

LETTER • OPEN ACCESS

Fishery observers address arctic fishery discards

To cite this article: Hunter T Snyder and James T Erbaugh 2020 *Environ. Res. Lett.* **15** 0940c4

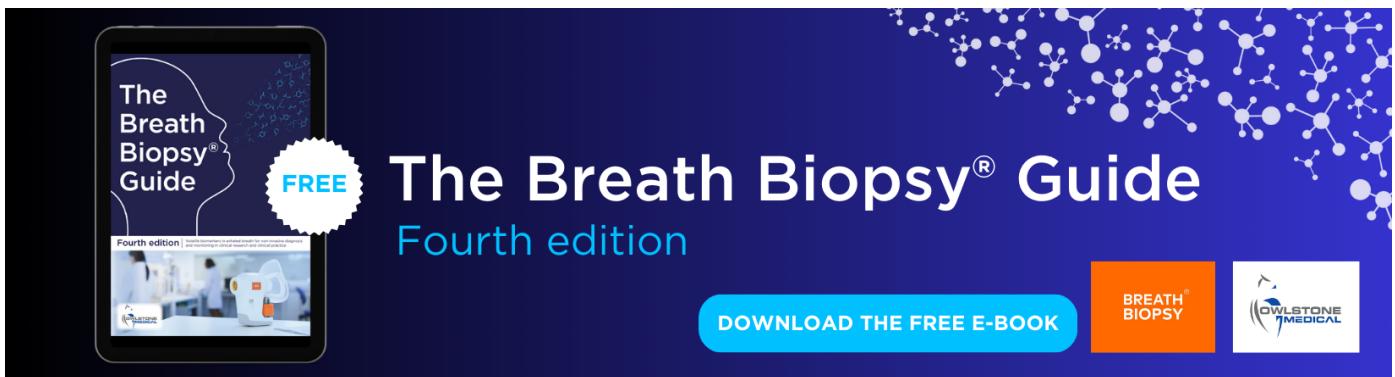
View the [article online](#) for updates and enhancements.

You may also like

- [Small innovation for sustainable use of fisheries resources](#)
Tatsuro Matsuoka

- [A novel method to reduce false alarms in ECG diagnostic systems: capture and quantification of noisy signals](#)
Wenliang Zhu, Lishen Qiu, Wenqiang Cai et al.

- [Bycatch from seagrass fisheries: implication for conservation](#)
R Ambo-Rappe, Y A La Nafie, A A Marimba et al.



The Breath Biopsy® Guide
Fourth edition

FREE

BREATH BIOPSY

OWLSTONE MEDICAL

Environmental Research Letters

**OPEN ACCESS****LETTER**

Fishery observers address arctic fishery discards

Hunter T Snyder^{1,3}  and James T Erbaugh² **RECEIVED**
21 April 2020**REVISED**
17 June 2020**ACCEPTED FOR PUBLICATION**
13 July 2020**PUBLISHED**
11 September 2020

Original content from this work may be used under the terms of the Creative Commons Attribution 4.0 licence.

Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.

¹ Graduate Program in Ecology, Evolution, Environment, and Society, Dartmouth College, Hanover, NH 03755, United States of America² Environmental Studies Program, Dartmouth College, Hanover, NH 03755, United States of America³ Author to whom any correspondence should be addressed.E-mail: hunter.gr@dartmouth.edu**Keywords:** matching, fisheries, discards, compliance, enforcement, fishery observersSupplementary material for this article is available [online](#)**Abstract**

Fishery observers are prevalent actors in the global effort to reduce discards in fisheries, but there remains considerable uncertainty about how effective they are. We analyzed high-resolution logbook records of individual hauls ($n = 127\,415$) across five-and-a-half-years (2012–2018) for all of Greenland's large-scale fisheries to determine if onboard fishery observers influence the mandatory reporting of discards. To do so, we used exact matching to compare reported discards for observed and unobserved hauls (each time a catch is recorded), thus controlling for systematic differences between monitored and unmonitored practices. After adjusting for variables that represent species caught, gear, vessel, owner, year, license, and location, we found that skippers systematically underreport discards when no observers are on board. Systematic underreporting was most pronounced in less valuable fisheries, in contrast to theoretical arguments in previous studies. The differences between reported discards from observed and unobserved fishing leads us to assume that onboard observers encourage more faithful logbook records. Thus, onboard observers play a vital role in improving information on the environmental impact of fishing and in turn, make a key contribution to sustainable fisheries management.

1. Introduction

The accurate monitoring of marine capture fisheries represents a pressing and global conservation challenge. Fish and shellfish are essential food sources in marine and freshwater food webs (Power 1990, Pauly 1998), they provide nourishment for more than 3.2 billion people, and they are the most widely traded food commodity (Blanchard *et al* 2017, FAO 2018). However, nearly a third of marine capture fisheries are overfished (FAO 2018). In addition, offshore and high seas fisheries are among the most costly and challenging to monitor, control, and surveil (Day 1997, Flewwelling 2003). Improving our understanding of fishing behavior is key to identifying overharvesting, ensuring sustainable fisheries, and maximizing the benefits that humans derive from living marine resources.

Despite its importance, monitoring fishing activities remains challenging. Satellite or AIS techniques rapidly verify and track vessel positions, but they remain ineffective for monitoring on-board fishing

activity (Mills *et al* 2007, Lee *et al* 2010). The use of sensors and video to monitor fishing activity without a human observer on board (electronic monitoring), is growing in popularity among fishery enforcers, but it is unpopular among some skippers, is costly and computationally-intensive, and often requires human resources for post-hoc review of fishing activity (Ames 2005, van Helmond *et al* 2015, Needle *et al* Gilman *et al* 2015, Plet-Hansen *et al* 2017, 2019). Sampling vessels at port can monitor landed catches, but it does not monitor catch discarded at sea (Gilman *et al* 2019). Due to the difficulty with which onboard activities are monitored, few studies address the costs and benefits of monitoring marine capture fisheries (Sutinen and Andersen 1985, Kuperan and Sutinen 1998, Sutinen and Kuperan 1999). For these reasons, discards remain particularly difficult to manage.

Discards are a classic common pool resource problem, and they can generate negative ecosystem, social, and economic impacts. Fishers are incentivized to discard unwanted catch in order to increase the

value of their landings and comply with their license to target a specific species. It is estimated that about 10.8% of all fish are discarded globally, on average (Pérez Roda *et al* 2019), with a majority of discards occurring in trawl fisheries. Discards cost individual fishing operations little, but their increase results in negative outcomes for other fishers due to declines in fish stock and community. Increased mortality of living marine organisms can alter marine food webs (Pauly 1998, Essington *et al* 2006), and selective mortality reduces the reproductive value of a targeted stock (Myers *et al* 1995, Keith and Hutchings 2012). Socially, discards are foregone animal proteins and therefore represent wastage, and in some cases, can threaten adequate animal protein intake among coastal populations (FAO 1996). Discards are also economically wasteful and represent poor maximization of fishery resource rents (Alverson *et al* 1994). Conservationists, industry, and policymakers alike agree that discards must be minimized to meet sustainable development goals and to maximize the blue economy (Sigurðardóttir *et al* 2015, Asche *et al* 2018).

Reducing discards is costly. They occur because of (1) suboptimal decision-making when choosing fishing areas, (2) poor on-board harvesting and processing techniques, (3) a lack of investment in more selective fishing gear, and (4) because bycatch are not required to be landed (Kronbak *et al* 2009, Catchpole and Gray 2010, Condie *et al* 2013). In other cases, management instruments designed to improve economic efficiency and secure conservation outcomes can have the unintended consequence of creating discards. In fisheries that employ quotas, such as a total allowable catch, highgrading—the process of discarding less valuable fish to make room for more valuable ones (Anderson 1994, Vestergaard 1996)—can occur if not deterred by policy design and regulation.

Working together, fisheries engineers, industry, and academia have made technological advances to pilot, develop, and deliver more selective fishing gear, real-time monitoring of fishing, and other data-enhancement techniques, to reduce fishery discards (Catchpole and Gray 2010). Government are also addressing discards through a range of efforts, including the auditing of logbook data from fishing vessels, at-sea boarding of fishing vessels by coast guard authorities, and through at-sea fishery observer programs (Condie *et al* 2013, Sardà *et al* 2015, Sigurðardóttir *et al* 2015). Fishery observers are deployed for monitoring and control purposes as well as for scientific assessment of fish stocks (Gilman *et al* 2019). Studies that evaluate the performance of fishery observers as an enforcement tool are descriptive but not analytical, showing that fishery observers prosecute for discarding and reporting violations (Porter 2010), and that observers and skippers may underestimate discards (Catch, Effort and Discard Estimates in Real time 2008). These studies, however, do not clarify the extent to which—if any—fisheries observers

influence the reporting and production of discards (Queirolo 1995, Catch, Effort and Discard Estimates in Real Time 2008, Feekings *et al* 2012). However, one Arctic fishing nation has collected comprehensive data on observed and unobserved commercial fishing, which facilitates the estimation of how observers influence discard reporting.

Greenland is a semi-autonomous Arctic territory, and 99.4% of its exports are derived from fish and shellfish products (Kâjangmat 2020). Greenland legislative provisions ban—with few exceptions—skippers from discarding fish and shellfish (Government of Greenland 2011). Commercial fishing consists of targeted catch, bycatch, and discards (figure 1). Targeted catch is the catch a skipper desires, is licensed, and has a quota to fish. Bycatch are fish caught accidentally, such as Atlantic redfish (*Sebastes marinus*) or Greenland shark (*Somniosus microcephalus*) caught in trawls while skippers target Northern prawn (*Pandalus borealis*). Some bycatch have market value (e.g. Atlantic redfish) and are kept and landed, whereas other bycatch (e.g. Greenland shark, or corals, starfish, and sponges) do not. Discards constitute primarily unmarketable catch damaged during production (e.g. fishes bruised from a net, stepped upon, or dropped from a conveyor belt onto a factory floor). Few exceptions allow for the discarding of bycatch (Government of Greenland 2011).

Skippers and fishery observers must document all targeted catch, bycatch, and discards. Bycatch and targeted catch must be stowed/landed, and they cannot be discarded, whereas discards are disposed of at sea.⁴ Hauls consisting of more than 10% bycatch require skippers to move to another position. Skippers that contravene these provisions are subject to fine, confiscation of gear and the value of their entire catch, or both. The Government of Greenland has a history of prosecuting violators (Nedergaard 2018). This legislation and regulation exists to minimize discards because discards represent a waste of living marine resources, the benefits of which cannot be captured and returned to the Greenlandic citizens as taxable revenue on exports. A description of relevant legislation related to Greenlandic fisheries management is provided in supplementary materials (SI table 1 (available online at stacks.iop.org/ERL/15/0940c4/mmedia)). Within this regulatory framework, fisheries observers are deployed to keep track of and minimize discarding.

Using logbooks that record each time an offshore or nearshore vessel in Greenland hauled in fishing gear, this research examined the impact of onboard observers on discard reporting. Assuming fishers do not want to overreport discards, we tested three hypotheses. First, we hypothesized that if

⁴In nearly all cases, discards are disposed of at sea. However, new vessels have the capability and authorization to render discards into fishmeal and stow them in the hold, rather than wasting them.

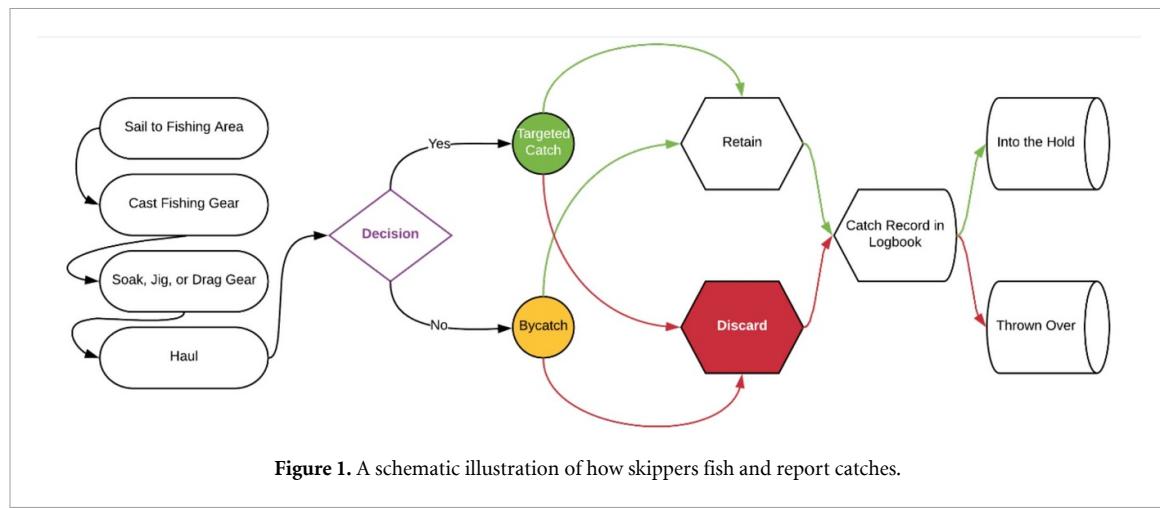


Figure 1. A schematic illustration of how skippers fish and report catches.

observation demonstrates a positive effect on reported discards, then fishers are likely to be systematically underreporting their discard weights when unobserved (Zwanenberg and Smith 1983, Porter 2010). Second and alternatively, we hypothesized that if observation demonstrates a negative reporting effect, onboard observers likely deter discarding behavior when onboard (Becker and Landes 1974, Furlong 1991). And third, we posit a null hypothesis that a nonsignificant relationship between observation and discard reporting would demonstrate that onboard monitoring has no impact on reporting behavior.

2. Methods

We analyzed all nationwide offshore and nearshore fishing in Greenland where fishery observers are deployed. Small-scale fishers, defined as fishers using vessels less than 6-m length, are exempt from onboard monitoring in Greenland. We conducted nationwide and fishery-specific analyses, focusing on the four largest (in terms of live weight of landings) and economically significant (in export value) Greenlandic fisheries: Northern prawn (*Pandalus borealis*), Atlantic mackerel (*Scomber scombrus*), Greenland halibut (*Reinhardtius hippoglossoides*), and Atlantic cod (*Gadus morhua*). Figure 1 depicts how commercial fishing takes place and how skippers and fishery observers document catches, which in turn constitute logbook data. We were able to identify reported discard discrepancies because logbooks of a given fishing trip record targeted catch, bycatch, and discards each time fish are caught. All catches, including discards, are weighed to the kilogram with scales and baskets in accordance with current fisheries legislation (Government of Greenland 2010).

The use of high-resolution, haul-level logbook data is uncommon in the study of how conservation efforts influence fishing behavior. Haul-level analyses are often preferred to trip-level analyses, due to the higher resolution information they provide (Catch, Effort and Discard Estimates in Real Time 2008).

We used logbook data on individual hauls to adjust estimates of observer impact on discard reporting of live weights of fish or shellfish (kg) based on variables that confound this causal relationship. Specifically, we adjusted our estimates based on the gear type, species caught, vessel, skipper, license type, and location recorded for each haul (table 1).

We used anonymized logbook records from January 1, 2012 to May 21, 2018. We chose 2012 as a temporal baseline because data quality conventions introduced in that year increased our confidence in the integrity and consistency of logbooks from 2012 and onward. The supplemental information contains further details on the rigor and usefulness of logbook data. Our data is comprised of 129 741 unique, individual hauls during 2724 fishing trips conducted by 213 fishing vessels, representing every time that fishers hauled in their gear while catching fish in Greenlandic waters. The Greenlandic fishing fleet is largely considered to be aged, but a handful of state-of-the-art vessels employ highly selective gear and fish detection systems, and effectively haul and process catches to minimize discards (Geraae 2019, KNR 2020). Vessels often have licenses and quotas to fish multiple species (e.g. targeting prawns but catching redfish as bycatch), but rarely target more than one species at a time.

Several studies of observer programs have cited treatment bias as a major barrier to studying their effectiveness (Catch, Effort and Discard Estimates in Real Time 2008, Porter 2010). To control for treatment bias, we conducted exact matching (King 2010), which pre-processes a dataset to include treated and non-treated units that are exactly similar across categorical variables. Matching methods are becoming common in the environmental sciences (Agrawal 2014) because they improve the estimation of causal effects of an environmental intervention by limiting model estimates to only include treated units and the most similar control units (Baylis *et al* 2016, Ferraro *et al* 2019). As is regularly the case in observational studies of environmental interventions in fisheries, a

Table 1. Table of all variables tested, which are known to drive discards in fisheries.

Variable Name	Name	Description
SPECIES_ENGLISH	Species English	Species name in English (e.g. cod, prawn)
GEAR_CAT	Gear Category	The types of gear used (e.g. trawl, longline, pot, seine)
VESSEL_NATION	Vessel Nation	Foreign or Greenlandic vessel
QUOTA_NATION	Quota Nation	Foreign or Greenlandic holder of a quota to fish in Greenlandic waters
AREA_DESC_1UK	Area Description English	NAFO designations of fishing areas (e.g. 1D, 1E, 1A)
YEAR	Year	The year of the fishing activity
LICENSE_OWNER_ID	License Owner ID	The number assigned to the person or firm that owns the fishing license
VESSEL_IDF:	Vessel ID	The number assigned to the vessel involved in fishing

relatively small portion of the overall population are exposed to a treatment, with most of the population left untreated (Rosenbaum and Rubin 1985). An appropriate example of this is a fishery observer, who can only be deployed on a small portion of the total fishing fleet for reasons of cost, convenience, and access. No matching studies have been conducted on the impacts of fishery observers on catch outcomes. This research leveraged the large number of haul observations within Greenlandic logbook data—an important prerequisite for effective matching research (King 2011, Agrawal 2014)—to rigorously estimate the effect of on-board monitoring.

To ensure the robustness of our findings, we matched observed hauls to unobserved hauls using three approaches that make explicit use of spatial information at the haul-level (King 2011). First, we matched all unobserved hauls to observed hauls using exact matching for all variables in table 1 (Match 1). Second, we matched the single most similar unobserved haul to each observed haul using Mahalanobis nearest neighbor matching on latitude and longitude as well as exact matching for all aforementioned variables (Match 2). Third, we matched the (up to) three most similar unobserved hauls to observed hauls using Mahalanobis nearest neighbor matching for the latitude and longitude of observed hauls (0.25 caliper) as well as exact matching for all aforementioned variables except the Northwest Atlantic Fisheries Organization (NAFO) fishing areas (Match 3). These three different approaches represent different methods for controlling the location in which a haul occurred. We adjust for time by matching hauls within a year, and we check the robustness of our results to matching within season and year.

After matching observed to unobserved hauls, we regressed reported discards onto treatment (observed or unobserved) to estimate the effect of observation on the hauls that were observed. We then use these models to estimate reported discards for all hauls, were they to have been observed. The difference between reported and estimated discards represents the observer effect. Assuming that (1) discards are faithfully reported when observers are onboard, and (2) our results do not suffer from omitted

variable bias, estimating an observer effect provides insight into fishery discards from hauls that were unobserved. We performed all matching and modeling in R (Ho *et al* 2007, 2011).

3. Results

We found that discards comprise a small and decreasing percentage of overall targeted catches, but observed hauls had higher reported discards than did unobserved hauls before adjustment. For all hauls between 2012 and 2018 with discarded or retained catch ($n = 129\,741$), discards composed 7.4% of individual haul weight. The increase in overall discard weight and the decrease in the proportion of discards by overall catch indicates annual increases in fishing volume and efficiency (figure 2).

After adjusting for confounding variables, onboard observation had a significant, positive impact on reported discards. Observed hauls vary widely across time, space, and fisheries which enables efficient statistical matching (table 2). Exact matching (Match 1) generated a dataset of 24 160 of observed and 39 053 unobserved hauls ($n = 63\,663$) that shared identical values for key variables associated with observation and discard reporting (figure 3). Across all fisheries, between 36.3 kg and 38.6 kg more discards are reported when compared to unobserved hauls, depending on the matching approach (SI table 3). All matches are visualized in the supplemental information (SI figure 1), and the observer effect is robust to seasonal variation (SI table 2 and SI table 3).

All estimates, regardless of matching method, report a significant and positive observer effect, with the greatest difference between reported discards in the cod fishery. Matches 1 to 3 and their associated models estimate the average observed discard per haul to be 6.5 kg to 8.8 kg lower than unmatched models. This suggests that matching adjusted for a small selection bias in the occurrence of onboard observation. Our data suggest that fishery observers have a positive and significant effect on reported discard weights per haul. We therefore reject both the alternative hypothesis that fishery observers deter skippers from creating discards, and the null hypothesis that

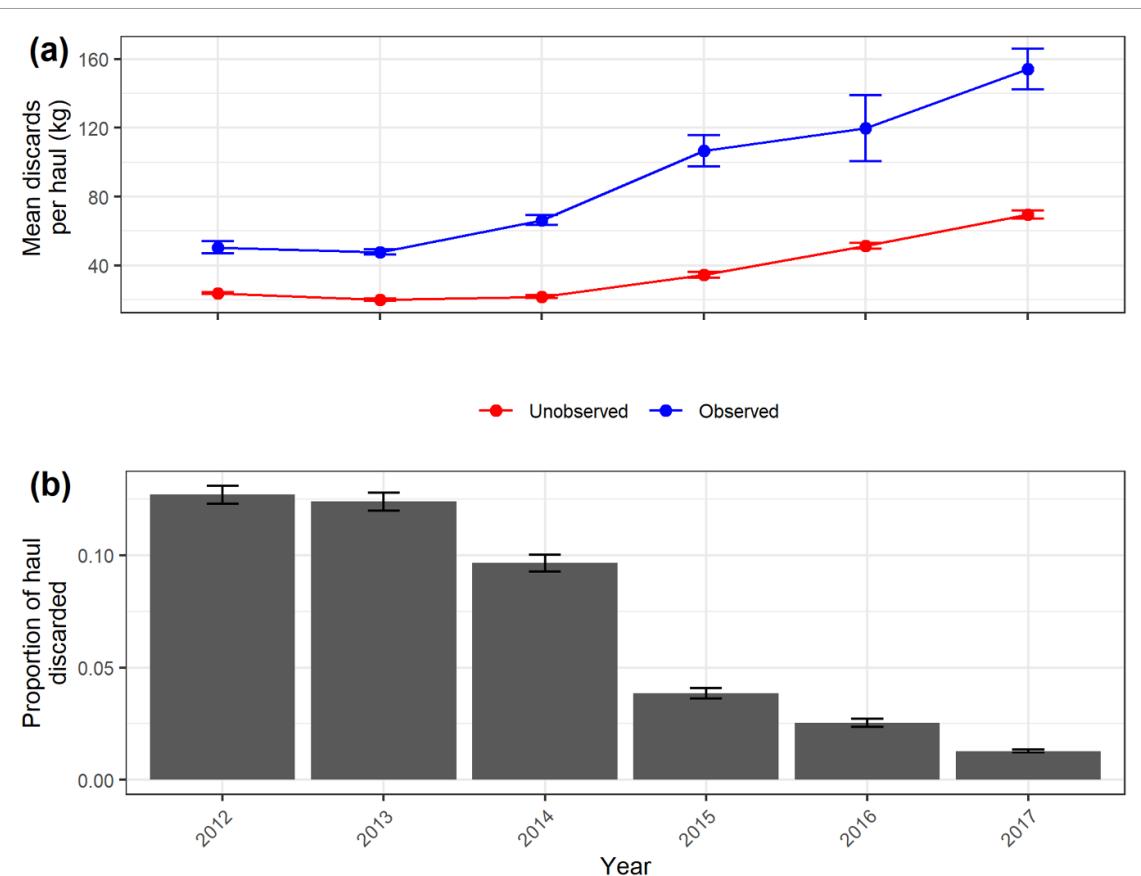


Figure 2. Panel A: Line chart of discard weight differences between observed and unobserved hauls. Panel B: Bar chart of yearly decreasing trends of the proportion of discards per haul, 2012–2017. Error bars represent 95% confidence intervals.

Table 2. Matching variables, sample sizes, and outcomes. Checkmarks indicate that a variable was matched across observed and unobserved hauls. All matching was exact except for Latitude and Longitude, which were matched via Mahalanobis matching.

Variable	Unmatched	Match 1	Match 2	Match 3
		Matched (Standardized Mean Difference)		
Majority species hauled	X	✓	✓	✓
Fishing gear	X	✓	✓	✓
Vessel nation	X	✓	✓	✓
Quota nation	X	✓	✓	✓
Area category	X	✓	✓	X
Year	X	✓	✓	✓
Vessel identification	X	✓	✓	✓
License owner	X	✓	✓	✓
Latitude	X (0.43)	X (-0.083)	✓ (0.01)	✓ (-0.0036)
Longitude	X (-0.40)	X (-0.16)	✓ (-0.016)	✓ (0.016)
<i>Fishery Category</i>				
All Species	129 864 (29 529: 100 335)	63 663 (24 160: 39 503)	39 448 (19 724: 19 724)	42 051 (25 848: 12 203)
Atlantic Cod	16 670 (1975: 14 695)	4491 (1184: 3307)	1813 (906: 907)	2830 (1630: 1200)
Greenland Halibut	22 061 (2656: 19 405)	2460 (1084: 1376)	1431 (702: 729)	2311 (1629: 682)
Mackerel	6693 (1840: 4853)	2211 (816: 1395)	1388 (685: 703)	1374 (816: 558)
Prawn	61 294 (19 802: 41 492)	41 130 (18 687: 29 443)	31 119 (15 539: 15 581)	31 344 (19 245: 12 099)

fishery observers have no systematic effect on discard reporting.

4. Discussion

Discards in fisheries are a threat to the conservation of living marine resources (FAO 1996), but

methods for quantifying the extent of discards and the effectiveness of discard mitigation efforts remain wanting (Catchpole *et al* 2014, Rochet *et al* 2014, Sigurðardóttir *et al* 2015). Discard estimates are useful for understanding how fishing fleets are improving their performance and reducing their resource waste; however, they say little about how much discarded

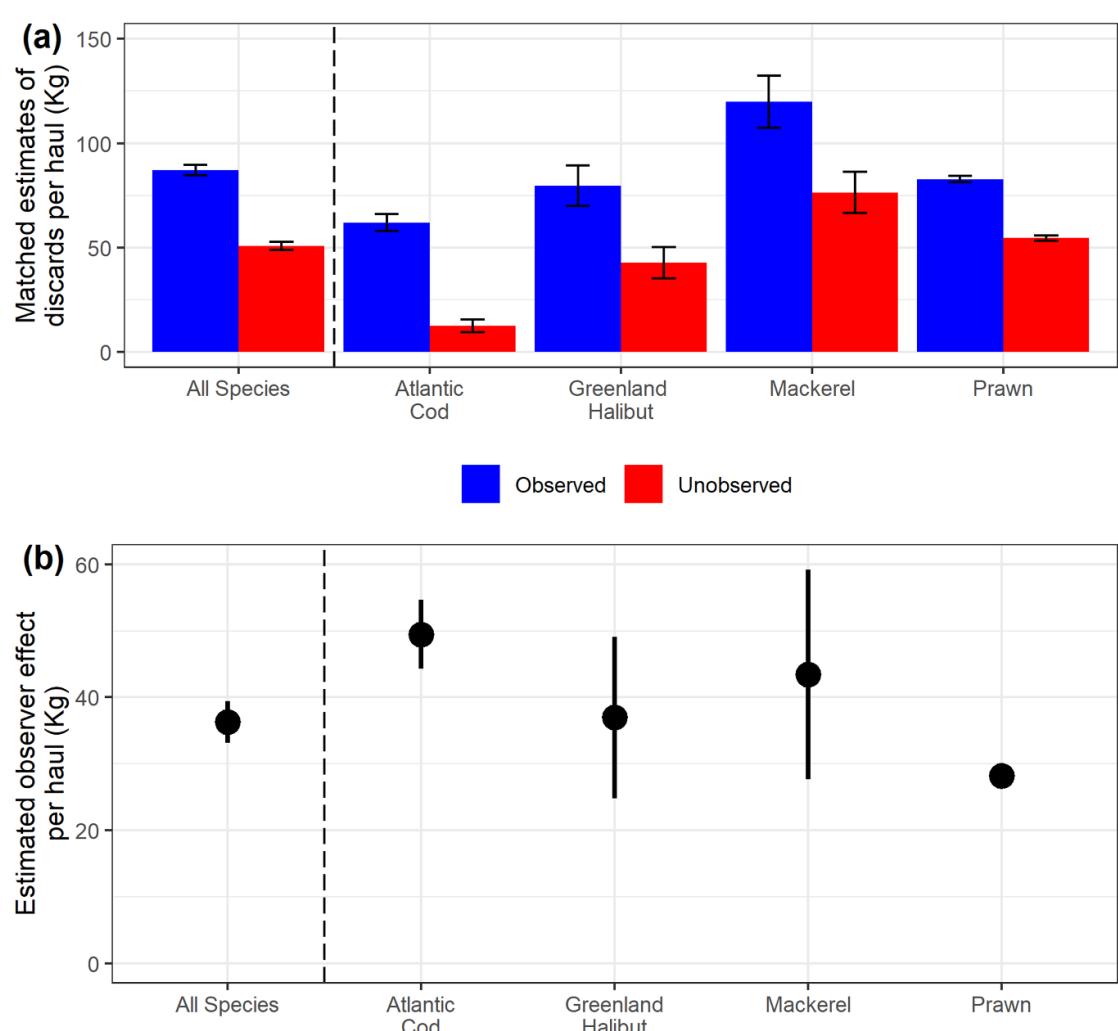


Figure 3. Estimates of average discard weights per haul (a) and observer effect on discard reporting (b). All Species refers to all species that are commercially fished in Greenland, including Atlantic Cod, Greenland Halibut, Mackerel, and Prawn. Point estimates use Match 1. Error bars represent 95% confidence intervals.

fish are underreported when fishery observers are not on board. Leveraging data rich logbooks and variation between observed and unobserved hauls, our study provides a methodology for estimating the extent of discards in Greenlandic commercial fisheries.

We support the conclusion that discards are underreported when fisheries observers are not onboard. Focusing on Greenland, our study shows that high levels of underreporting occur despite great effort to monitor onboard fishing activity. Using matching techniques, we estimated that 36.3 kg to 38.6 kg per haul of discards are not reported, and that reported discards account for 57.2% to 58.5% of total discards. This finding emphasizes the importance of accounting for potential reporting bias using additional information included in reports or logbooks. These results suggest that fishery observer programs are an effective tool in an ecosystem-based approach to fisheries management and they improve our understanding of the environmental impacts of commercial fishing.

We encourage future research that advances the monitoring of fishing activity at sea. Other fishing nations with similar monitoring protocols may exhibit similar trends. The analyses presented here would be feasible in other contexts where haul-level logbook data and information on observer—both human and electronic/video-based—coverage are available. Unlike human fishery observers, electronic monitoring can reduce costs and occupational hazards to human observers while still helping to address the problem of underreporting discards (Hoar 2005, van Helmond *et al* 2015). Advances in electronic monitoring may further reduce observer deviation from true discard weights, which are known to occur among human fishery observers (Catch, Effort and Discard Estimates in Real Time 2008).

Our data suggest that all commercial fishing trips in Greenland exhibit significant discrepancies in discarding percentages between trips with and without observers onboard. These discrepancies are a problem because current global estimates of fishing pressure do not include this source of resource waste

(Anticamara *et al* 2011, Watson *et al* 2013, Kroodsma *et al* 2018). We estimate discards can be underreported by as much as 41.5%. Although underreporting percentages will vary across global fisheries, including precise and reliable underestimates can improve future assessments of global fishing pressure.

There are several reasons why skippers systematically might report fewer discards when nobody is watching. First, weighing discards is prone to human error. Though the law requires weight of discards to the kilogram, discards may be approximated without using a scale. Even if weighed by scale, discards are handwritten in logbooks and not entered digitally, potentially leading to another source of human error. Whereas an observer is tasked with documenting discards in the logbook when present, a skipper is responsible for several tasks at once and may not be able to immediately and faithfully record discards from all production facilities. Finally, it may be the case that skippers intentionally underreport discards when they are not observed to conceal noncompliant fishing practices.

On a positive note, our results suggest that the proportion that discards make of the total catch is decreasing each year. Greenland's performance in this area runs counter to the increase of discards produced globally, which increased slightly since it was last estimated (Kelleher 2005, Pérez Roda *et al* 2019). In addition, Greenland's discard percentage is several times lower than the most recent global average of 10.8% (Pérez Roda *et al* 2019). This result suggests that Greenland's commercial fishing fleet continues to maximize economic efficiency and reduce its waste of living marine resources. It also suggests that an ecosystem-based approach to fisheries may not be mutually exclusive with the goal of profit maximization.

However, the results of our study also illustrate surprising characteristics for systematically underreporting discards. For example, the effect of observers on discards was lowest for the highest value fisheries, which runs counter to studies of the costs and benefits of engaging in unlawful activity on both conceptual and empirical grounds (Becker and Landes 1974, Hønneland 1999, Keane *et al* 2008). During fishing trips for the highest value species, such as Greenland halibut or Northern prawn, we found the lowest differences in discard reporting, with and without observers present. This result is surprising, given that prawn fisheries are prone to highgrading (i.e. mass-discarding of smaller shrimp to make room for larger shrimp). The result might indicate shrimp fishers upheld a legislative ban on highgrading, and that institutional measures for controlling discards can have unintended consequences on lower value species (Catchpole *et al* 2014) and exacerbate non-compliance in fisheries with limited monitoring, control, and surveillance (Condie *et al* 2014).

The effect of fishery observers on lower value species can be seen in the case of Atlantic cod fishing. Though Atlantic cod stocks surrounding Greenland are stable and improving (International Council for the Exploration of the Sea 2019, Snyder 2020), discarding cod in comparatively larger quantities should alarm managers, as fishing pressure for cod is likely to continue to increase under current conditions (International Council for the Exploration of the Sea 2019). It is important to note that Atlantic cod hauls were observed at the lowest percentage (11.8%), as compared to the top four fisheries in Greenland. Our finding that a lower valued fishery was observed less frequently and contained more underreported discards underscores why fishing activity of all value classes can benefit from improved monitoring, general communication to skippers of best practices for reporting catches, and continued vetting protocols or technology to streamline catch reporting at sea (van Helmond *et al* 2015, Larcombe *et al* 2016). This finding also suggests fisheries that bear ecolabels and thus receive additional enforcement attention, such as Greenland's Northern prawn fishery, may have unintended consequences on the allocation of enforcement resources to other fisheries.

Our results outline the magnitude of the problem, but there is still a need for future research to examine other sources of error in the reporting of marine capture fisheries. Knowing how much skippers' reports discards deviate from true discards demands additional research because fishery observers, while intimately familiar with the regulations and practices of handling discards, are also prone to underestimating discard weights (Catch, Effort and Discard Estimates in Real Time 2008). Further evaluation of how well enforcement efforts work may help skippers, conservationists, and government alike, decide whether they feel that increased observation of fishing activities is warranted and legitimate.

In Greenland, in a region with world-class fisheries enforcement, the underreporting of discards is extensive. Our findings that underreporting exists—be it intentional or accidental—underscores the need for fisheries managers and enforcement entities worldwide to understand the extent and the origins of underreporting. Improved understanding of how discards are produced is an important next step for minimizing discards and conserving marine resources. While command-and-control enforcement with fishery observers significantly alters catch reporting behavior, it is time to develop more inclusive, transparent, and collaborative approaches to deal with fishing fleets' waste of living marine resources.

Acknowledgments

We acknowledge funding from a Dartmouth College, Joint Science Education Project, and the Neukom

Institute for Computational Science. We sincerely thank Greenland Fisheries License Control Authority (GFLK) and members of Greenland's large-scale fishing fleet for their openness, trust, and collaboration.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

ORCID iDs

Hunter T Snyder  <https://orcid.org/0000-0002-1943-6563>

James T Erbaugh  <https://orcid.org/0000-0002-0602-9045>

References

- Agrawal A 2014 Matching and mechanisms in protected area and poverty alleviation research *Proc. Natl Acad. Sci.* **111** 3909–10
- Alverson D L *et al* 1994 *A Global Assessment of Fisheries Bycatch and Discards* (Rome: FAO)
- Ames R T 2005 *The efficacy of electronic monitoring systems: a case study on the applicability of video technology for longline fisheries management* 64
- Anderson L G 1994 An economic analysis of highgrading in ITQ fisheries regulation programs *Mar. Resour. Econ.* **9** 209–26
- Anticamara J A, Watson R, Gelchu A and Pauly D 2011 Global fishing effort (1950–2010): trends, gaps, and implications *Fish. Res.* **107** 131–6
- Asche F *et al* 2018 Three pillars of sustainability in fisheries *Proc. Natl Acad. Sci.* **115** 11221–5
- Baylis K, Honey-Rosés J, Börner J, Corbera E, Ezzine-de-blas D, Ferraro P J, Lapeyre R, Persson U M, Pfaff A and Wunder S 2016 Mainstreaming impact evaluation in nature conservation: mainstreaming impact evaluation *Conserv. Lett.* **9** 58–64
- Becker G S and Landes W M 1974 *Essays in the Economics of Crime and Punishment* (New York: National Bureau of Economic Research; distributed by Columbia University Press)
- Blanchard J L *et al* 2017 Linked sustainability challenges and trade-offs among fisheries, aquaculture and agriculture *Nat. Ecol. Evol.* **1** 1240–9
- Catch, Effort and Discard Estimates in Real Time 2008 Joint Research Centre
- Catchpole T L, Feekings J P, Madsen N, Palialexis A, Vassilopoulou V, Valeiras J, Garcia T, Nikolic N and Rochet M-J 2014 Using inferred drivers of discarding behaviour to evaluate discard mitigation measures *ICES J. Mar. Sci.* **71** 1277–85
- Catchpole T L and Gray T S 2010 Reducing discards of fish at sea: a review of European pilot projects *J. Environ. Manage.* **91** 717–23
- Condie H M, Catchpole T L and Grant A 2014 The short-term impacts of implementing catch quotas and a discard ban on English north sea otter trawlers *ICES J. Mar. Sci.* **71** 1266–76
- Condie H M, Grant A and Catchpole T L 2013 Does banning discards in an otter trawler fishery create incentives for more selective fishing? *Fish. Res.* **148** 137–46
- Day D 1997 Addressing the weakness of high seas fisheries management in the North-West Atlantic *Ocean Coast. Manage.* **35** 69–84
- Essington T E, Beaudreau A H and Wiedenmann J 2006 Fishing through marine food webs *Proc. Natl Acad. Sci.* **103** 3171–5
- FAO 1996 *Report of the Technical Consultation on Reduction of Wastage in Fisheries*. Tokyo, Japan, 28 October - 1 November 1996 FAO, Rome
- FAO 2018 *The State of World Fisheries and Aquaculture 2018 - Meeting the Sustainable Development Goals* (Rome: FAO)
- Feeckings J, Bartolino V, Madsen N and Catchpole T 2012 Fishery discards: factors affecting their variability within a demersal trawl fishery *Plos One* **7** e36409
- Ferraro P J, Sanchirico J N and Smith M D 2019 Causal inference in coupled human and natural systems *Proc. Natl Acad. Sci.* **116** 5311–8
- Flewelling P 2003 *Recent Trends in Monitoring Control and Surveillance Systems for Capture Fisheries* (Rome: FAO)
- Furlong W J 1991 The deterrent effect of regulatory enforcement in the fishery *Land Econ.* **67** 116
- Geraae L 2019 *Fiskeri 2019* (Nuuk: Grønlands Statistik)
- Gilman E, Legorburu G, Fedoruk A, Heberer C, Zimring M and Barkai A 2019 Increasing the functionalities and accuracy of fisheries electronic monitoring systems *Aquat. Conserv. Mar. Freshwater Ecosyst.* **29** 901–26
- Government of Greenland 2010 *Executive Order on Surveillance of Off-Shore Fisheries*
- Government of Greenland 2011 *Executive Order No. Xx of Xx Xx 2011 on Fishing Bycatches*
- Ho D E, Imai K, King G and Stuart E A 2007 Matching as nonparametric preprocessing for reducing model dependence in parametric causal inference *Political Anal.* **15** 199–236
- Ho D E, Imai K, King G and Stuart E A 2011 MatchIt: nonparametric preprocessing for parametric causal inference *J. Stat. Softw.* **42**
- Hønneland G 1999 A model of compliance in fisheries: theoretical foundations and practical application *Ocean Coast. Manage.* **42** 699–716
- International Council for the Exploration of the Sea 2019 'North Western Working Group 2019' ICES (<http://doi.org/10.17895/ices.pub.5298>) (Accessed: 3 January 2020)
- Kåjangmat J 2020 'Detailed Imports and Exports by Transaction, Month, Unit, Product and Time' Statistics Greenland http://bank.stat.gl/pxweb/en/Greenland/Greenland__IE/IEXDET.px/ (Accessed: 21 May 2020)
- Keane A, Jones J P G, Edwards-Jones G and Milner-Gulland E J 2008 The sleeping policeman: understanding issues of enforcement and compliance in conservation *Anim. Conserv.* **11** 75–82
- Keith D M and Hutchings J A 2012 Population dynamics of marine fishes at low abundance *Can. J. Fish. Aquat. Sci.* **69** 1150–63
- Kelleher K 2005 *Discards in the World's Marine Fisheries: An Update* (Rome: FAO)
- King G 2010 'Exact Matching' https://riq.harvard.edu/docs/matchit/2.4-15/Exact_Matching.html (Accessed February 14, 2019)
- King G, Nielsen R, Coberley C, Pope J E and Wells A 2011 Comparative effectiveness of matching methods for causal inference
- KNR 2020 'Royal Greenland: Største Rejefangst Nogensinde i Grønland' <https://knr.gl/da/nyheder/royal-greenland-største-rejefangst-nogensinde-i-grønland>
- Kronbak L G, Nielsen J R, Jørgensen O A and Vestergaard N 2009 Bio-economic evaluation of implementing trawl fishing gear with different selectivity *J. Environ. Manage.* **90** 3665–74
- Kroodsma D A *et al* 2018 Tracking the global footprint of fisheries *Science* **359** 904–8
- Kuperan K and Sutinen J G 1998 Blue water crime: deterrence, legitimacy, and compliance in fisheries *Law Soc. Rev.* **32** 309
- Larcombe J, Noriega R and Timmiss T 2016 *Catch Reporting Under E-Monitoring in the Australian Pacific Longline Fishery* (Canberra: ABARES) (www.wcpfc.int/system/files/WCPFC-2016-ERandEMWG2-DP01%20Australian%20ETBF%20e-monitoring.pdf)
- Lee J, South A B and Jennings S 2010 Developing reliable, repeatable, and accessible methods to provide high-resolution estimates of fishing-effort distributions

- from vessel monitoring system (VMS) data *ICES J. Mar. Sci.* **67** 1260–71
- Mills C M, Townsend S E, Jennings S, Eastwood P D and Houghton C A 2007 Estimating high resolution trawl fishing effort from satellite-based vessel monitoring system data *ICES J. Mar. Sci.* **64** 248–55
- Myers R A, Barrowman N J, Hutchings J A and Rosenberg A A 1995 Population dynamics of exploited fish stocks at low population levels *Science* **269** 1106–8
- Nedergaard M 2018 Interview on GFLK Fishery Observer Program
- Needle C L, Dinsdale R, Buch T B, Catarino R M D, Drewery J and Butler N 2015 Scottish science applications of remote electronic monitoring *ICES J. Mar. Sci.* **72** 1214–29
- Pauly D 1998 Fishing down marine food webs *Science* **279** 860–3
- Pérez Roda M A, Gilman E, Huntington T, Kennelly S J, Suuronen P, Chaloupka M, Medley P A H and Food and Agriculture Organization of the United Nations 2019 *A Third Assessment of Global Marine Fisheries Discards* (Rome: FAO)
- Plet-Hansen K S, Eliasen S Q, Mortensen L O, Bergsson H, Olesen H J and Ulrich C 2017 Remote electronic monitoring and the landing obligation – some insights into fishers' and fishery inspectors' opinions *Mar. Policy* **76** 98–106
- Porter R D 2010 Fisheries observers as enforcement assets: lessons from the North Pacific *Mar. Policy* **34** 583–9
- Power M E 1990 Effects of fish in river food webs *Science* **250** 811–4
- Queirolo L E 1995 Bycatch, Utilization, and Discards in the Commercial Groundfish Fisheries of the Gulf of Alaska, Eastern Bering Sea, and Aleutian Islands p 157
- Rochet M-J, Catchpole T and Cadrin S 2014 Bycatch and discards: from improved knowledge to mitigation programmes *ICES J. Mar. Sci.* **71** 1216–8
- Rosenbaum P R and Rubin D B 1985 Constructing a control group using multivariate matched sampling methods that incorporate the propensity score *Am. Stat.* **39** 33–8
- Sardà F, Coll M, Heymans J J and Stergiou K I 2015 Overlooked impacts and challenges of the new European discard ban *Fish Fish.* **16** 175–80
- Serreze M C and Barry R G 2005 *The Arctic Climate System* (Cambridge: Cambridge University Press)
- Sigurðardóttir S *et al* 2015 How can discards in European fisheries be mitigated? Strengths, weaknesses, opportunities and threats of potential mitigation methods *Mar. Policy* **51** 366–74
- Snyder H T 2020 Atlantic cod (*Gadus morhua*) value shifts and crashes at Greenland *Arctic Crashes: People and Animals in the Changing North* ed I Krupnik and A L Crowell (Washington, DC: Smithsonian Institution Scholarly Press) p 576
- Sutinen J G and Andersen P 1985 The economics of fisheries law enforcement *Land Econ.* **61** 387
- Sutinen J G and Kuperan K 1999 A socio-economic theory of regulatory compliance *Int. J. Soc. Econ.* **26** 174–93
- van Helmond A T M, Chen C and Poos J J 2015 How effective is electronic monitoring in mixed bottom-trawl fisheries? *ICES J. Mar. Sci.* **72** 1192–200
- Vestergaard N 1996 Discard behavior, highgrading and regulation: the case of the Greenland shrimp fishery *Mar. Resour. Econ.* **11** 247–66
- Watson R A, Cheung W W L, Anticamara J A, Sumaila R U, Zeller D and Pauly D 2013 Global marine yield halved as fishing intensity redoubles *Fish Fish.* **14** 493–503
- Zwanenberg K C T and Smith S J 1983 Comparison of finfish length-frequency distributions estimated from samples taken at sea and in port *Sampling commercial catches of marine fish and invertebrates* vol 66 (Canadian Special Publication of Fisheries and Aquatic Sciences) pp 189–93