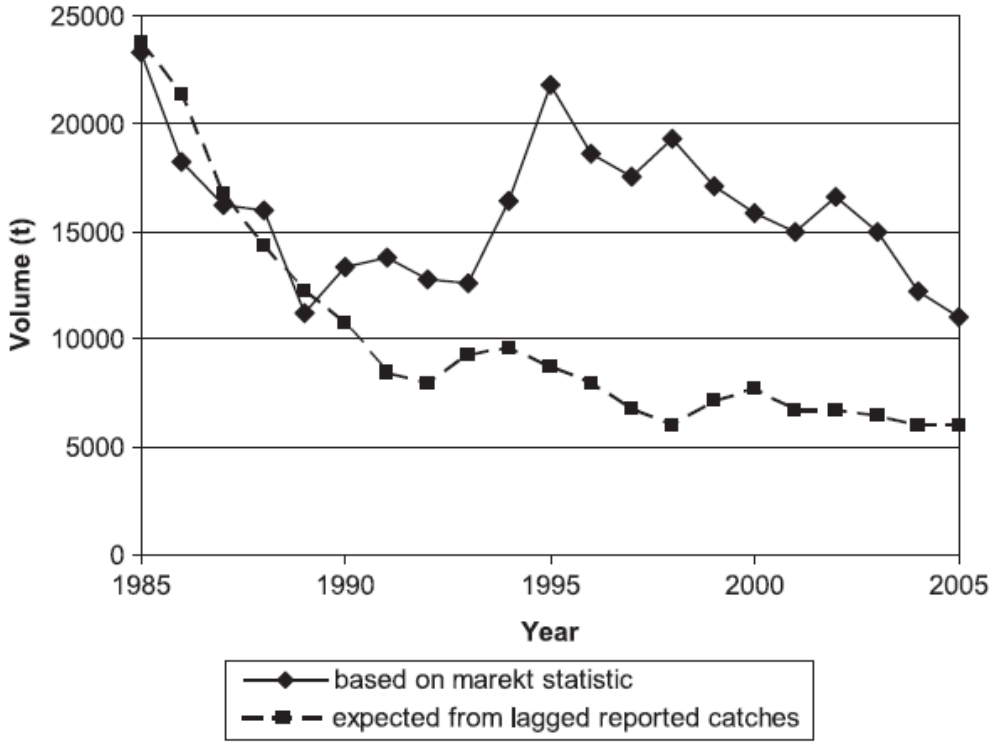


Fig. 2. Estimate of the total volume of SBT in Japanese markets based on the Case 1, 1985–2005 estimates provided to the CCSBT SC and SAG compared to the estimated volume based on reported catches taking into account the lag between the time of catch and time of sales (see [18] for details). This figure is based on Fig. 2 in of Attachment 4 of [18]. Note the numerical values are approximate as they were taken from estimating the values base on reading the *y*-axis in these figures.

Polacheck 2012

Challenges of quantifying IUU fishing

- Example 4: Convention on the Conservation of Antarctic Marine Living Resources IUU estimation

Table 1: Fisheries protection vessel (FPV) sightings of IUU incidents by year (Agnew, 2004).

Year	% of the year spent patrolling in Subarea 48.3	Number of IUU incidents sighted
1998/99	8	1
1999/00	24	8
2000/01	32	1
2001/02	35	0
2002/03	37	0
2003/04	40	0

The estimated number of days fi shing for the IUU cruise$_1$ detected by an FPV, i, in year y, $D_{i,y}$, was thus calculated from FPV encounters with IUU vessels as:

$$D_{i,y} = L_{i,y} - E_{i,y} \quad (1)$$

where L is the latest and E is the earliest date from which the vessel can have been fi shing.

Then the fish catch of the cruise was

$$C_{i,y} = A_{i,y} CPUE_{a,y} \quad (3)$$

where $CPUE$ was the average CPUE of licensed vessels in that area in year y.

Agnew and Kirkwood 2005

Narrowing down the uncertainty:

IDENTIFYING THE DATA GAPS AND HOW TO FILL THEM

Outline

- Study planning
- Study execution

Study planning

Identify the objectives

- What do we want *to achieve*?
  - Overall estimation to better stock assessment?
  - Specific IUU activities over specific species for urgent regulation?
  - Improve socioeconomic for fishers?
  - Monitoring changes in IUU activities?

How to know what we should want to achieve?

- Stakeholder participation!

Study planning

Narrowing down the scope

- What should we *look at*?
  - Which fisheries/sectors?
  - Which species?
  - Which area/region?
  - Which timeframe?
  - Which parts of IUU fishing?

Be specific

Think about practicality, feasibility and the resources available

Study planning

Narrowing down the scope

- *Risk assessment* can help specifying the scope

"In the context of IUU fishing estimation, risk identification is the process of identifying and defining actual and potential IUU fishing activities within a fishery unit" – FAO 2023

Study planning

Narrowing down the scope

- *Risk assessment* can help specifying the scope

Group	Category	#	Types of activity	Notes
Fishing outside regulations	Encroachment (IPOA-IUU description categories 3.1.1, 3.1.3, 3.3.1)	1	• Fishing in the waters of a country without a valid licence, authorization or permit by the relevant national authority, where required • Fishing in the waters of an RFMO without a valid licence, authorization or permit	Note if this is within a country or by an RFMO contracting party flag State it is illegal; if in an RFMO area by a non-party it is unregulated. Where there is activity within an exclusive economic zone (EEZ) that is not required to be licensed, this is often referred to by IUU fishing analyses as unregulated but strictly speaking it is not according to the FAO definition – see below category 3.
	Absence of authentic documentation (3.1.3)	2	• Fishing in the waters of a country or an RFMO with false documentation • Fishing as a stateless vessel (not registered with a national registry, or registered simultaneously on more than one)	
	Legal non-reporting of activity	3	• Lack of reporting of fishing activities where this is **not** required either by national law or in international waters by RFMO and/or flag State regulations	Examples include fisheries that are often unregulated such as artisanal, subsistence and recreational fisheries. As above, note that this is not necessarily unregulated according to the IUU fishing definition.

Table 1. Example categorization of common types of illegal, unreported and unregulated activity relevant to estimation studies

FAO 2023

Study planning

Narrowing down the scope

- *Risk assessment* can help specifying the scope

Group	Category	#	Types of activity	Notes

Fishing in contravention of regulations	Non-compliance with technical measures (3.1.3)	4	• Vessels may be licensed and have authentic documentation, but are:
			  ▸ fishing in an area and/or season in contravention of management measures
			  ▸ engaging in directed fishing for a stock or species which is subject to a moratorium or for which fishing is prohibited
			  ▸ using fishing gear which is prohibited or non-compliant with applicable laws and conservation and management measures
			• Non-compliance with, or contravention of, technical requirements relating to a fishing access contract/agreement
			• Unauthorized transshipment of fish and fishery products without authorization from the coastal or flag State or in contravention of the requirements of an RFMO, and/or without a designated and accredited observer to witness and record the transshipment operation if required	

Study planning

Narrowing down the scope

- *Risk assessment* can help specifying the scope

Group	Category	#	Types of activity	Notes
Fishing in contravention of regulations	Illegal non-reporting and misreporting (3.2.1, 3.2.2)	5	• Lack of reporting of fishing activities where required either by national law or in international waters by RFMO and/or flag State regulations • Lack of reporting of catches, discards, and other incidental impacts of the use of fishing gear, where required by regulations • Over-reporting of catch (for example, to load logbooks in advance of allocations based on catch history)	A distinction is made between legal and illegal non-reporting. Normally IUU fishing studies restrict themselves to estimating retained catch and discards, but some have gone further to estimate mortality from ghost fishing.
	Legal non-reporting of catches and discards	6	• Lack of reporting of catches and discards where this is **not** required either by national law or in international waters by RFMO and/or flag State regulations	If not required in law, non-reporting discards is not unreported according to the IUU fishing definition. Despite not being *sensu stricto* IUU fishing, estimating these volumes is often one of the primary objectives of IUU fishing studies, and should be considered in any future IUU fishing studies.

FAO 2023

Study planning

Looking for available data

- Are there existing monitoring schemes that could help within your scope?
  - Scope: overall estimation of *unlicensed fishing* and *catches quantity* within *an area*
    - Surveillance (at sea or arial)
    - Satellite imagery
    - Assuming the gear and activities are the same to licensed fishing: *extrapolate unlicensed catches* using CUPE of licensed fishing.

Study planning

Looking for available data

- Are there existing monitoring schemes that could help within your scope?
  - Scope: *underreported catch* by *licensed fisheries*
    - Logbooks
    - Onboard observers
    - Port inspection
    - Electronic monitoring (i.e. camaras)

Study planning

Looking for available data

- Are there existing monitoring schemes that could help within your scope?
  - Scope: How much *illegal transhipment* being done by *a certain fishing sector*
    - VMS/AIS
      - Potential fishing hours (based on velocity)
      - Potential transhipping position
    - Satellite imagery
    - Expected CPUE

Study planning

There are data gaps. Can we fill them?

- Depending on resources available.
- Depending on the scope.
- Depending on the data type.

Study planning

There are data gaps. Can we fill them?

- Which one of these can probably be realistically gathered more?
  - Trade data between 2015-2025
  - Arial survey (getting on an actual plane)
  - Drone survey
  - At sea patrol
  - Catch sampling at ports

Study planning

There are data gaps. Can we fill them?

- Examples of old school data
  - Market estimation (with expert opinions) vs logbooks

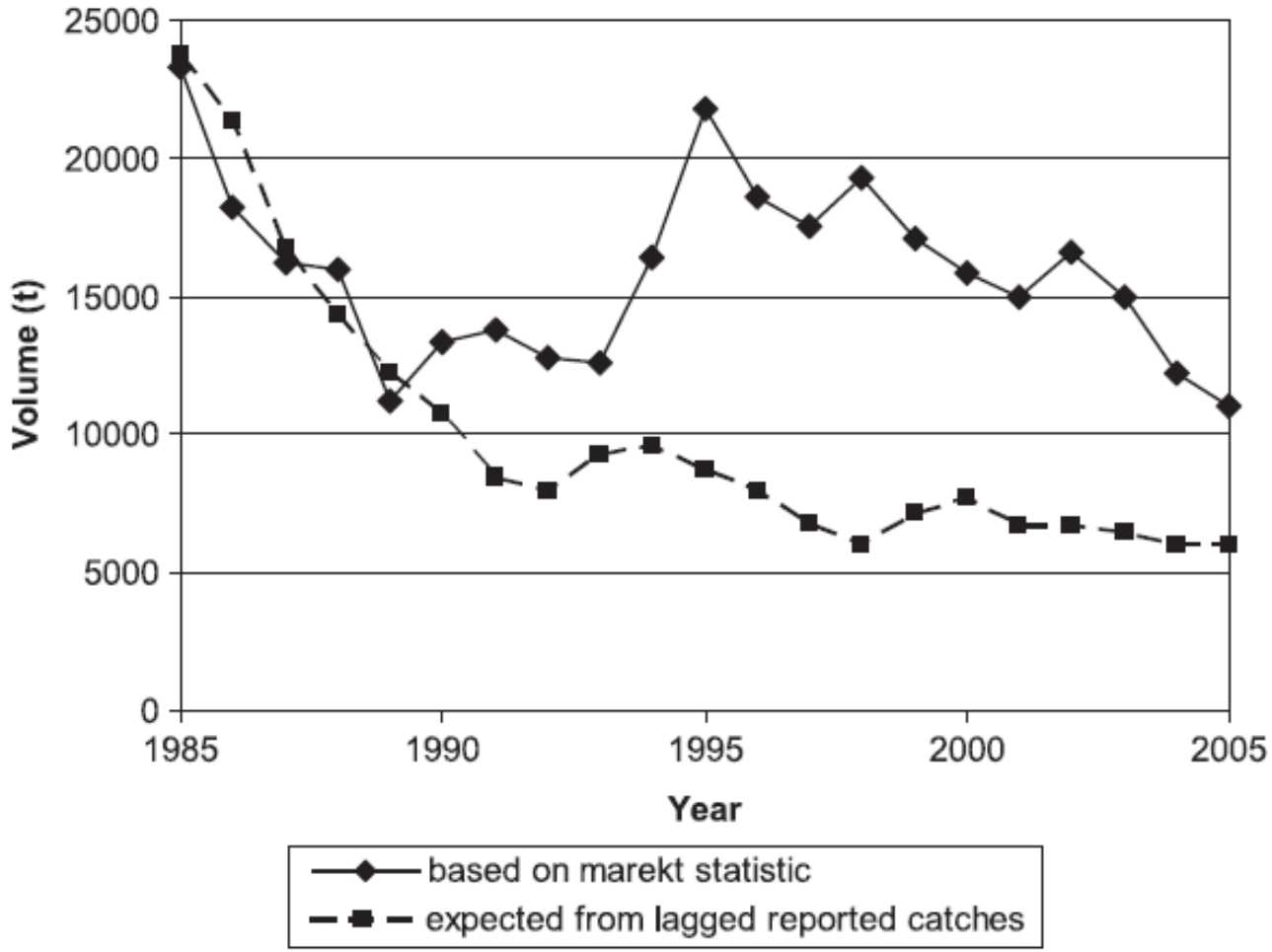


Fig. 2. Estimate of the total volume of SBT in Japanese markets based on the Case 1, 1985–2005 estimates provided to the CCSBT SC and SAG compared to the estimated volume based on reported catches taking into account the lag between the time of catch and time of sales (see [18] for details). This figure is based on Fig. 2 in of Attachment 4 of [18]. Note the numerical values are approximate as they were taken from estimating the values base on reading the *y*-axis in these figures.

Polacheck 2012

Study planning

There are data gaps. Can we fill them?

- Examples of old school data
  - Applying modelling approach to help find probability

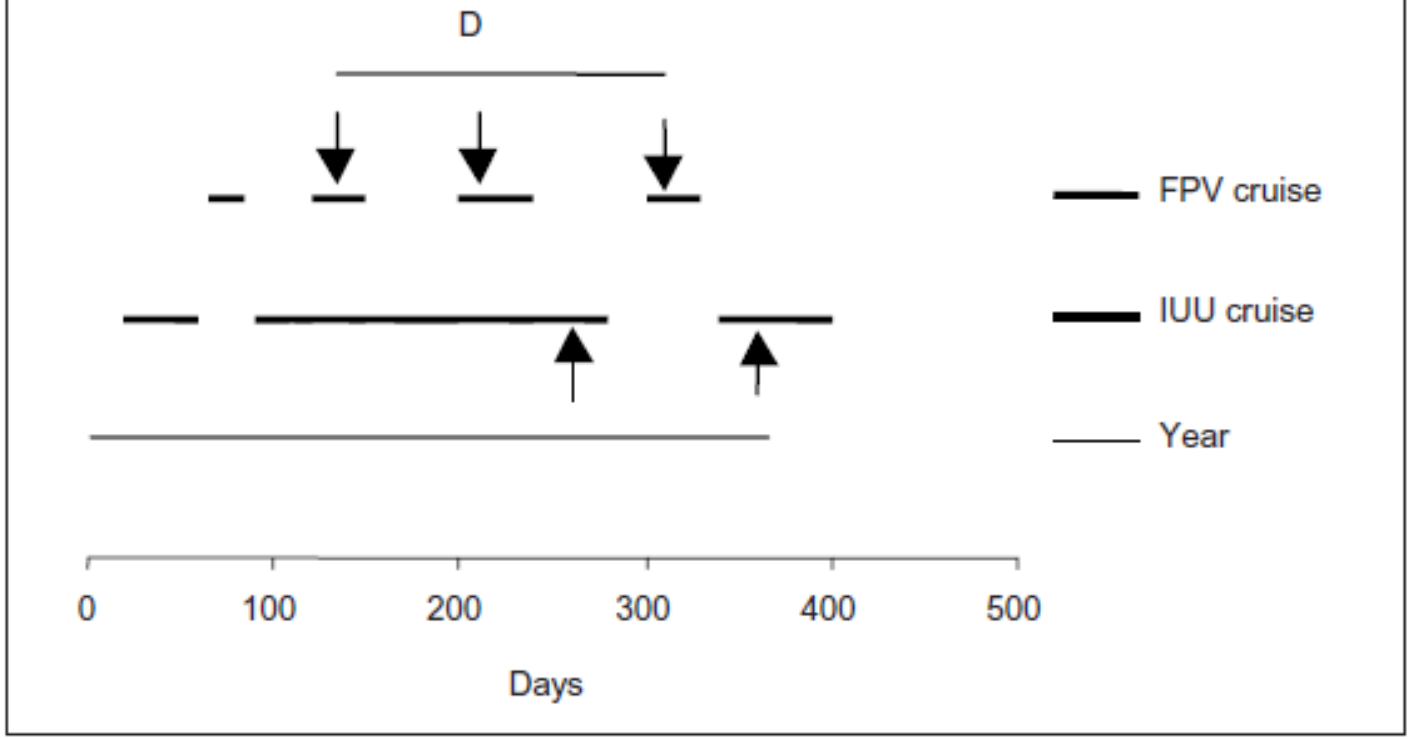


Figure 2: Schematic representation of the stochastic model.

Agnew and Kirkwood 2005

Study planning

There are data gaps. Can we fill them?

- Examples of technological helpers

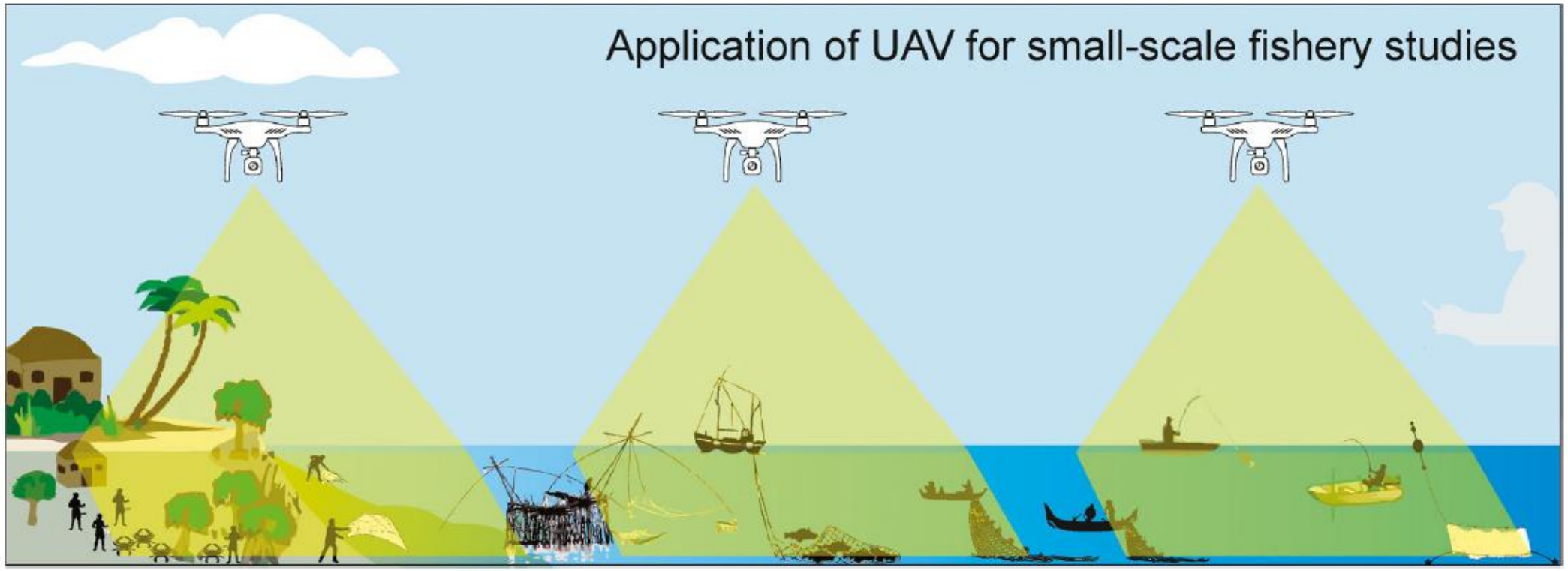


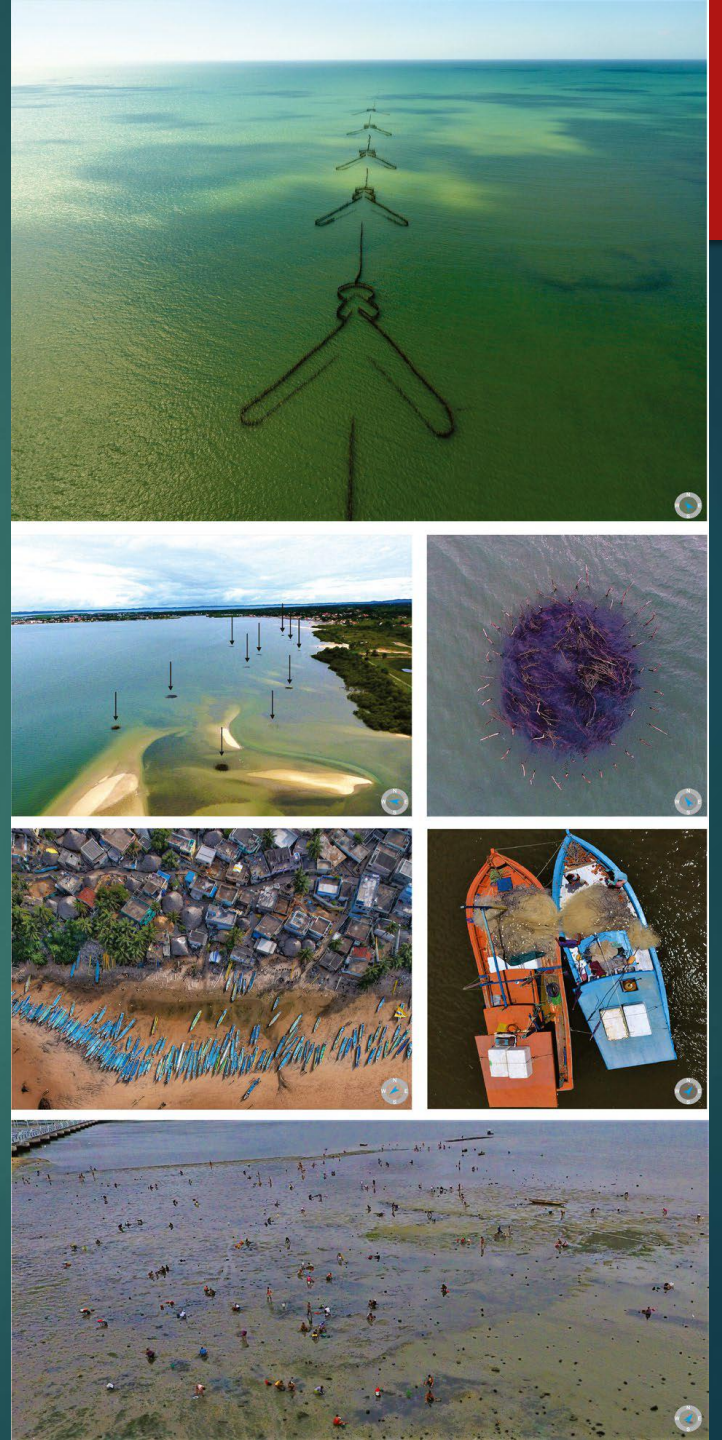
Figure 1. Diagram of the application of an unmanned aerial vehicle (UAV) for small-scale fishery inspections evidencing the range of types of fishing practices.

Reis-Filho and Giarrizo 2022

Study planning

There are data gaps.
Can we fill them?

- Examples of technological helpers



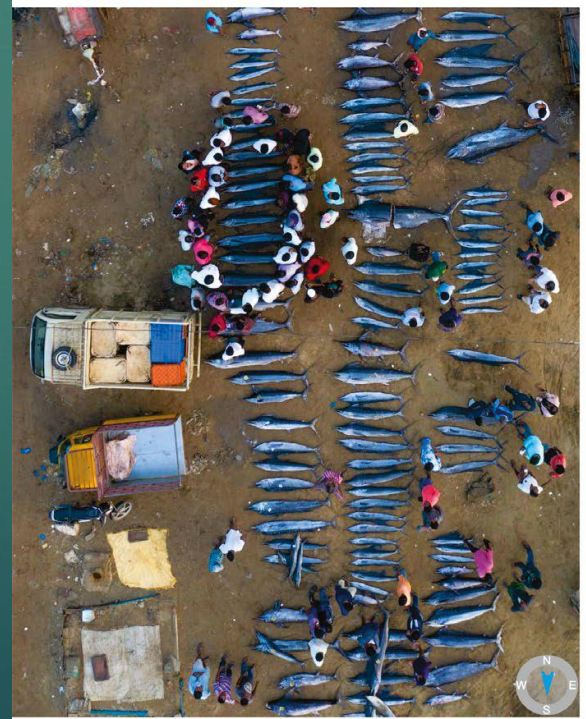
Reis-Filho and Giarrizo 2022

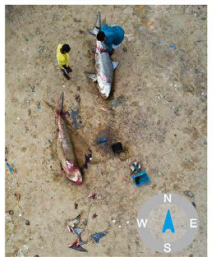
Figure 2. Identification and documentation of varied small-scale fishing practices using unmanned aerial vehicle system. (A) A visualization of stationary fishing devices used to catch (top image) and attract fish. At the image on the right it is possible see that the device is functional due amount of mangrove wood kept inside. (B) A rapid identification and count of boats employed in fishing activities as well as documentation of cultural fishing practices. (C) A count and effort estimation of shellfish gleaning in shoreline. Images credits: A top. Tommaso Giarrizzo; Panel A lower left, panel A lower right, and panel C. José Amorim Reis-Filho; Panel B left, Srikanth Mannepuri.

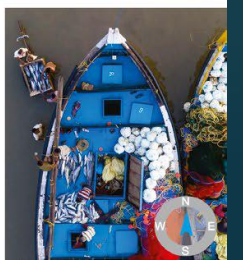
Study planning

There are data gaps.
Can we fill them?

- Examples of technological helpers







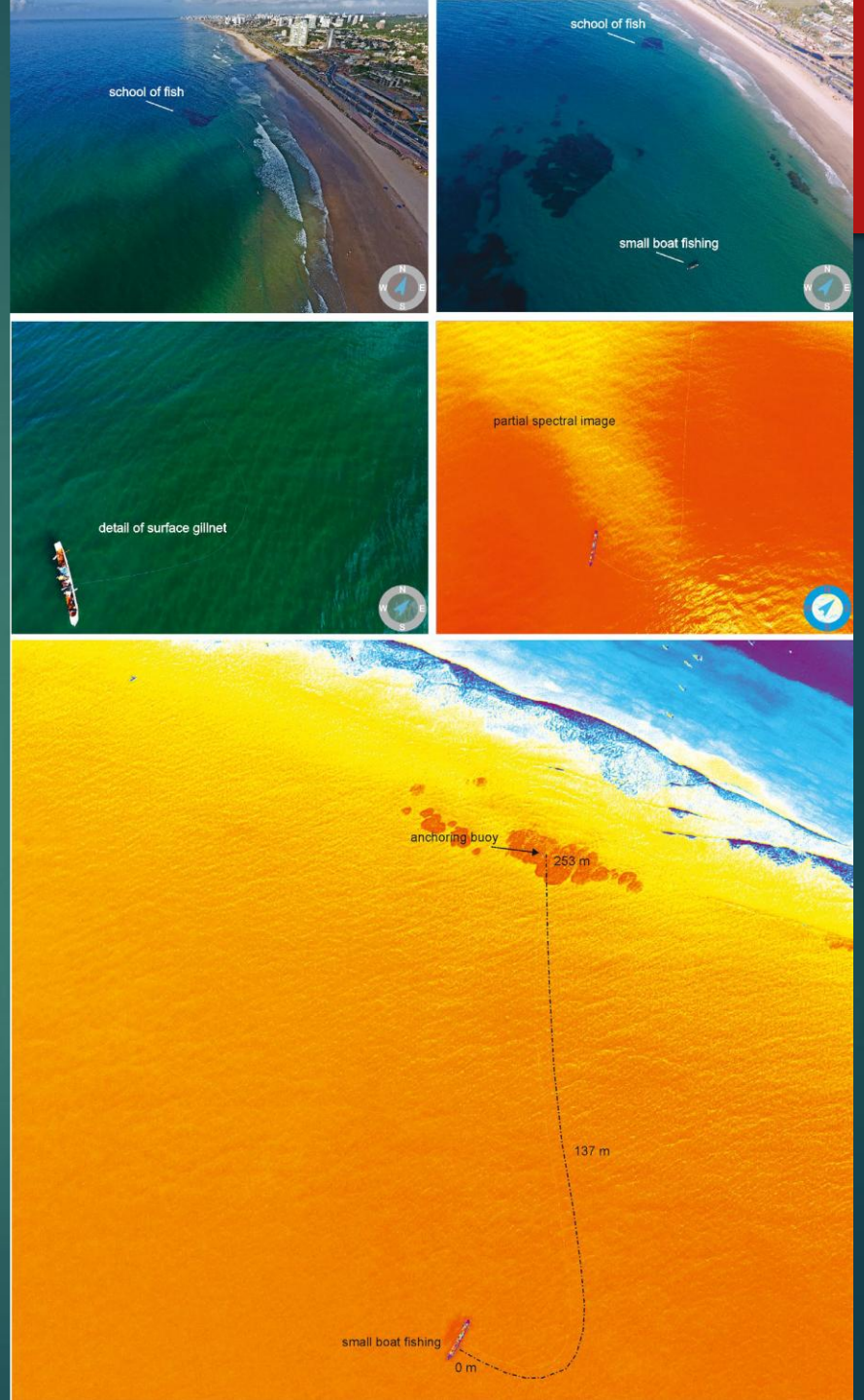
Reis-Filho and Giarrizo 2022

Figure 4. Fisheries yields exposed on a beach for sale and just after fishing operation have been performed. (**A**, **B**) A huge landing of Striped Marlin *Kajikia audax* and few individuals of Indo-Pacific Blue Marlin *Makaira mazara*; (**C**–**E**) rays, tuna, Pompano Dolphinfish *Coryphaena equiselis,* and sharks handled by fishers to sell and consume; (**F**) landing of tuna fish from artisanal fishing operation. Images credits: Srikanth Mannepuri.

Study planning

There are data gaps. Can we fill them?

- Examples of technological helpers



Reis-Filho and Giarrizo 2022

Figure 6. Unmanned aircraft system-derived data products at a 0.040 km2 (10-acre) shoreline including: (A) Identification of fish shoal; (B) identification of fish shoal in relation the small-fishing boat; (C) detail of position of boat and use of fishing gear (i.e., gillnet); (D) digital surface model with near-infrared hyperspatial imagery; and

Study planning

There are data gaps.
Can we fill them?

- Examples of technological helpers

Li *et.al.* 2021

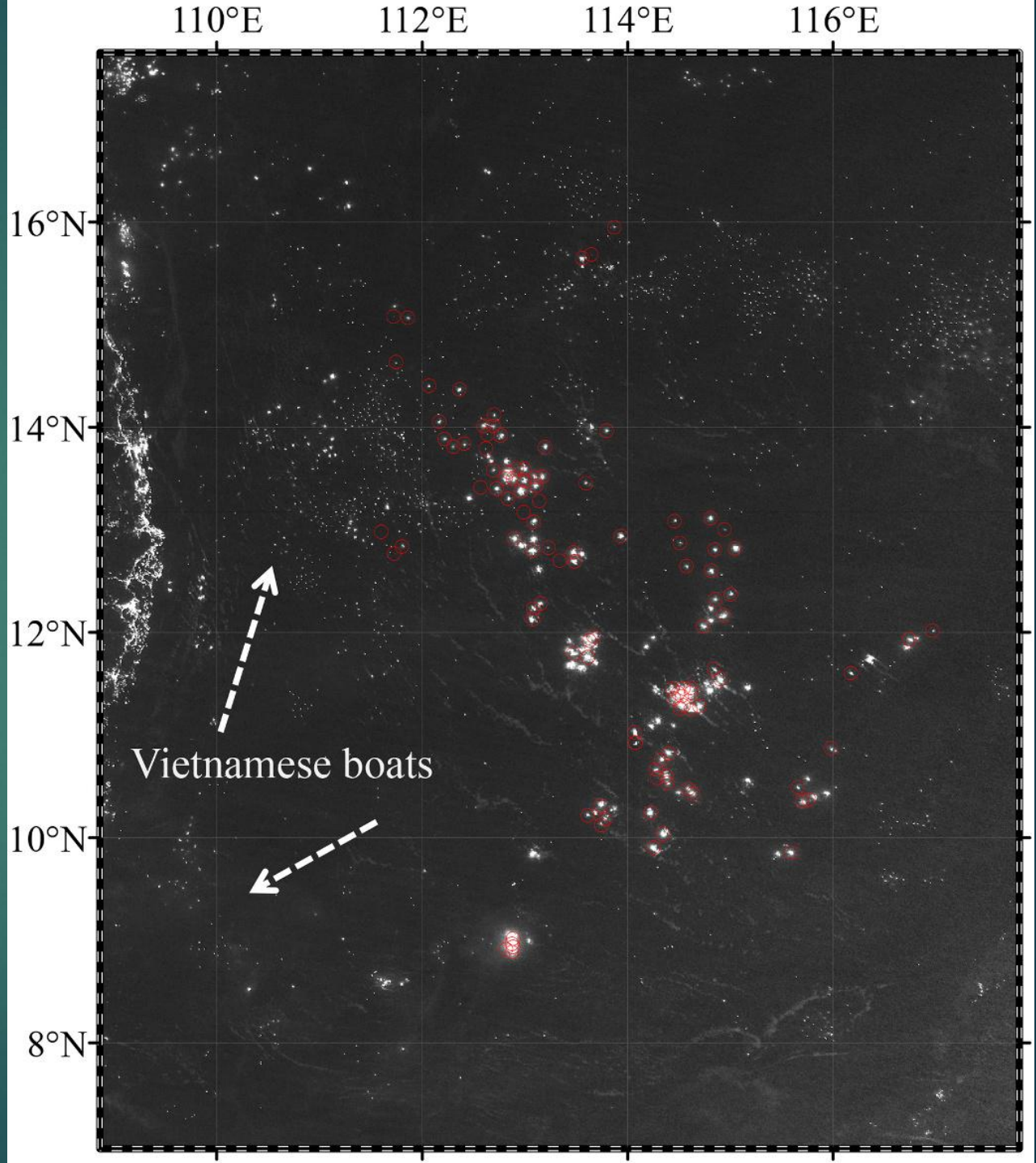


Figure 6. Day Night Band (DNB) image from 1716 UTC on April 13, 2018. Red marks are VMS-reported fishing positions of the large-sized, light-falling-net vessels. (For interpretation of the references to colour in this figure legend, the reader is referred to the

Study planning

There are data gaps.
Can we fill them?

- Examples of technological helpers

Oozeki *et.al.* 2018

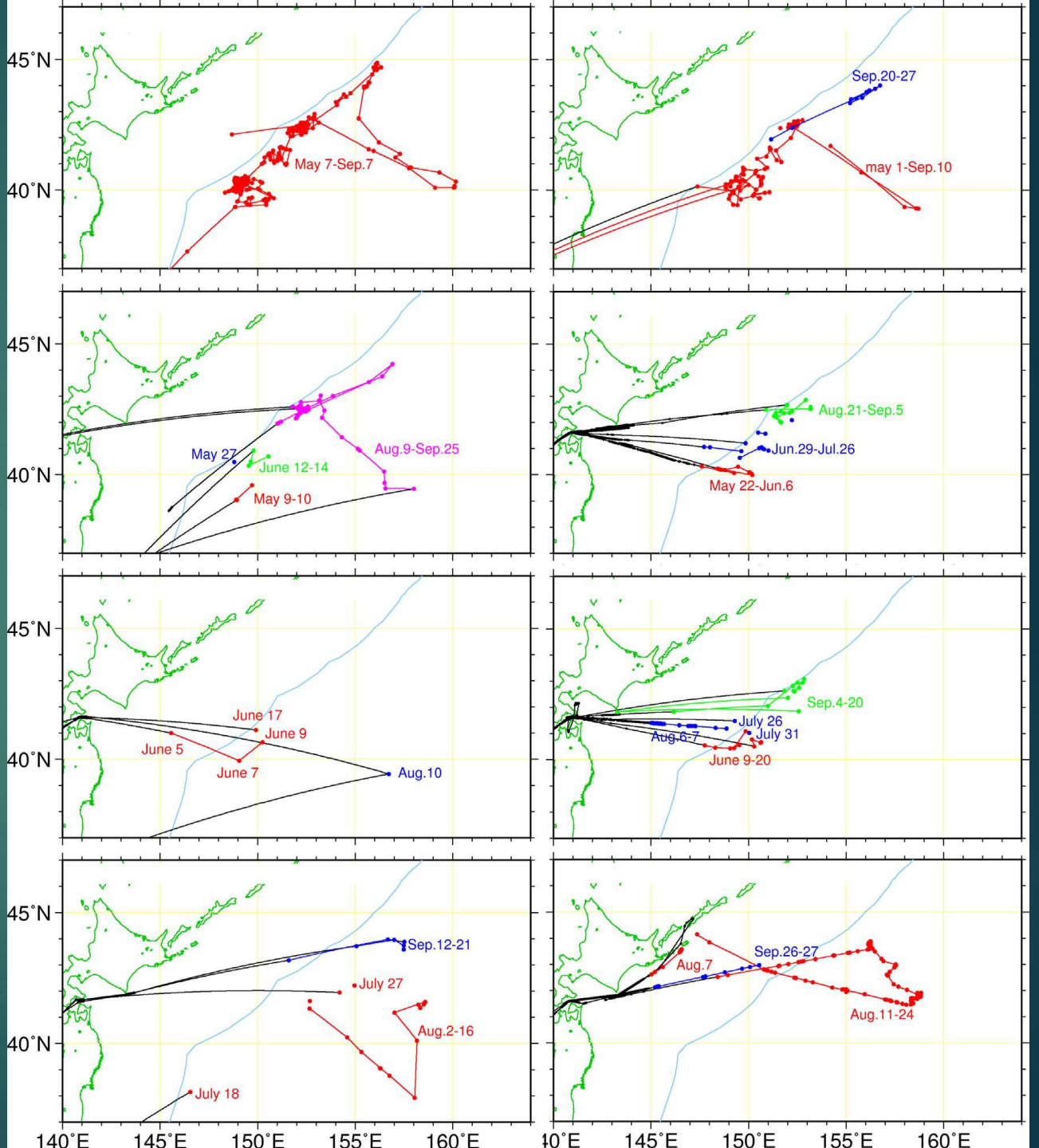
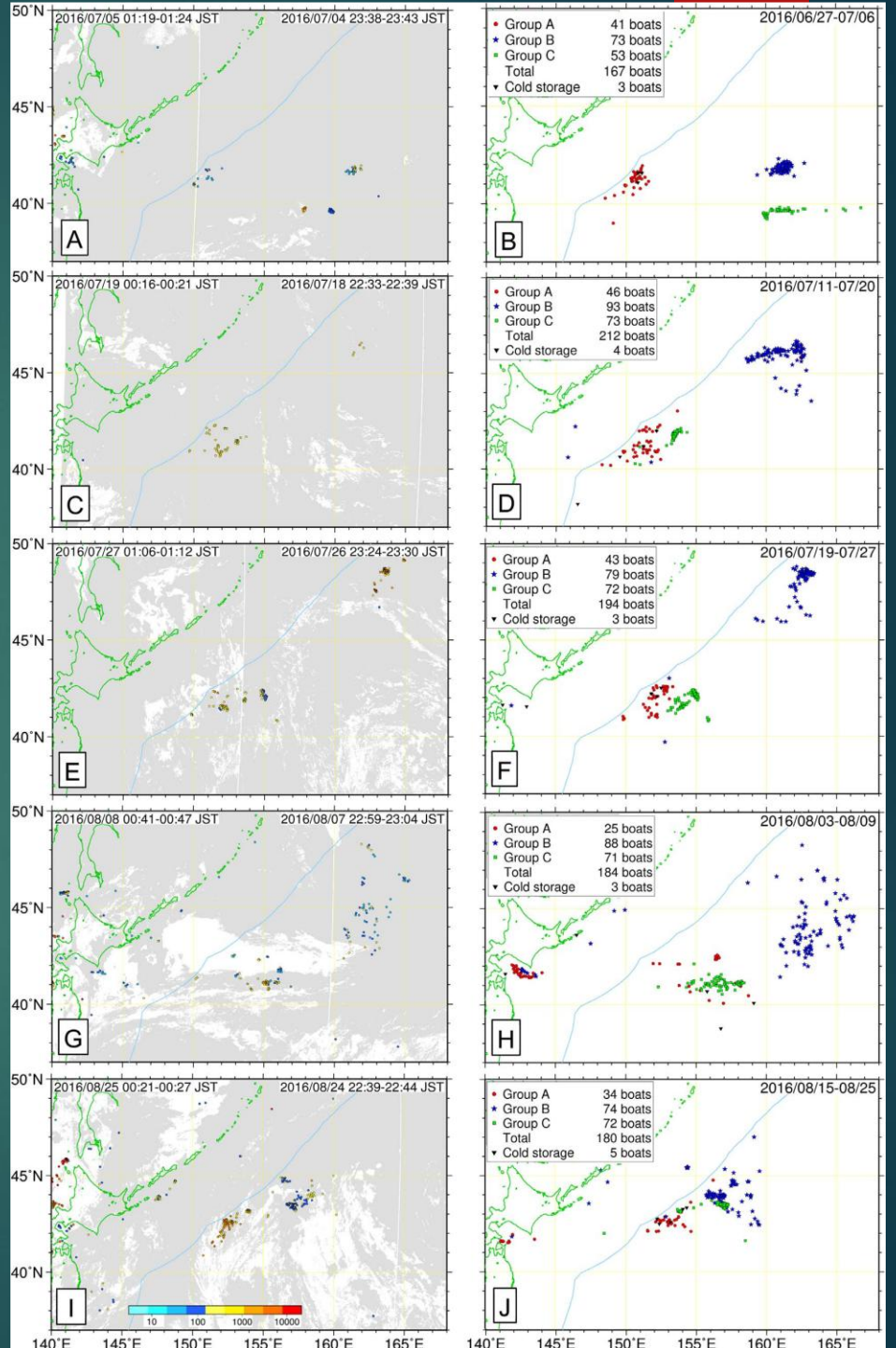


Fig. 5. Navigation tracks of eight Chinese refrigeration factory ships obtained from AIS information during May and mid-September. The colors indicate the ship tracks of different cruises and the blue line indicates the

Study planning

There are data gaps.
Can we fill them?

- Examples of technological helpers



Oozeki *et.al.* 2018

Fig. 4. Temporal changes in light point distribution from VIIRS DNB data (left panels) compared with those of the locations of fishing vessels estimated from AIS information on the corresponding date (right panels) during the summer season in 2016 (A & B: July 5th; C & D: July 19th; E & F: July 27th; G & H: August 8th; I & J: August 25th). These panels correspond to the data shown in Table 1. The color chart indicates the relative values of radiance in ×10−10 W cm−2 sr−1 in the left panels. (For interpretation of the references to color in

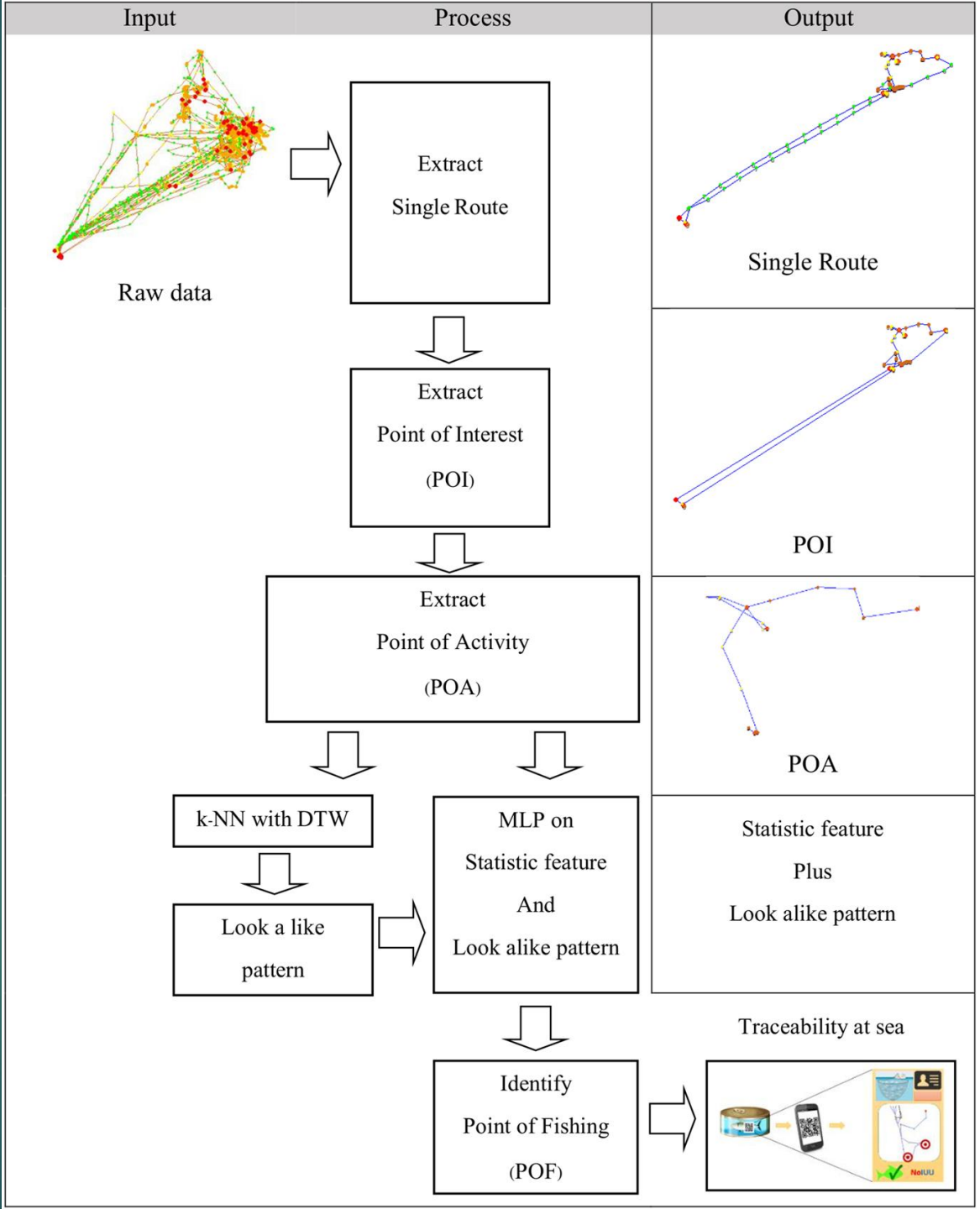
Study planning

There are data gaps.
Can we fill them?

- Examples of technological helpers

Fishing Vessels Behavior Identification for Combating IUU Fishing: Enable Traceability at Seas

Chauysi and Kiattisin 2020



Study planning

There are data gaps. Can we fill them?

- Examples of technological helpers

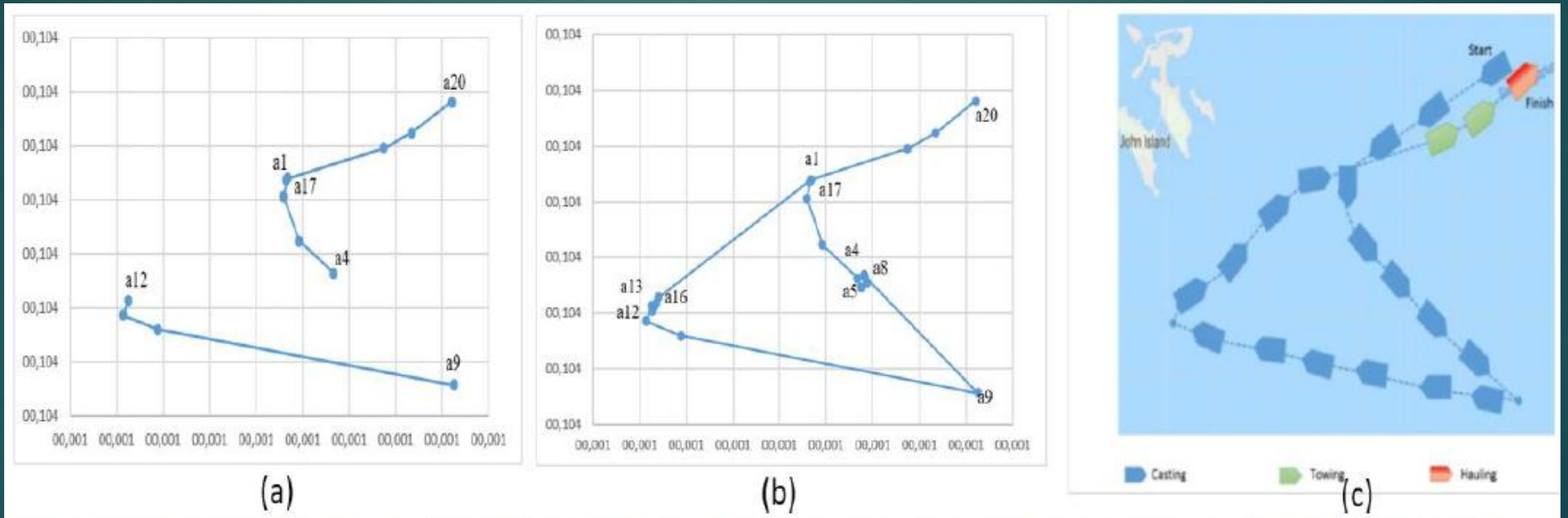


Figure 5. (a) Spot data on ship trajectory when there is missing AIS data on vessel movements from points a4 to a9 and a12 - a1 (position in the Singapore Strait), (b) Ship trajectory results are predictors for ranges a4 - a9, (c) Fishing vessel in real trajectory according to AIS data.

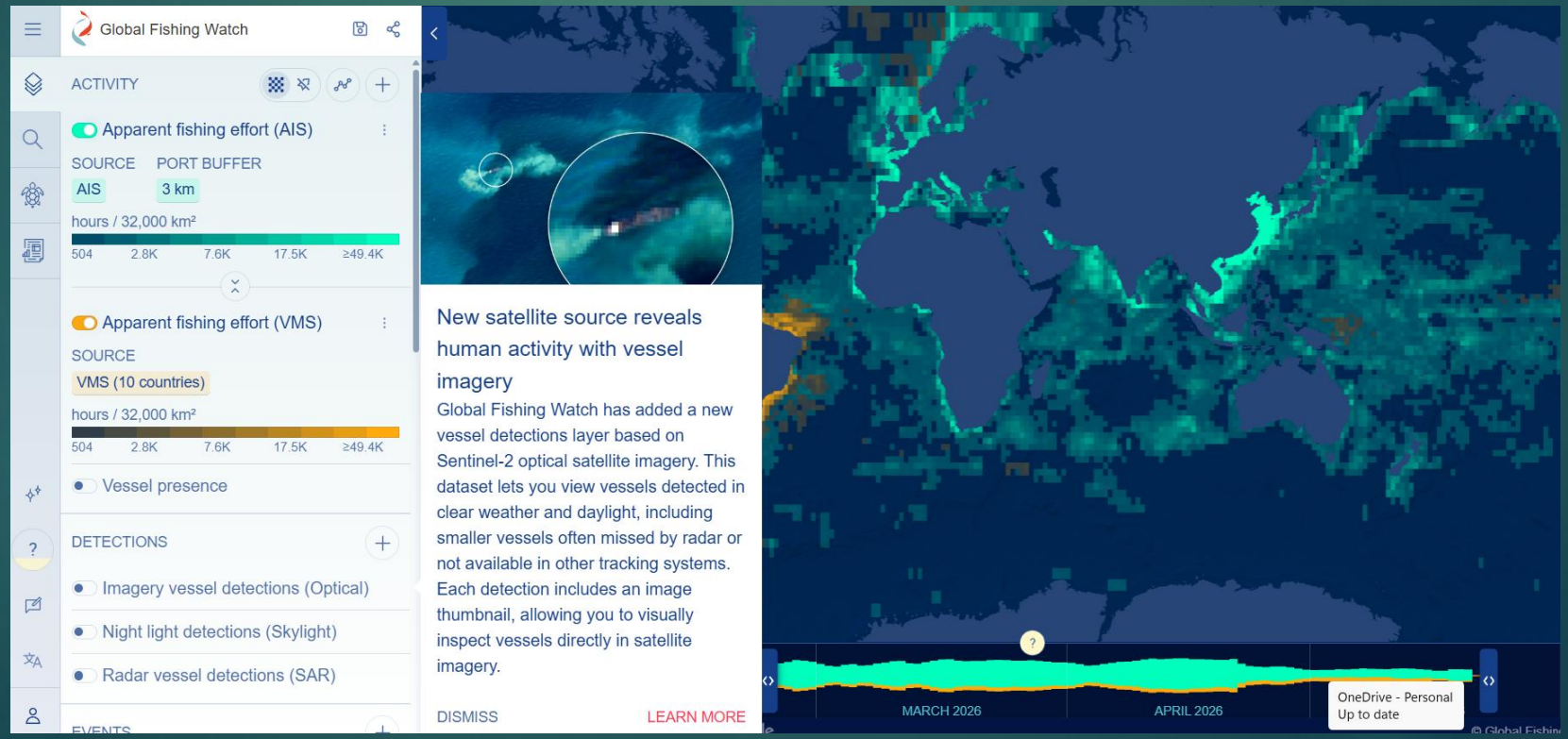
Masroeri *et al*. 2021

Study planning

There are data gaps. Can we fill them?

- Examples of technological helpers

https://globalfishingwatch.org/map

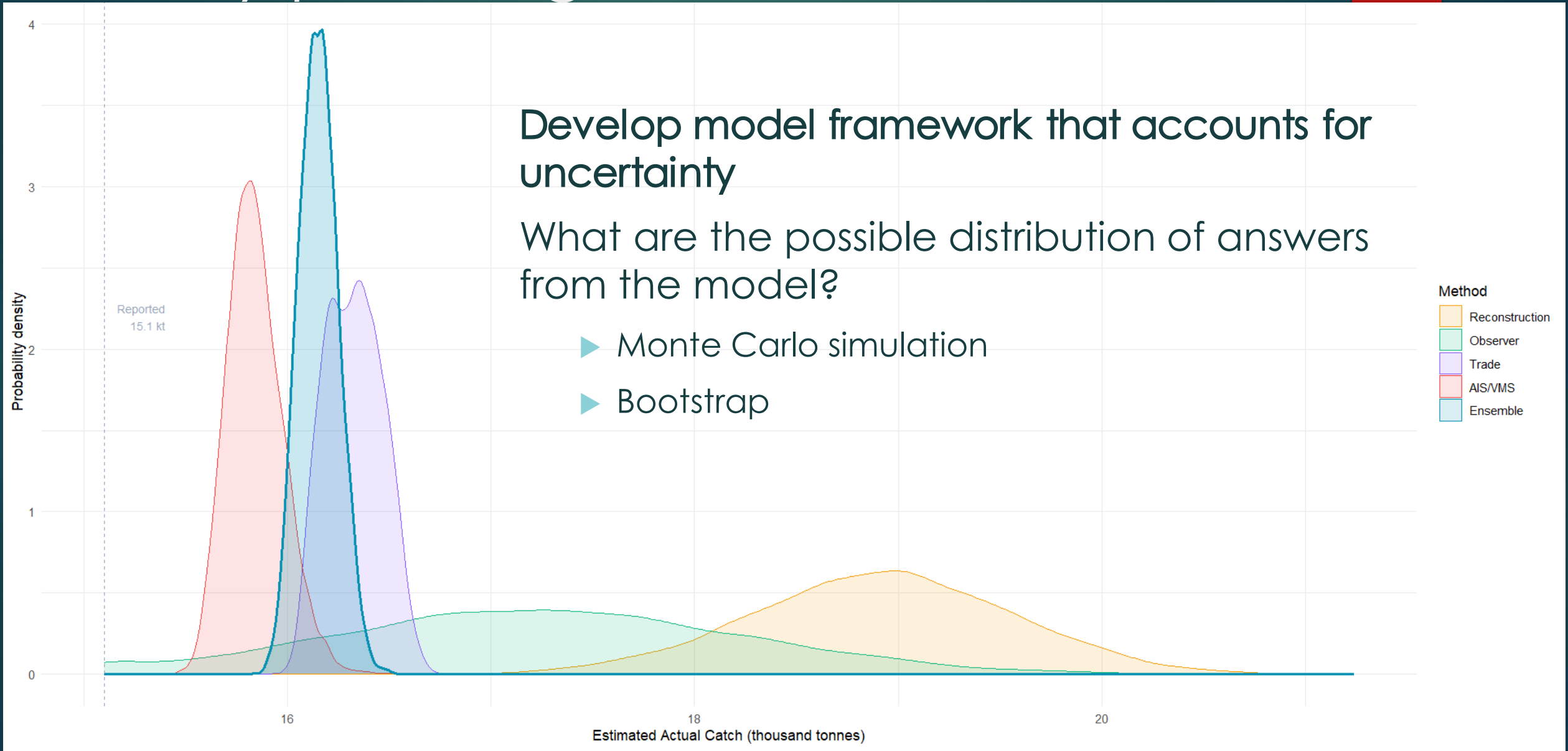


Study planning

There are data gaps. Can we fill them?

- State the uncertainty, regardless of the data robustness
  - Estimating middle values: Always show e.g. standard error, interquartile, range
  - Model predictions: Always show confident intervals
  - Don't be confidently wrong

Study planning

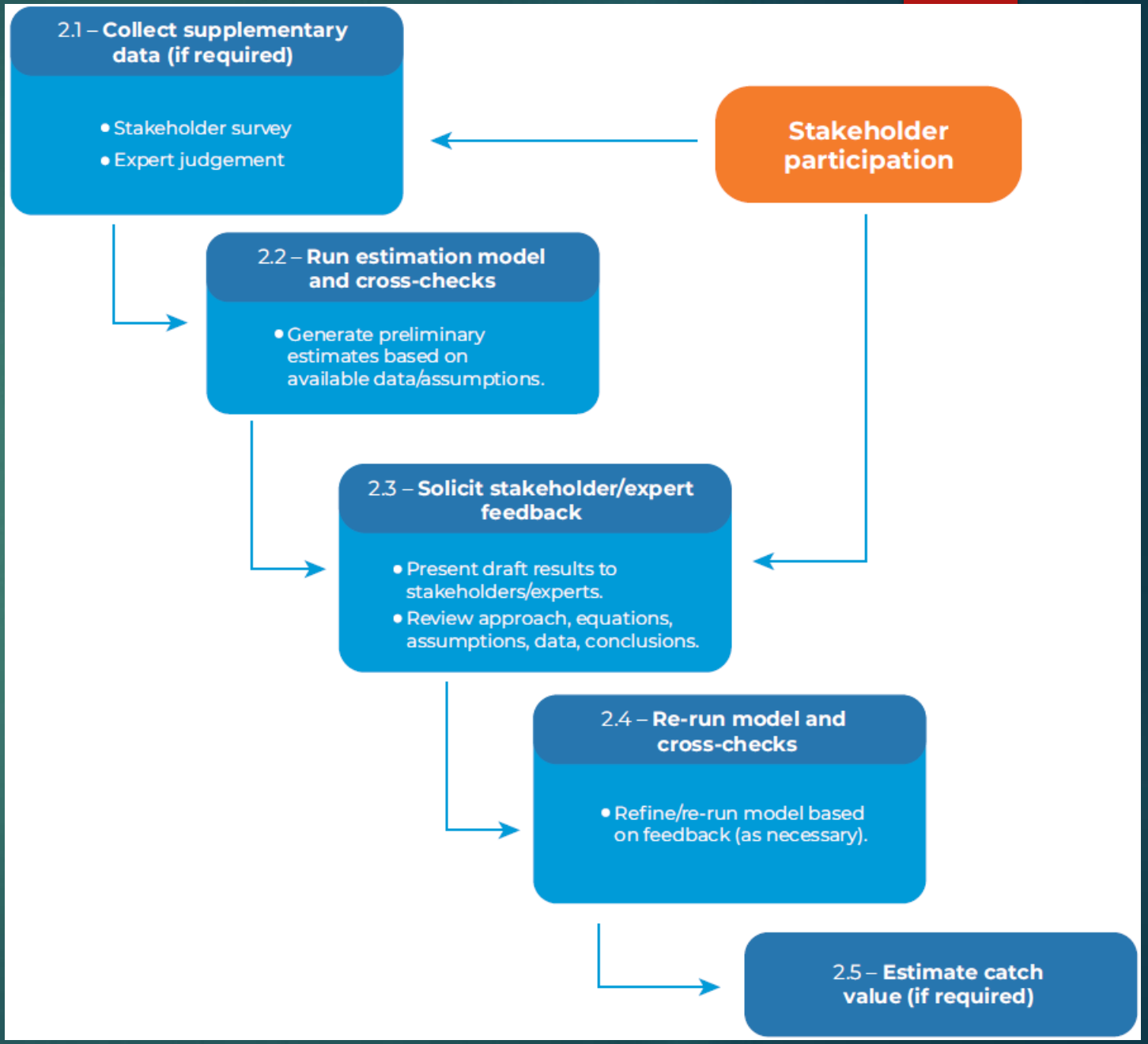


Develop model framework that accounts for uncertainty

What are the possible distribution of answers from the model?

- Monte Carlo simulation
- Bootstrap

Study execution



FAO 2023

Examples

nature COMMUNICATIONS

ARTICLE

Received 27 Feb 2015 | Accepted 19 Nov 2015 | Published 19 Jan 2016

DOI: 10.1038/ncomms10244 OPEN

Catch reconstructions reveal that global marine fisheries catches are higher than reported and declining

Daniel Pauly[1] & Dirk Zeller[1]

Examples

Pauly and Zeller 2016

- Objective
  - To know the magnitude of *unreported* catch from the overlooked sources
- Scope
  - Global (very ambitious)
  - Artisanal *and* industry fishing
  - Unreported commercial, subsistence, recreational and discard

Example

Pauly and Zeller 2016

- Methods
  - (1) Identification, sourcing and comparison of baseline catch times series
  - (2) Identification of sectors (for example, subsistence, recreational), time periods, species, gears and so on, not covered by (1), that is, missing data components
  - (3) Sourcing of alternative information sources on missing sectors identified in (2), via literature searches (peer-reviewed and grey) and consultations with local experts

Example

Pauly and Zeller 2016

- Methods
  - (4) Development of data 'anchor points' in time for each missing data item, and expansion of anchor point data to country-wide catch estimates
  - (5) Interpolation for time periods between data anchor points, either linearly or assumption based for commercial fisheries, and generally via per capita (or per fisher) catch rates for non-commercial sectors

Example

Pauly and Zeller 2016

- Methods
  - (6) Estimation of total catch times series. A reconstruction is completed when the estimated catch time series derived through steps 2–5 are combined and harmonized with the reported catch of step 1
  - (7) Quantifying the uncertainty associated with each reconstruction

Example

Pauly and Zeller 2016

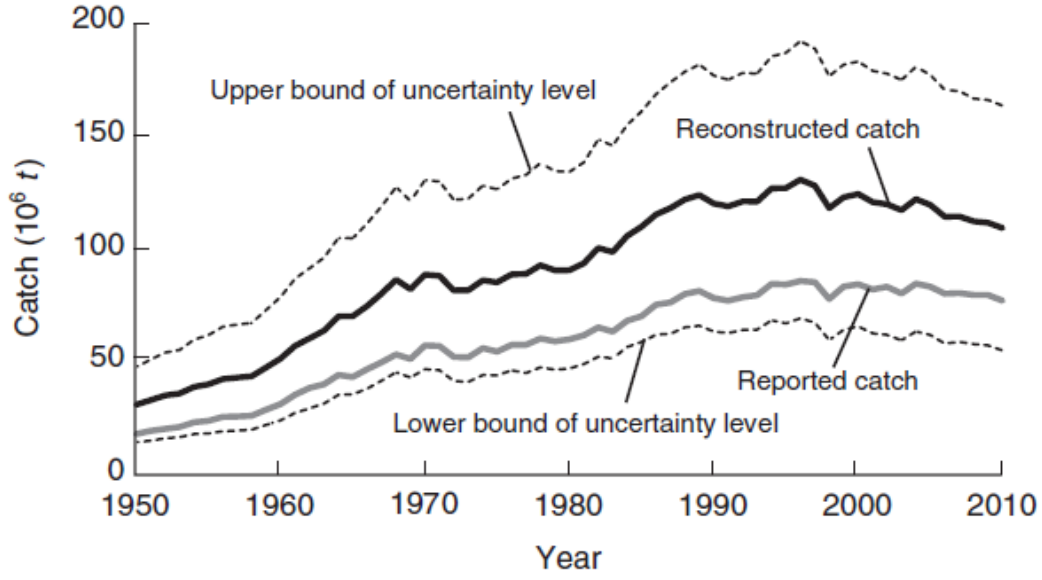


Figure 1 | Trajectories of reported and reconstructed marine fisheries catches 1950–2010. Contrast between the world's marine fisheries catches, assembled by FAO from voluntary submissions of its member countries ('reported') and that of the catch 'reconstructed' to include all fisheries known to exist, in all countries and in the High Sea ('reconstructed' = 'reported' + estimates of 'unreported'). The mean weighted percentage uncertainty of the reconstructed total catches (over all countries and fisheries sectors) based on the quality scores attributed to each sector in each country and territory (dashed line) is also shown.

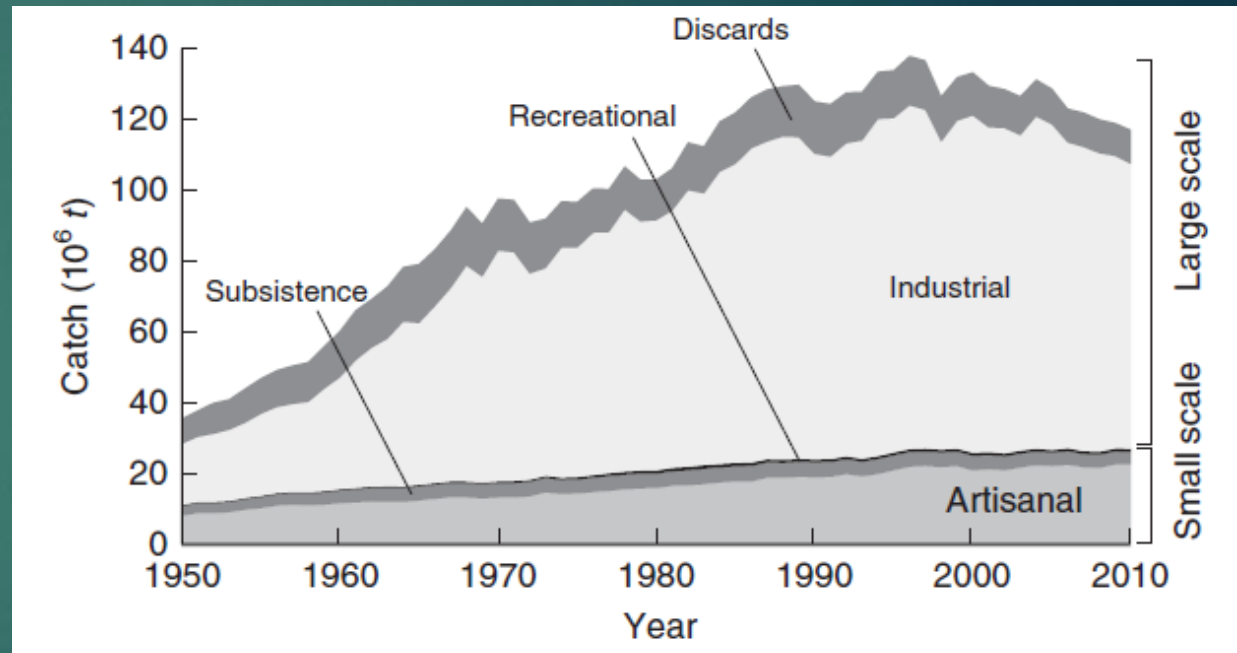


Figure 4 | Reconstructed global catch by fisheries sectors. Reconstructed catches for all countries in the world, plus High Seas, by large-scale (industrial) and small-scale sectors (artisanal, subsistence, recreational), with discards (overwhelmingly from industrial fisheries) presented separately.