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The impact of electronic monitoring on fleet wide discarding of small cod in Scottish demersal fisheries

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In Europe, uptake of electronic monitoring (EM) has been hindered by a lack of potential cost savings, given low existing observer coverage, and resistance from industry to greater enforcement of the landing obligation. To assess why certain vessels volunteer for EM and what their subsequent changes in behaviour tell us about those of the wider fleet over time, this study investigates effects of EM on discarding of North Sea cod by Scottish demersal trawlers. As discard data were limited, weight of small cod (grade 5) landed per trip was selected as an indicator of discarding and modelled to describe discard patterns from 2006 to 2016 encompassing the EM-verified cod quota management scheme (2010–2016). Findings show that EM leads to reduced instances of discarding of small cod by participants. However, evidence suggests non-participant vessels were driven to greater levels of discarding due to quota acquisition by participants. Vessels volunteering for EM trials were not predisposed towards greater compliance. Landings data do not support the trial objective of incentivising avoidance of small cod being met. The influence of participants on non-participants has implications for how vessels are selected, and management of behavioural adaptions required to ensure participants remain representative of the wider fleet.

Keywords: catch data, discard ban, discarding, electronic monitoring, fully documented fisheries, *Gadus morhua. L.*

Introduction

Accurately accounting for the amount of discards from a fishery each year is essential (Gilman *et al.*, 2020). Stock assessments for commercial fish stocks managed using catch quotas typically rely on capturing the full age-length structure of catches to estimate fishing mortality-at-age by year (Cook, 2019). Under-reporting of discards could result in fishing mortality or abundance of younger ages being underestimated. This could affect estimates of recruitment, spawning stock biomass, and reference points, and reduce the goodness-of-fit of assessment models (Ulleweit *et al.*, 2010).

Quantifying discarding patterns that reflect true practices and are representative of the wider fleet is technically challenging (Batsleer *et al.*, 2015). Often less than 1% of fishing trips carry scientific observers (van Helmond *et al.*, 2020) and the short-term presence of an observer may result in fishers altering their discarding patterns, giving rise to an "observer effect" (Liggins *et al.*, 1997; Benoît and Allard, 2009). There are, however, indicators used to identify likely instances of discarding. One such indicator used by the European Fisheries Control Agency to measure compliance with the landing obligation is whether the proportion of the grade sizes of fish landed by a vessel are consistent with those derived from the sales notes of reference data (e.g. inspections or vessels operating with video surveillance) (European Fisheries Control Agency, 2018). Other indicators include anecdotal observations by shore-based samplers such as a complete absence of smaller size classes or minimal "token" landings of these classes disproportionate to the landings of larger size classes.

A limitation hindering accurate estimation of discarding has been the lack of reference catch composition data from vessels verified as fully compliant with either the landing obligation or the EU high-grading ban (European Union, 2008). Theoretically, the difference between reference catch composition data and data derived from vessels where only landings are documented should be the discarded component of the catch for the non reference data. Unlike inspectors, observers have no compliance enforcement powers and vessels carrying observers may be more willing to discard than those with either inspectors or video surveillance. However, if fishers are trying to present a more compliant fishery to an observer the levels of discarding could be reduced in comparison to vessels with neither observers, inspectors nor video surveillance (Babcock *et al.*, 2003). Thus discard estimates from observer programmes should lie between the ideal reference and landings only data and could be adjusted to better represent unobserved fishing activity. Without data from verified vessels, also known as being fully documented, there are no reference data from which to assess the impact of "observer-effects" or alternative management approaches to discarding.

Over the last decade, Electronic Monitoring (EM), consisting of a global positioning system, activity sensors, computer hardware, and video surveillance, has emerged as an effective tool to accurately document catches (Bartholomew *et al.*, 2018), provide "gold-standard" reference data, and verify compliance with regulations (Plet-Hansen *et al.*, 2017). As EM adoption becomes more widespread, methods to extract data are fine-tuned, and types of observations expanded, EM has the potential to revolutionise data collection within marine ecosystems by effectively enabling equipped vessels to double up as survey vessels. Future applications may include tracking the presence of invasive species, monitoring marine macro plastics pollution, and providing input and/or ground truth data to improve species distribution models and predicted lo-

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cations of nursery grounds (Asjes *et al.*, 2016). Within a fisheries compliance context in Europe, several EM trials have tested the efficacy of Catch Quota Management (CQM) (van Helmond *et al.*, 2020), where all catches (rather than just the landings) of one or more species are counted against the vessel's quota. ICES advice switched from landings to catch-based (i.e. CQM) in 2014 after several EM-verified CQM trials had commenced. Vessels under CQM, prior to the introduction of the landing obligation, were typically eligible for a quota uplift for the managed species (Bergsson *et al.*, 2017) provided they did not discard individuals, irrespective of size. CQM requires close monitoring of catches (Kindt-Larsen *et al.*, 2011) to confirm absence of discarding, hence the role of EM. Although CQM is now the standard in European fisheries, there are currently no fleets operating with EM-verified monitoring of catches, therefore understanding fishers' discarding behaviour remains relevant as compliance cannot be assumed.

In EM trials fishers are typically incentivised towards adopting more selective fishing practices via economic incentives and enhanced catching opportunities (van Helmond *et al.*, 2020). However, maintaining compensation for participation is often not viable in a complex landscape of evolving regulation. For behavioural or selectivity changes to be adopted long-term, fishers must be able to maintain pre-trial catches and/or profit margins after compensation has ceased. Whilst studies have observed temporary changes in fishers' behaviour (van Helmond *et al.*, 2016; Mortensen *et al.*, 2017), including an increase in landings of small cod and a decrease in the mean individual cod weight (Kindt-Larsen *et al.*, 2011; Ulrich *et al.*, 2015), research to date has not sought to document or explain long-term changes.

Usually EM trials enlist a subset of vessels within a fleet as costs of implementation at fleet level, including installing and maintaining equipment, can be considerable (Mangi *et al.*, 2015). Hence, equipping only part of the fleet with EM during a trial or to act as a "reference fleet" appeals to agencies underwriting the costs of compliance with fishing regulations (Scottish Environment Link, 2019). Reference fleets fulfil an enhanced data collection role on the assumption that they sufficiently represent the activity of the fishery overall (Pennington and Helle, 2011). However, their self-selecting nature can lead to bias with willingness to volunteer likely to be intrinsically linked to their fishing practices and attitudes towards compliance (Clegg *et al.*, 2022). Little is known about the variability in vessels within fleets exposed to EM-verified CQM and how such variability affects self-selection to participate.

Comprehensive vessel-specific information is available for the 2010–2016 Scottish EM-verified cod CQM scheme (hereafter referred to as the scheme) (Needle *et al.*, 2014). Participants were awarded up to 30% additional cod quota and extra days-at-sea in exchange for landing all cod caught in the North Sea. A high proportion of the Scottish demersal whitefish fleet participated (up to 25% annually) and, although the participants did not remain constant, several participated for extended periods ($\leq$ 6 years). These data provide a unique analytical opportunity to address key knowledge gaps concerning fishers cod discarding behaviour.

This paper investigates whether fishers' discarding behaviour changed when participating in the scheme. To quantitatively represent discarding behaviour the paper focusses on the weight of small cod landed on each fishing trip, where small cod are defined as those of the smallest marketable size (grade 5), broadly corresponding to marketable lengths less than the estimated size at first maturity. Variability in the weight of small cod landed is modelled in terms of explanatory variables that cover scheme participation, cod population metrics, spatial and temporal information about fishing activity, stock management, economics, and landings characteristics. Of particular interest is whether the weight of small cod landed differed between non-participating vessels and participating vessels before they joined the scheme, changed once a vessel joined the scheme, and/or differed between the first and subsequent years of participation. As many trips landed no small cod the model is developed in two stages, first modelling the presence of small cod in the landings ($\mathbf{P}_{\text{sml}}$) and second modelling the weight of small cod landed conditional on presence ($\mathbf{W}^{+}_{\text{sml}}$). The analysis is based on the data from 11 965 fishing trips on 173 Scottish vessels in the North Sea between 2006 and 2016.

Materials and methods

The scheme

The scheme operated voluntarily with vessels bidding for additional quota (uplift) and participants selected in the order lowest uplift to highest. Participating vessels were subject to EM and required to stop fishing once their North Sea cod quota was exhausted. Vessels could join the scheme in any year (2010–2016) with 14–27 participants annually and the average length of participation being 4 years. Uplifts were renegotiated each year, a process taking 1–5 months. During this time participants from the previous year retained EM systems on-board with an agreement that no activity would be audited. For the purposes of this study this is referred to as the not-auditable phase.

Study fleet

Whilst predominant gear use was not considered in the scheme award process most successful applicants were whitefish trawlers. Consequently demersal trawlers, targeting gadoids, were chosen as the focus of this study regardless of scheme participation (146–202 vessels annually, of which 14–24 were participants) (Marine Scotland Science, 2020). The fleet primarily operates in the northern North Sea using otter trawls with mesh sizes $\geq$ 100mm and trips lasting 4–10 days.

Trip selection

Fishing trips by the study fleet between 2006 and 2016 were included in the analysis if cod was among the species landed, fishing activity was exclusively within the North Sea (ICES Divisions 4.a-c, those covered by the scheme T&Cs), the vessel fished using bottom trawl gear with a mesh size $\geq$ 120mm and the catch was sold at Peterhead market. Including only trips where cod was landed focused attention on trips "targeting" cod, but will have excluded some trips where all cod that was caught was discarded. Trips with mesh sizes $\geq$ 120mm were selected as this was the preferred mesh size of participant vessels. The restriction on mesh size also reduced the effects of selectivity on the resulting catch composition. Landings were limited to Peterhead to control for differences in catch processing strategies and landing compositions between markets. The study period included the years that the scheme operated (2010–2016) and the four previous years (2006–2009) which acted as a benchmark against which change was measured.

Table 1. Specified weight (kg) of EU market grades of cod and corresponding lengths (cm) using the length-weight conversion of (Coull *et al.*, 1989). *A lower limit of 35 is applied as this is the legal minimum landing size.

Grade	Weight	Approximate Length
1	>7.0	92+
2	4.0–7.0	76–91
3	2.0–4.0	59–75
4	1.0–2.0	47–58
5	0.3–1.0	*35–46

Landings data

Landings data for each trip were obtained from records of first sale fish held by Marine Scotland. These specified the weight of cod landed at each EU grade (1–5) (Table 1) (European Commission, 1996). Trips were removed if any cod were not landed as gutted fish (with heads and tails intact) or if any weight was assigned to grade 0 as it was unclear what this grade represented. Here, small cod are defined as those landed as EU grade 5.

Explanatory variables

The candidate explanatory variables (Table 3) are described in turn, split into seven categories.

EM engagement

Three variables characterised different features of a vessel's engagement with EM. 1) Group was a two-level categorical variable that distinguished between vessels that participated in the scheme (*participant*) and those that did not (*control*). 2) Phase was a four-level categorical variable that described the EM status of the vessel at the time of each trip. All *control* trips were characterised as *pre-scheme*. *Participant* trips were characterised as *pre-scheme* when the vessel had not yet been fitted with an EM system; *auditable* when the scheme was live and fishing activity was available for audit; not-auditable when the scheme incentives were under negotiation and fishing activity was not available for audit; and *post-scheme* when the vessel had withdrawn from the scheme (Supplementary Figure S1). The number of trips by each Group and Phase combination and by year is presented in Tables 2 and 3) Duration was a two-level categorical variable (0–1 or > 1) that differentiated between the first and subsequent years of participation in the scheme. *Control* vessels and *participant* vessels in the *pre-* and *post-scheme* Phase were all coded as Duration = 0–1.

The variables were structured like this to make it possible to compare the *control* vessels with the *pre-scheme participant* vessels (by fitting the main effect of Group), whilst also testing for Phase and Duration effects within the *participant* Group (by fitting the main effects of Phase and Duration). Note that Phase and Duration cannot interact with Group because the Phase and Duration of the *control* vessels is always set to the reference level (*pre-scheme* or 0–1, respectively).

Population metrics

Two metrics of local cod abundance were constructed using research-vessel Catch Per Unit Effort (CPUE) data from the International Bottom Trawl Survey (quarters 1 and 3) within the North Sea, held in the ICES DATRAS database (ICES, 2020a). The metrics represented the absolute ($\mathbf{CPUE_{Abs}}$) and proportional ($\mathbf{CPUE_{Prop}}$) abundance of small cod. For each quarter and year, the numbers of small cod caught per hour in each haul (rounded to the nearest integer) were modelled as a tensor product smooth of haul latitude and longitude assuming a Poisson distribution and a log link. Random effects were included for ICES statistical rectangle and over-dispersion. Model predictions were made for all statistical rectangles and linear interpolation between quarters 1 and 3 was then used to predict small cod abundance ($\mathbf{CPUE_{Abs}}$) for the nominal latitude and longitude and month of each trip. $\mathbf{CPUE_{Prop}}$ was constructed similarly by modelling the proportion of small cod (by number) in each haul assuming a binomial distribution and a logistic link.

Spatial information

Lat and Lon were the nominal latitude and longitude of each trip, taken to be the central point of the ICES statistical rectangle where the largest weight of cod landings was assigned in the vessel's electronic logbook. Lat and Lon were always included together in a spatial smooth and were intended to capture spatial variation not explained by the cod population metrics.

Stock management

Two regulatory variables based on quota measured how restrictive catch limits were at the time of each trip. $\mathbf{Quota_{TAC}}$ was the annual North Sea cod TAC for the year in which the trip occurred (ICES, 2020b). $\mathbf{Quota_{Av}}$ was a measure of quota availability calculated at a finer temporal resolution using monthly quota uptake information from Marine Scotland. Essentially, $\mathbf{Quota_{Av}}$ was the surplus or deficit in quota remaining at the start of the month compared to that expected

Table 2. Number of trips and unique vessels (shown in parenthesis) for the *control* and *participant* Groups by Phase and Year.

	Control	*Participant*			
Year	*Pre-scheme*	*Pre-scheme*	*Auditable*	*Not-auditable*	*Post-scheme*
2006	754 (55)	435 (23)			
2007	651 (48)	436 (23)			
2008	557 (48)	442 (25)			
2009	616 (62)	535 (27)			
2010	561 (55)	373 (27)	243 (13)		
2011	392 (42)	159 (13)	488 (23)	18 (8)	
2012	435 (48)	136 (6)	416 (22)	55 (20)	
2013	491 (52)	131 (11)	409 (18)	59 (13)	47 (2)
2014	478 (44)	41 (8)	290 (22)	129 (14)	41 (2)
2015	528 (54)		457 (21)	44 (18)	38 (5)
2016	544 (48)		220 (14)	88 (13)	228 (9)

Table 3. Description of explanatory variables. Continuous variables are summarised by their median value and range in parenthesis. Categorical variables are summarised by their levels.

Variable	Description	Type	Summary (Number of Levels or Median and Range)
Group	Participating or non-participating vessel in the Scottish cod EM-verified CQM scheme	Categorical	2 levels: *participant* and *control*
Phase	Phase of EM participation	Categorical	4 levels: *pre-scheme*; *auditable*; *non-auditable*; *post-scheme*
Duration	First of subsequent years of EM participation	Continuous	2 levels: 0–1 and > 1
$\mathbf{CPUE}_{\mathbf{Abs}}$	Predicted CPUE (n/hour) of grade 5	Continuous	1.242 (0.001–21.427)
$\mathbf{CPUE}_{\mathbf{Prop}}$	Predicted proportion of grade 5 cod (by number) in the catch	Continuous	0.38 (0.01–0.97)
Lat	Centroid latitude of the ICES statistical rectangle with the largest cod weight assigned for the landing	Continuous	59.25 (53.75–61.75)
Lon	Centroid longitude of the ICES statistical rectangle with the largest cod weight assigned for the landing	Continuous	0.50 (-3.50–7.50)
$\mathbf{Quota}_{\mathbf{TAC}}$	Annual TAC (t) for cod in ICES Subarea 4 (North Sea)	Continuous	26 842 (19 957–33 651)
$\mathbf{Quota}_{\mathbf{Av}}$	Percentage of annual quota available at the start of the month relative to equal uptake	Continuous	0.97 (-12.20–7.47)
Price	Average sale price (£/kg) of grade 5 cod at Peterhead market in 9 days before landing adjusted for inflation to 2016	Continuous	1.95 (1.06–3.22)
$\mathbf{W}_{\mathbf{other}}$	Combined weight of cod (t) grades 1–4 in landing	Continuous	2.733 (0.000–29.561)
Month	Month of landing	Continuous	6 (1–12)
Year	Year of landing	Continuous	2011 (2006–2016)

under even annual uptake, and was calculated as

$$\mathbf{Quota}_{\mathbf{Av}} = Q_m - \frac{13-m}{12}100$$

where Q_m was the percentage of the annual quota remaining at the start of month m ($m = 1\ldots12$) in any given year. Thus, $\mathbf{Quota}_{\mathbf{Av}} = 0$ for all trips in January, but could be positive or negative thereafter.

Economics

Whilst the quota variables reflect broad economic drivers through limitations on catch opportunities, they do not capture specifics of the market for small cod. The variable Price was the average value (£/kg) of grade 5 cod sold at Peterhead market in the nine days before the trip landed. This value was adjusted for inflation using the Bank of England inflation calculator to the year 2016, the final year of the scheme (Bank of England, 2020). Anecdotal evidence suggests fishers access market prices daily, so decisions on discarding based on price will be made during the trip. Nine days was used as it was the 75th percentile of trip length in the data set.

Catch characteristics

$\mathbf{W}_{\mathbf{other}}$ was the total weight of cod in grades 1–4, which broadly correspond to lengths greater than or equal to the estimated size at first maturity, landed in the trip (Nash *et al*., 2010; ICES, 2021). This variable was used as a proxy for fishing effort, both in terms of trip duration and in targeting of cod.

Temporal information

The Month and Year were included to capture any systematic change over months or years not explained by the other variables and factors.

$\mathbf{CPUE}_{\mathbf{Abs}}$ and $\mathbf{W}_{\mathbf{other}}$ were square root transformed to reduce skewness. All continuous variables were centred and scaled to aid model convergence.

Statistical analyses

The weight of landed small cod ($\mathbf{W}_{\mathbf{sml}}$) was modelled as a function of the explanatory variables using generalised additive mixed models. However, as small cod were only landed in 61% of trips, the modelling was done in two stages following a "hurdle" model approach (Cragg, 1971). First, the presence/absence of small cod in the landings were modelled to characterise the probability of landing small cod ($\mathbf{P}_{\mathbf{sml}}$). Second, the data set was restricted to the trips in which small cod were landed. The weight of small cod in these trips, denoted $\mathbf{W}^{+}_{\mathbf{sml}}$ because they are all positive, was then modelled to characterise the weight of landed small cod conditional on presence. For simplicity, these are referred to as the landing probability and weight+models respectively. Zero-inflated models (e.g. Zuur *et al.* (2012)) that would model $\mathbf{W}_{\mathbf{sml}}$ in one stage were not pursued because of the complexity of the fixed and random effects formulations (see below). Both modelling stages involved a forwards-backwards stepwise model selection procedure in which a starting model that included all the explanatory variables was fitted to the data and then simplified or extended by sequentially dropping or adding terms. The model selection procedure is described in detail for $\mathbf{P}_{\mathbf{sml}}$ and then adapted for $\mathbf{W}^{+}_{\mathbf{sml}}$. All models were fitted by maximum likelihood in the R package gamm4 (Wood and Scheipl, 2016) in R, version 4.0.3 (R Core Team, 2020).

$\mathbf{P}_{\mathbf{sml}}$ was modelled assuming the presence/absence of small cod in the landings had a Bernoulli distribution and assuming a logistic link. The starting model had fixed effects of the form:

$$\begin{aligned} &logit\mathbf{P}_{\mathbf{sml}} \sim \mathbf{Group} + \mathbf{Phase} + \mathbf{Duration} + \mathbf{Phase} : \mathbf{Duration} \\ &+ \mathbf{Group} : (\mathbf{Year} + \mathbf{Month} + \mathbf{W}_{\mathbf{other}} + \mathbf{Quota}_{\mathbf{Av}} + \mathbf{Quota}_{\mathbf{TAC}} \\ &+ \mathbf{Price} + \mathbf{CPUE}_{\mathbf{Abs}} + \mathbf{CPUE}_{\mathbf{Prop}} + \mathbf{s}(\mathbf{Lon}, \mathbf{Lat})) \end{aligned}$$

The model included the main effect of Group, the main effects and two-way interaction (:) between Phase and Duration and the two-way interaction between Group and the continuous explanatory variables in Table 3. The interaction with Group means that a separate relationship for *control* and *participant* vessels was fitted for each continuous variable. The continuous variables were included as linear (logistic) terms apart from Lon and Lat which were modelled as a tensor product spatial smooth.

The starting model was simplified by dropping interactions (replacing them with main effects) and then removing main effects. The model was extended by allowing all continuous variables to become smooths rather than linear terms and by introducing interactions between these and Phase. The maximal model allowed Group and Phase to interact with smooth functions of all the continuous variables. Given the relative simplicity of the expected responses, all smoothers (apart from the spatial smooth) were fitted as thin plate regression splines with four basis functions allowing at most a cubic-like response. The spatial smooth was unconstrained. Model selection was based on the Bayesian Information Criterion (BIC) (Schwarz, 1978) with the sample size taken to be the number of vessels in the data set (173). Only single terms were dropped or added at each stage of the model selection process. However, once a "final" model had been selected, further candidate models that dropped several terms simultaneously were explored to ensure no further model simplification was possible.

Eight random effects terms were included in all models. These were based on preliminary analysis with the fixed effects model in Eq.2 and allowed for vessel effects (at several levels of temporal resolution) and additional random temporal and spatial variation unaccounted for by the fixed effects. The random effects structure was:

$$\begin{aligned} \mathit{logit}\ \mathbf{P}_{\mathbf{sml}} \sim\ & \mathbf{Year} + \mathbf{Group} : \mathbf{Year} + \mathbf{Rectangle} + \mathbf{Group} \\ & : \mathbf{Rectangle} + \mathbf{Vessel} + \mathbf{Vessel} : \mathbf{Year} + \mathbf{Group} : \mathbf{Year} : \mathbf{Month} \\ & + \mathbf{Vessel} : \mathbf{Year} : \mathbf{Month} \end{aligned}$$

where Rectangle denotes the statistical rectangle associated with each trip (section 2.5.3). All the terms in Eq.3 were treated as categorical with 173, 11, 97, 12 and 2 levels for Vessel, Year, Rectangle, Month and Group respectively. The last term is effectively an over-dispersion term since it accounts for variation within Vessels at the finest spatial and temporal resolution.

There were 7304 trips in which small cod were landed. $\mathbf{W}^{+}_{\mathbf{sml}}$ was log-transformed and modelled assuming a Gaussian distribution and an identity link. All other aspects of the model selection procedure were identical to the process used for $\mathbf{P}_{\mathbf{sml}}$. Before analysis, very low weights (1% of trips), likely representing a few cod landed in a box of mixed species, were rounded up to 22.5 kg, half a typical fish box weight, to avoid unduly affecting the results.

The model results were summarised by tables giving the variable importance and significance of each term in the model, and by plots of the model effects. Variable importance was indicated by the change in BIC when the term was removed from the model, and significance was based on likelihood ratio tests. Unless otherwise stated, the effects plots were conditioned on the median values of the continuous explanatory variables, the Lon and Lat where most cod were landed, and the *pre-scheme* Phase of the *participant* Group (with Duration = 0–1). The effects were back-transformed for ease of interpretation and adjusted for bias (due to the random effects being normally distributed on the logistic or log scale respectively) by simulating from the final model conditional on the estimated variance components.

When an explanatory variable affected both $\mathbf{P}_{\mathbf{sml}}$ and $\mathbf{W}^{+}_{\mathbf{sml}}$, the overall effect on $\mathbf{W}_{\mathbf{sml}}$ was estimated by simulating from the posterior distributions of the effect in the $\mathbf{P}_{\mathbf{sml}}$ and $\mathbf{W}^{+}_{\mathbf{sml}}$ models (conditioned on the other explanatory variables as described above), back-transforming to the probability or weight scale respectively, and multiplying the two together.

By including the landed weight of grade 1–4 cod $\mathbf{W}_{\mathbf{other}}$ as an explanatory variable, the models above explore differences in $\mathbf{W}_{\mathbf{sml}}$ between Groups and Phases *conditional* on $\mathbf{W}_{\mathbf{other}}$. The results can thus be interpreted as differences in discarding behaviour conditional on a particular cod catch composition (assuming negligible discarding of grade 1–4 cod). Any systematic differences in $\mathbf{W}_{\mathbf{other}}$ between Groups and Phases will affect the *marginal* distribution of $\mathbf{W}_{\mathbf{sml}}$, which can be thought of as a combination of discarding behaviour and effort targeted at cod. However, modelling $\mathbf{W}_{\mathbf{other}}$, is beyond the scope of this paper.

Results

Annual summary plots of the raw data (Fig. 1) suggest that in the years before the scheme (2006–2009), *participant* vessels tended to land more small cod and more grade 1–4 cod per trip than *control* vessels, but that there was little difference in the proportion of trips in which small cod was landed. The data also suggest that the proportion of trips landing small cod and the weight of small and grade 1–4 cod landed increases in *auditable* trips once vessels have joined the scheme.

Landing probability

The final model for $\mathbf{P}_{\mathbf{sml}}$ was:

$$\begin{aligned} \mathit{logit}\ \mathbf{P}_{\mathbf{sml}} \sim\ & \mathbf{Group} + \mathbf{Phase} + \mathbf{Year} + \mathbf{Group} : \mathbf{Year} \\ & + \mathrm{s}\left(\mathbf{W}_{\mathbf{other}}\right) + \mathrm{s}\left(\mathbf{CPUE}_{\mathbf{Prop}}, \mathrm{by} = \mathbf{Group}\right) + \mathrm{s}\left(\mathbf{Quota}_{\mathbf{Av}}\right) \end{aligned}$$

The model included the main effects of Group and Phase, a two way interaction of Group and Year, and smooth terms in $\mathbf{W}_{\mathbf{other}}$, $\mathbf{CPUE}_{\mathbf{Prop}}$ and $\mathbf{Quota}_{\mathbf{Av}}$

Phase was the most important term (Fig. 2b; Table 4) with pairwise comparisons showing that the landing probability was significantly greater in the *auditable* Phase than in all other Phases (Fig. 2b; Table 5). However, the landing probability in the *non-auditable* and *post-scheme* Phases did not differ significantly from that in the *pre-scheme* Phase (Table 5).

Group and Year and their interaction were the least important terms in the model (Table 4). At the start of the study, the landing probability was similar for both Groups. The landing probability in the *control* Group then decreased over the study period whilst staying relatively stable in the *participant* Group (Fig. 2a), albeit with considerable fluctuations from year-to-year which were accommodated by the random effects (cf. Fig. 1a). To better interpret changes over time in the *participant* Group beyond 2010, when the scheme started, it is necessary to consider the joint effect of Year and Phase, since the two are somewhat confounded. Fig. 2c illustrates this for the case of a vessel which joined the scheme in 2010 and left at the end of 2013 in comparison to a *control* vessel.

The landing probability depended nonlinearly on $\mathbf{W}_{\mathbf{other}}$, $\mathbf{CPUE}_{\mathbf{Prop}}$ and $\mathbf{Quota}_{\mathbf{Av}}$ (Fig. 3). It increased with $\mathbf{W}_{\mathbf{other}}$ up to ~7 t, flattened out and then decreased (albeit with wide confidence intervals); increased for both Groups with $\mathbf{CPUE}_{\mathbf{Prop}}$ (at low $\mathbf{CPUE}_{\mathbf{Prop}}$ *participant* vessels landed more often but by the

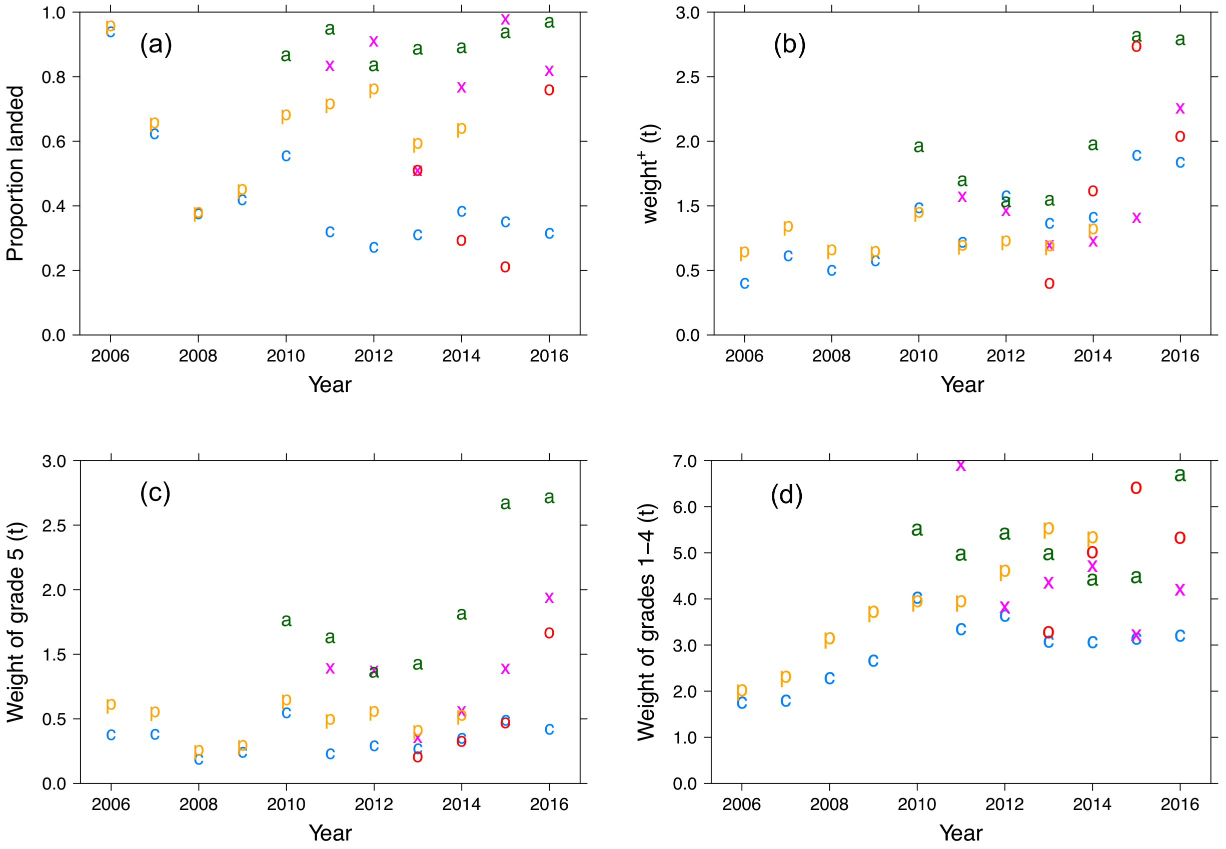

Figure 1. Mean annual values per trip by Year, Group and Phase of (a) proportion of trips landing small cod; (b) weight^{+}; (c) weight landed of small cod; and (d) weight landed of other cod. c = *control* Group in *pre-scheme* Phase, p, a, x, and o represent the *participant* Group in the *pre-scheme*, *auditable*, *not-auditable* and *post-scheme* Phases respectively.

time $\mathbf{CPUE}_{\mathrm{Prop}}$ was close to 1 the Groups probabilities were similar); and increased sharply with $\mathbf{Quota}_{\mathrm{Av}}$ until the relative quota became positive, peaked at ~2%, and then decreased slightly.

Weight+

The final model for $\mathbf{W}^{+}_{\mathrm{sml}}$ was

$$\log \mathbf{W}^{+}_{\mathrm{sml}} \sim \ \mathbf{Phase} + \mathbf{Duration} + \mathrm{s}\,(\mathbf{Month}) + \mathrm{s}\,(\mathbf{W}_{\mathrm{other}})$$

$$+\ \mathrm{s}\,(\mathbf{Quota}_{\mathrm{Av}}) + \mathbf{Price} + \mathrm{s}\left(\mathbf{CPUE}_{\mathrm{Prop}}\right) + \mathrm{s}\,(\mathbf{Lon}, \mathbf{Lat})$$

The model included the main effects of Phase and Duration, nonlinear effects of $\mathbf{W}_{\mathrm{other}}$, $\mathbf{CPUE}_{\mathrm{Prop}}$, $\mathbf{Quota}_{\mathrm{Av}}$ and Month, a spatial smooth of Lon and Lat, and a (log) linear effect of Price.

The EM variables Phase and Duration were amongst the least important terms in the model (Fig. 4; Table 6). Pairwise comparisons showed that $\mathbf{W}^{+}_{\mathrm{sml}}$ was significantly greater for trips in the *auditable* Phase than in both the *pre-scheme* and *not-auditable* Phases (Fig. 4a; Table 5) by an estimated 37% and 27% respectively. Vessels in the second (or later) year of the scheme also had a greater $\mathbf{W}^{+}_{\mathrm{sml}}$ than vessels in their first year by an estimated 39% (Fig. 4b; Table 5).

The most important term in the model was $\mathbf{W}_{\mathrm{other}}$ (Table 6), with $\mathbf{W}^{+}_{\mathrm{sml}}$ increasing steeply with $\mathbf{W}_{\mathrm{other}}$ up to ~5 t and slowly thereafter (Fig. 5a). Similarly $\mathbf{W}^{+}_{\mathrm{sml}}$ increased steeply with $\mathbf{CPUE}_{\mathrm{Prop}}$ up to ~0.7 and then more slowly (Fig. 5b) and increased with $\mathbf{Quota}_{\mathrm{Av}}$ up to about ~2% and then stabilised (Fig. 5c). $\mathbf{W}^{+}_{\mathrm{sml}}$ was higher in the second half of the year (Fig. 5d). $\mathbf{W}^{+}_{\mathrm{sml}}$ was greater in the Fair Isle region and in the central North Sea around the Dogger and Fisher banks (Fig. 5e). Price (Fig. 4f) was the least important term in the model and had a negative effect on $\mathbf{W}^{+}_{\mathrm{sml}}$.

Weight

Phase, $\mathbf{W}_{\mathrm{other}}$, $\mathbf{CPUE}_{\mathrm{Prop}}$, and $\mathbf{Quota}_{\mathrm{Av}}$ all affected both $\mathbf{P}_{\mathrm{sml}}$ and $\mathbf{W}^{+}_{\mathrm{sml}}$. Their overall effect on $\mathbf{W}_{\mathrm{sml}}$, obtained by combining the individual effects, is shown in Fig. 6. In each case, the individual effects had similar shapes which are magnified when combined. In particular, participant vessels landed an estimated 75% more small cod in the *auditable* Phase than in the *pre-scheme* Phase.

Discussion

These analyses support existing evidence that discarding of cod was common practice in North Sea demersal trawl fisheries, and that EM is an effective control measure in reducing non-compliance with a landing obligation while documenting catches accurately (Kindt-Larsen *et al.*, 2011; van Helmond *et al.*, 2016; Plet-Hansen *et al.*, 2019). Our results indicate that participation leads to a behavioural change towards reduced discarding evidenced by Phase of EM participation affecting both $\mathbf{P}_{\mathrm{sml}}$ and $\mathbf{W}^{+}_{\mathrm{sml}}$, with both increasing in the *auditable* Phase compared to the *pre-scheme* Phase. In the landing probability model ($\mathbf{P}_{\mathrm{sml}}$), based on all trips, Phase was the most influential variable on model fit. In the weight + model ($\mathbf{W}^{+}_{\mathrm{sml}}$),

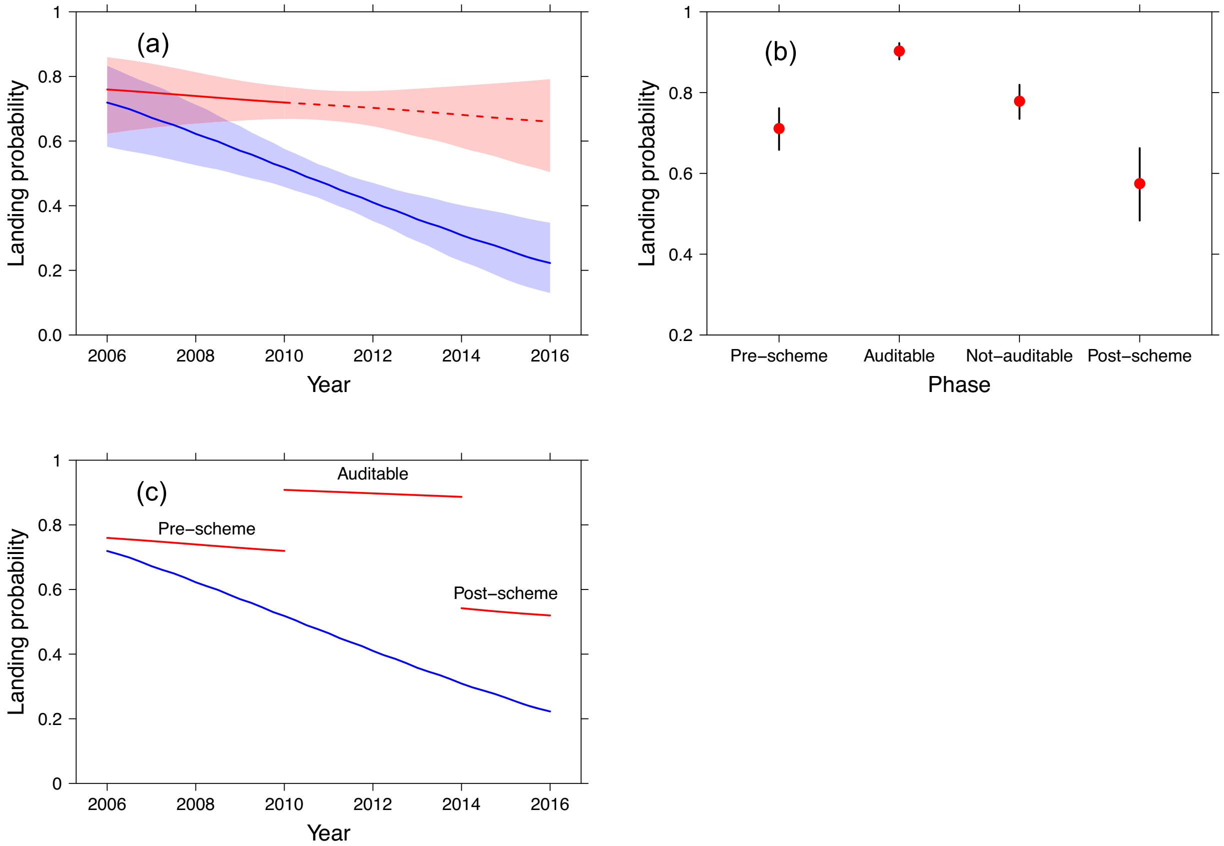

Figure 2. The partial effects of Group and Phase on P_{sml}; (a) the joint effect of Group and Year, with blue and red indicating *control* and *pre-scheme participant* vessels, respectively. Shaded areas indicate 95% confidence bands. The *participant* line is dashed from 2010 onwards indicating the start of the scheme; (b) the effect of Phase on the *participant* Group with 95% confidence limits; (c) the combined effect of Group.

Table 4. Variable importance in the P_{sml} model, indicated by the change in BIC when each term is removed. Values for Group, Year, and $CPUE_{Prop}$ indicate the overall effect of these variables (i.e. the main effect and interaction(s)). Degrees of freedom (df) and *p*-values of each term are also given.

Term	df	Δ BIC	*p*-val
Phase	3	116.225	<0.001
s(W_{other})	2	109.580	<0.001
s($Quota_{Av}$)	2	57.876	<0.001
s($CPUE_{Prop}$)	4	53.313	<0.001
Group	4	15.594	<0.001
Group: Year	1	8.015	<0.001
Year	2	7.953	<0.001
s($CPUE_{Prop}$, by = Group)	2	1.928	<0.01

based only on trips where small cod were landed, Phase was one of the least influential variables while still significant. Therefore the effect of Phase in the weight of small cod landed combined model ($\mathbf{W}_{sml}$), based on all trips, is driven primarily by the decision to land rather ($\mathbf{P}_{sml}$) than the quantity landed ($\mathbf{W}^{+}_{sml}$).

Compellingly, although the landing probability was significantly higher for the *participant* Group than for the *control* Group in the years the scheme was operational (Fig. 2a), inspection of the raw data (Fig. 1a) suggests there was little difference in landing probability between the two Groups before the start of the scheme (2010) implying that they were equally compliant. Whilst Group had no significant effect in the weight^{+} model, *participant* vessels did land slightly more cod in grades 1–4 before the start of the scheme (Fig. 1d), suggesting differences in fishing strategy between the two Groups, but not in discarding behaviour, debunking the assumption that voluntary EM participation attracts more compliant vessels *per se* (Ulrich *et al.*, 2015). Participants could be considered cod fishing "specialists" with the knowledge required to adapt their fishing behaviour to maximise returns on scheme incentives. It is therefore difficult to infer fishers' attitudes towards participation in a multi-species discard ban which would require specialist knowledge of multiple species and their interactions.

Any learned behaviour related to discarding practices resulting from scheme participation did not persist after withdrawal, as shown by the $\mathbf{W}_{sml}$ landed in the *post-scheme* Phase being similar to that of the *pre-scheme* Phase. Additionally, for trips where vessels knew they were not subject to auditing (i.e. the *not-auditable* Phase), both $\mathbf{P}_{sml}$ and $\mathbf{W}^{+}_{sml}$ were lower than in the *auditable* Phase. This evidences the expectation that when there are no consequences of regulatory noncompliance discarding takes place (Michelin *et al.*, 2018).

Incentivising adaptation to more selective fishing was a key objective of the scheme. However, although Duration (whether a vessel was in its 0–1 year or >1 year of participation) had a significant effect on $\mathbf{W}^{+}_{sml}$, *auditable* vessels landed more small cod per trip in subsequent years in the scheme. Thus the models found no evidence to support vessels successfully avoiding small fish. Reasons for significantly greater

Table 5. Significance of pairwise comparisons of the Phase effect on P_{sml} and on $\mathbf{W}^{+}_{\mathbf{sml}}$, *p*-values have been adjusted for the number of comparisons using Holm's procedure (Holm, 1979). Values significant at the 5% level are highlighted in bold.

Model	Phase	*Auditable*	*Not-auditable*	*Post-scheme*
P_{sml}	*Pre-scheme*	<0.001	0.076	0.076
	Auditable		<0.001	<0.001
	Not-auditable			0.002
W_{sml}	*Pre-scheme*	<0.001	1.000	1.000
	Auditable		0.019	1.000
	Not-auditable			1.000

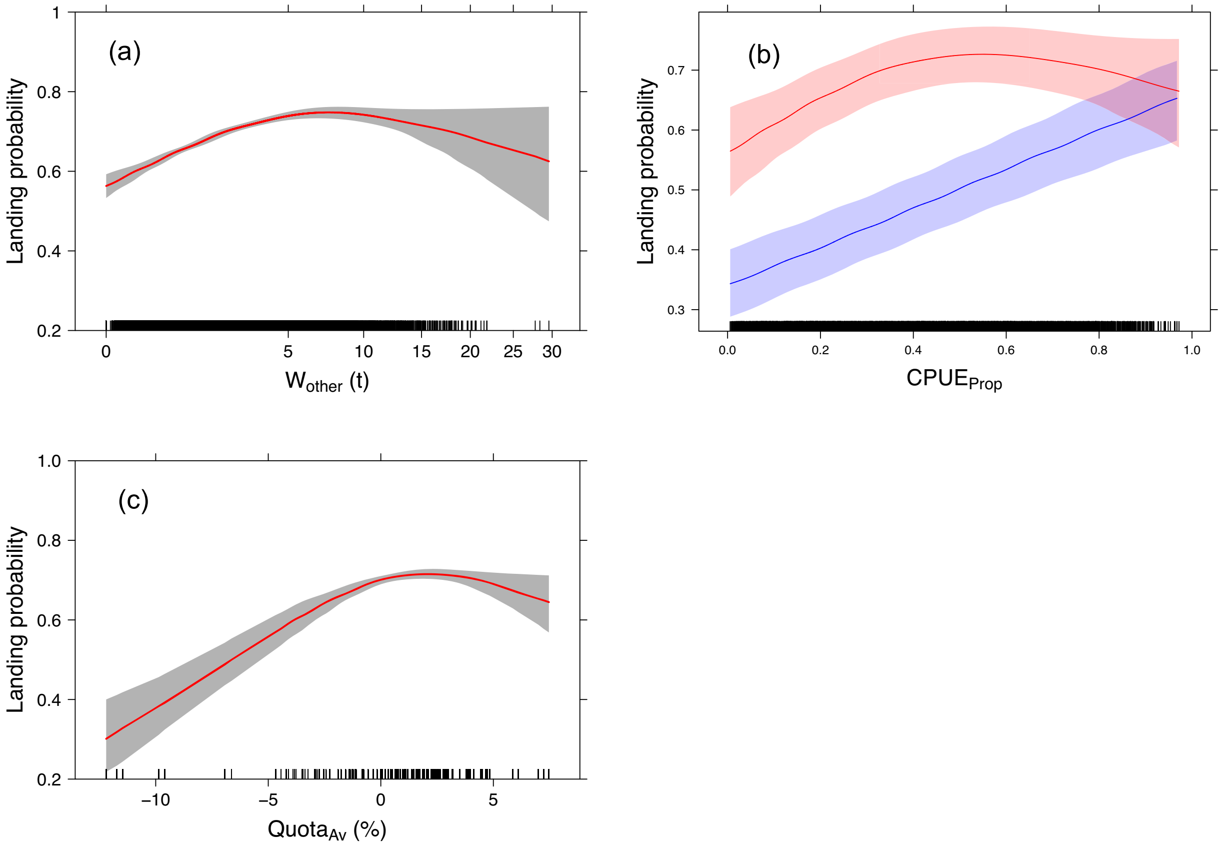

Figure 3. The partial effects of (a) W_{other}; (b) the joint effect of Group and $\mathrm{CPUE}_{\mathrm{Prop}}$, with blue and red indicating *control* and *pre-scheme participant* vessels respectively; (c) $\mathrm{Quota}_{\mathrm{Av}}$ on P_{sml} with 95% confidence bands. Tick marks on the x-axis show the marginal distribution of the explanatory variables.

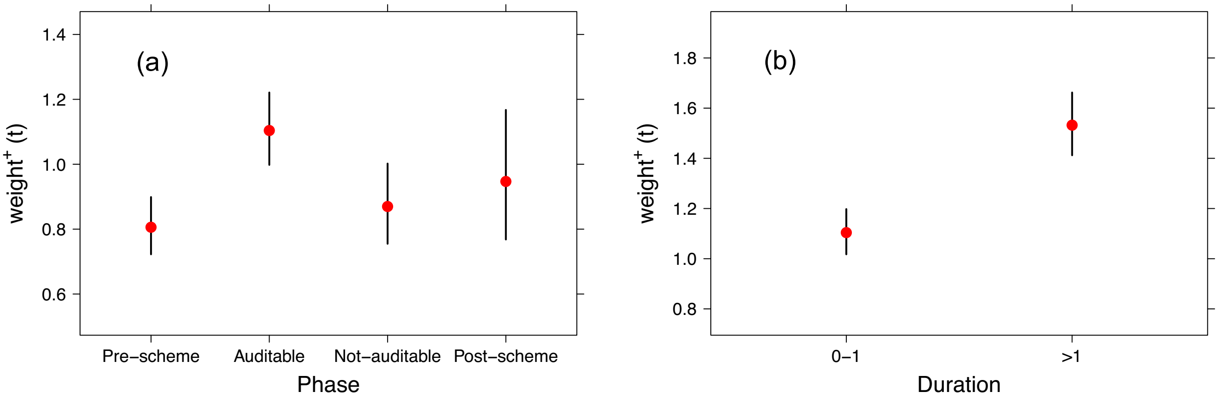

Figure 4. The partial effects of (a) Phase and (b) Duration on $\mathbf{W}^{+}_{\mathbf{sml}}$ with 95% confidence limits. The Duration effect is conditioned on the *auditable* Phase.

Table 6. Variable importance in the **W**$^{+}_{\mathbf{sml}}$ model, indicated by the change in BIC when the term is removed. Degrees of freedom (df) and *p*-values of each term are also given

Term	df	Δ BIC	*p*-val
s(W_{other})	2	1610.32	<0.001
s($CPUE_{Prop}$)	2	144.05	<0.001
s(Lon,Lat)	6	53.90	<0.001
s(Month)	2	24.70	<0.001
Duration	1	8.99	<0.001
Phase	3	7.36	<0.001
s($Quota_{Av}$)	2	7.08	<0.001
Price	1	1.38	<0.05

landings of small cod in subsequent years could be that fishers were not in fact fully compliant with scheme conditions in the first year, perhaps being given grace to adapt, or alternatively were overly cautious in avoiding small cod in the first year but not thereafter. Yet it may be that, by allowing participating vessels to unconditionally lease additional cod quota, any incentive towards greater selectivity was removed.

$\mathbf{W}_{\mathrm{other}}$ was a significant variable in both the landing probability and the weight^{+} model, and was the most influential variable in the latter. $\mathbf{W}_{\mathrm{other}}$ is a proxy for effort and accounts for catches of small cod typically being larger when total cod catches are larger. Importantly, the inclusion of $\mathbf{W}_{\mathrm{other}}$ allowed for the effects of EM on discarding to be disentangled from the degree to which a particular vessel targeted cod.

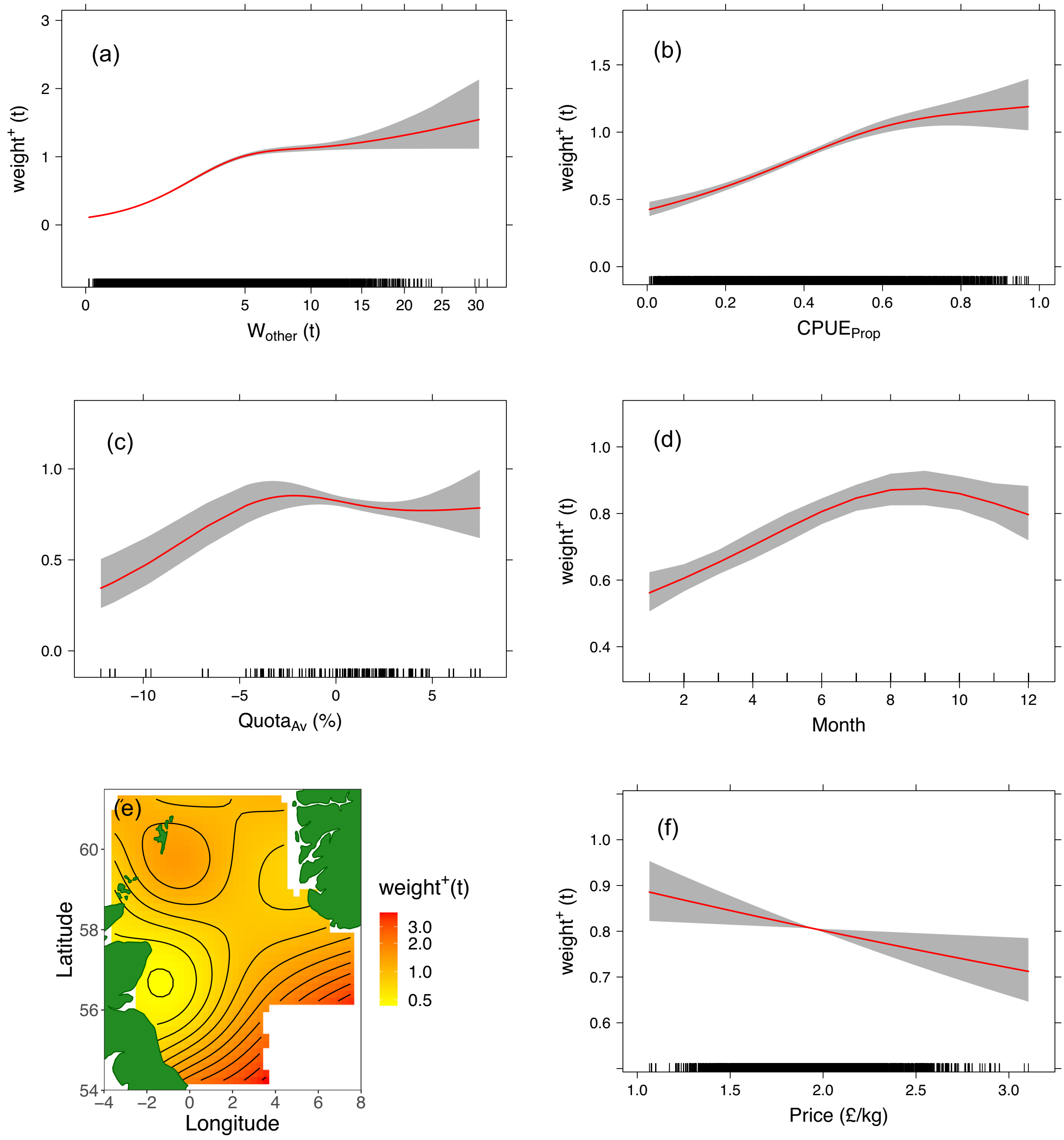

Figure 5. The partial effects of (a) W_{other}; (b) $CPUE_{Prop}$; (c) $Quota_{Av}$; (d) Month; (e) Lon and Lat; (f) Price on W^{+}_{sml} with 95% confidence limits. Tick marks on the x-axis (apart from panel E) show the marginal distribution of the explanatory variables.

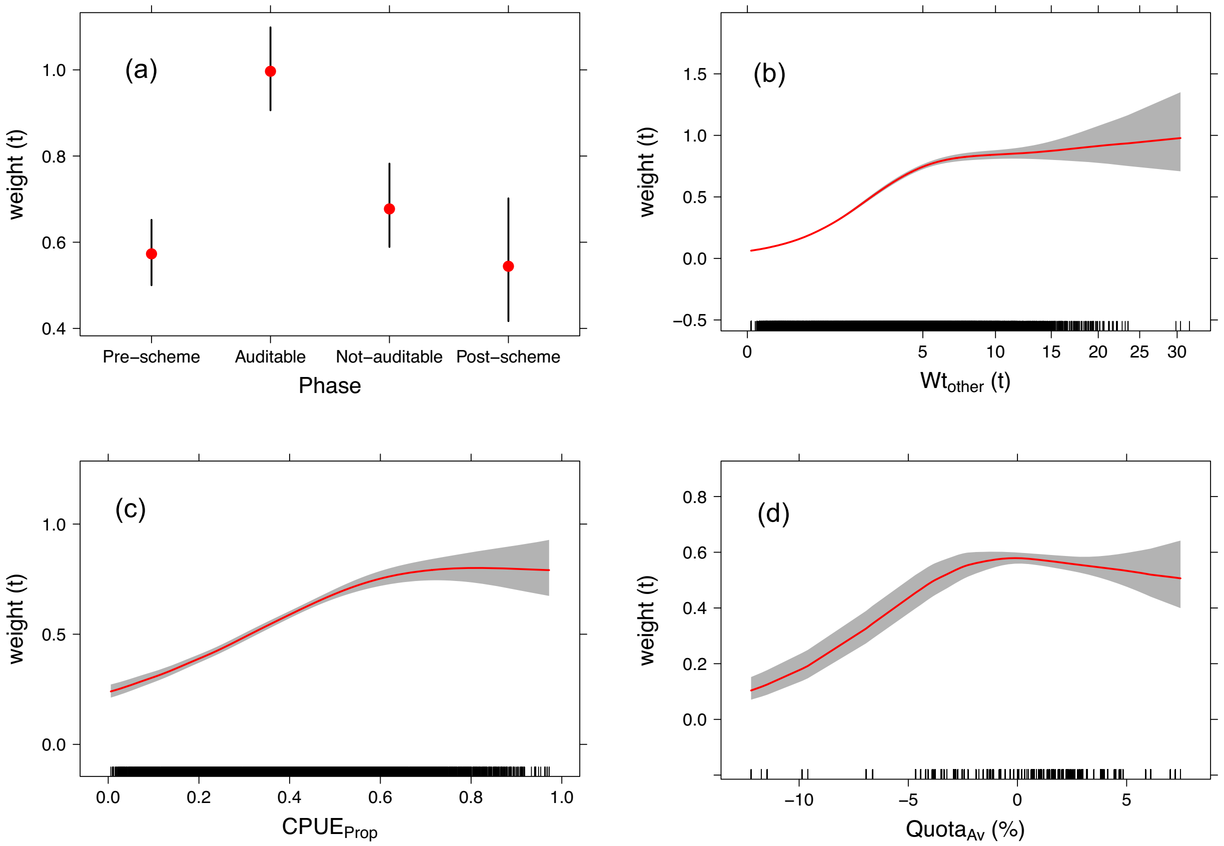

Figure 6. The overall effect of (a) Phase; (b) $\mathrm{W}_{\mathrm{other}}$; (c) $\mathrm{CPUE}_{\mathrm{Prop}}$; and (d) $\mathrm{Quota}_{\mathrm{Av}}$ on $\mathrm{W}_{\mathrm{sml}}$ with 95% confidence limits.

The results show that quota has a multi-faceted effect on discarding through its availability and distribution within the fleet. Previous studies found evidence that the value of TAC can modify the discarding behaviour of fishers (Macdonald *et al.*, 2014). Conversely, this study found that the amount of cod TAC set annually did not affect $\mathbf{W}_{\mathrm{sml}}$. Instead, the availability of quota on a finer temporal scale, relative to an even depletion rate throughout the year, was significant in both the $\mathbf{P}_{\mathrm{sml}}$ and $\mathbf{W}^{+}_{\mathrm{sml}}$ models. Where quota depletion was greater than anticipated at the start of the month, both landing probability and $\mathbf{W}^{+}_{\mathrm{sml}}$ was reduced. This finding has implications for how MCS agencies might identify periods of increased likelihood of discarding and incorporate risk into their MCS strategies.

Interestingly no evidence for differential use of space by the two Groups was found, although this may be attributable to the coarse level of spatial resolution (ICES rectangle) used. Whilst no evidence was found for $\mathbf{W}_{\mathrm{sml}}$ increasing in locations of higher abundance of small cod, $\mathbf{P}_{\mathrm{sml}}$ and $\mathbf{W}^{+}_{\mathrm{sml}}$ did increase in locations where there was higher proportional abundance of small cod. This suggests where cod catch is predominantly comprised of smaller fish fishers were less likely to discard. Possibly where fishers encounter high proportions of smaller fish it is an inefficient use of time to sort and discard a large number of individuals or to repeat a fishing activity in a new location sufficiently far away in the hope of catching larger individuals. This finding suggests that fishers could be encouraged to utilise results from fishery-independent surveys to avoid larger catches of small cod and that spatial management for reduction of discarding could be effective. However, due to the sparse temporal occurrence of surveys, real time reporting initiatives, such as BATmap in the West of Scotland (Marshall *et al.*, 2021) or spatial distribution models that relate the spatial distribution of a species to environmental variables (Asjes *et al.*, 2016), may be more beneficial.

The stability of the landing probability over time for *auditable* vessels (i.e. no effect of Duration) (Fig. 2a) may be the result of *participant* vessels adopting more consistent fishing practices: for example, returning more frequently to a reduced number of fishing locations. If we assume that the *participant* group's landing probability is the minimum probability of catching small cod for the fleet (conditional on catching marketable cod), fisheries scientists could use the combined $\mathbf{P}_{\mathrm{sml}}$ and $\mathbf{W}^{+}_{\mathrm{sml}}$ model along with the observed values of $\mathbf{W}_{\mathrm{other}}$ to estimate the total small cod discards for each trip by *control* vessels. This method for discard estimation could be extended to include other species and size grades that EM *participant* vessels are required to land. However, comparisons would need to take into account spatial, temporal and gear characteristics to compare like with like. Whilst this study is restricted to North Sea cod grade 5 landings, it has demonstrated an approach for using EM data for discard estimation that could have wider application across other stocks.

Implications for adoption of EM

The study has direct implications for fisheries management. When applied only to a subset of a fleet EM can create disparity between the behaviours of the *participant* and *control* vessels. The evidence for this is the joint effect of Year, Group, and Phase on landing probability which indicates increased discarding by *control* vessels over time (Fig. 2a). This could be a result of *participant* vessels aquiring additional cod quota from *control* vessels to prevent them being tied up having exhausted their cod quota, due to not discarding, in line with the scheme. *Control* vessels would then become quota restricted and hence discard more cod. This is also supported by the lack of a reduction in reported North Sea cod discard rates observed in the ICES stock assessment for this period (ICES, 2020b).

The disparity observed between the *participant* and *control* vessels supports a recommendation that EM be implemented across all vessels within a fleet where possible. However, there are many obstacles to blanket adoption of EM and fishers would often prefer a reference fleet approach (Ulrich *et al.*, 2015). Should this option be taken, consideration needs to be given to how vessels are selected for participation so that they remain representative of the wider fleet, and to how managers ensure that participating vessels do not influence the behaviour of the wider fleet.

In conclusion, the insights into the discarding behaviour of the fleet before and during an EM trial enhance the knowledge base for successful future implementation of EM in North Atlantic fisheries. Evidence continues to show that EM is an essential tool for realizing changes in fishers' behaviour consistent with achieving sustainably managed fish stocks. Results herein imply that when applied to a subset of vessels EM affected the behaviour of both the *participant* and *control* groups. It is likely that the percentage of the fleet participating is itself a key variable yet to be explored. A vital future investigation should be to find the optimum participation percentage needed to minimise discarding at the fleet level.

Supplementary material

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

Authors contributions

HH, CTM and CN conceived of the presented idea. RF advised on the statistical modelling. All authors discussed the results, contributed critically to the draft and gave final approval for publication.

Data availability statement

The data underlying this article cannot be shared publically due to commercial sensitivities and data protection laws.

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