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RESEARCH PAPER

High-grading and over-quota discarding in mixed fisheries

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Abstract High-grading is the decision by fishers to discard fish of low value that allows them to land more valuable fish. A literature review showed high-grading is reported in commercial and non-commercial fisheries around the world, although the number of observations is small. High-grading occurs in fisheries that are restricted to land their total catch due to management, market or physical constraints. Using the mixed flatfish fishery as a model system, a dynamic state variable model simulation showed that high-grading of certain grades occurs throughout the year when their ex-vessel price is low. High-grading increases with the degree of quota restriction, while the level of over-quota discarding is unrelated to the quota level. The size composition of the high-graded catch differs from the landed catch. Due to the differences in the seasonal variation in size specific ex-vessel price, the effect of quota restrictions on the size composition of the discarded catch is non-linear. High-grading is difficult to detect for the fishery inspection as it occurs on-board during the short period when the catch is processed. We conclude that high-grading is under-reported in fish stocks managed by restrictive quota, undermining the quality of stock assessments and sustainable management of exploited fish stocks.

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Introduction

Many fisheries around the world capture fish that are subsequently discarded back into the sea (Kelleher 2005). Discarding is mainly policy or market driven. Policy measures such as legal landings sizes or catch quota may forbid selling small fish (Harley et al. 2000; Rochet and Trenkel 2005; Depestele et al. 2011; Feekings et al. 2012) or over-quota catches (Copes 1986; Branch 2009; Poos et al. 2010), while market incentives prevent the sale of certain (by-catch) species or size classes (Gray and Kennelly 2003; Hara 2013; Eliasen et al. 2014).

Discarding of marketable fish in fisheries that are under catch quota management are of particular interest. Catch quotas or "Total Allowable Catches" (TAC) are used worldwide to regulate fisheries. The

intention of catch quotas is to control fishing mortality of a given stock to a specified level (e.g. to prevent overfishing). The use of such quotas relies on the premise that fishers adjust their fishing behaviour according to imposed catch limitations (Holden 1994; Daan 1997; Punt et al. 2006; Branch and Hilborn 2008). However, in reality TACs may control landings of fish but not the catch, because fishers may continue to fish and discard marketable fish exceeding the quota, as is likely in mixed fisheries (Pascoe 1997; Poos et al. 2010). As a result, the effectiveness of TAC management of mixed fisheries is questionable (Daan 1997).

As a refinement of the TAC system, individual transferable quotas (ITQs; Christy 1973) have been introduced world-wide to stop the "race for fish" (Copes 1986; Arnason 1993; Squires et al. 1998). ITQs provide a share of the TAC to participants in a fishery who are allowed to sell and lease their share of the quota (Davies 1992). Having rights to predetermined shares of the resource output, fishers can plan their fishing effort to secure their share of the catch, without having to account for the catches of other fishers. Although the ITQs have generally been considered successful (Branch 2009; Hamon et al. 2009; Hannesson 2013; Soliman 2014), they have not completely taken away the incentive for discarding parts of the marketable catch. Given that the quota is a predetermined share, fishers can optimize the economic return by "high-grading" their catch: that is to say, discarding those parts of the marketable catch that have the lowest value while quota is still available. Also in mixed fisheries, fishers can discard marketable fish once their quotas have been reached, termed "over-quota discarding". The survival of the discarded fish can be low (Van Beek et al. 1990; Yergey et al. 2012), depending on the type of fishery (Van Beek et al. 1990; Campbell et al. 2014), depth of catch (Sauls 2014), and other factors (Smith and Scharf 2011; Marçalo et al. 2013). Because the survival of the discarded fish can be low, high-grading is considered to be a waste of resources. In response, in 2009 the EU declared high-grading an illegal practice (Regulation (EU) 43/2009).

Theoretical studies suggest over-quota discarding and high-grading occur under specific conditions (Anderson 1994; Turner 1997; Parslow 2010; van Putten et al. 2012). However, empirical evidence for high-grading is scarce, although there is anecdotal information from the fishing industry. High-grading is

not only an unknown contribution to the waste of food resources, it may also reduce the accuracy of stock assessments that underpin the management of many fish stocks. Such stock assessments often rely on the age or length structure of the catches to estimate mortality in fish stocks. In the absence of observations of catches, landings are sometimes used as a proxy for catches. Since high-grading affects the age and length structure of the landed fish, the resulting stock assessment may lose accuracy in estimating the mortality and stock size, undermining the credibility of fisheries management (McCay 1995; Daan 1997; Rijnsdorp et al. 2007). Several studies have highlighted the importance of incorporating discards in stock assessments and propose methodologies for their inclusion (Punt et al. 2006; Aarts and Poos 2009).

This paper reviews literature on high-grading and over-quota discarding observations from different fisheries around the world, collating empirical evidence from a wide range of fisheries to study the conditions under which this may occur. In addition, we present a case study that applies a behavioural model to study high-grading decisions of fishers in a Dutch beam trawl mixed fishery under individual quota management (Gillis et al. 2008). This fishery is known for discarding marketable fish (Quirijns et al. 2008; Poos et al. 2010). The model assumes that a fisher chooses a strategy that maximizes annual net revenue. Size structured catches allow exploring the consequences of quota management on discarding of less valuable market size classes in time. The results allow us to forecast over-quota discarding and high-grading and explore the effect on age composition and the implications for stock assessment.

Literature review

A list of original publications on observations of high-grading and over-quota discarding was derived from literature searches. First a search in Scopus on high-grading was done using the query 'TITLE-ABS-KEY ((("high-grading" OR "highgrading") OR "individual quotas" OR ("individual" AND "quotas" AND "strategy") OR (discard* AND ("minimum landings size" OR "minimum legal length" OR "commercial species" OR "legislation"))) AND (fish*))'. This query thus included search terms for high-grading, and for terms that were expected to be linked to high-

grading observations. Papers that contained observations on high-grading, such as on-board observations, interviews, or skipper logbooks were included in the review. Papers hypothesizing high-grading based on conceptual models were not considered. Review papers were not included, but the original references were evaluated. In total, 336 papers were screened from which 44 contained observations on high-grading. For each of these 44 papers, the gear type, main species, geographical area, management system, type of observation, and a short description of the observation were recorded. Table 1 summarises the papers that report empirical observations of high-grading. Thirty of these reported observations were made by on-board observers. The fourteen other observations were mostly obtained by interviews, or self-sampling. In most cases where on-board observers were present, high-grading was inferred by generating sigmoid curves describing the length-based retention of individuals, and comparing these to minimum landing size (MLS) regulations. If the length at which 50 % of the individuals was retained was higher than the MLS, this indicates high-grading. In 16 of the papers, the authors mentioned the existence of high-grading in the title or abstract of paper. For the remaining 28 papers, the existence of high-grading was mentioned in the text of 17 papers, or inferred by us in the other 11. In general we inferred the existence of high-grading when (1) length-structured discards observations showed that fish larger than the MLS was discarded, or (2) there was a clear size difference between landings and discards in the absence of an MLS.

High-grading is reported from a wide range of areas and jurisdictions. In Europe, high-grading is observed in fisheries ranging from the Mediterranean Sea to the North-east Atlantic. In North-America, high-grading is reported in the Gulf of Mexico and the East coast. Additional observations are from Turkey, Greenland, New Zealand, Australia, and South Africa. The existence of some form of individual quotas in the fishery was mentioned in 18 papers. Other fisheries where individual vessels were able to plan the use of quota, such as trip limits and bag limits, also reported high-grading. The relatively large number of papers that are associated with ITQs may in part result from our query. Also, the concerns about high-grading in ITQ fisheries may have spurred empirical research into high-grading in those fisheries. Especially in New Zealand, the benefits and costs of adopting ITQs (and

associated problems with high-grading) appear to have been well studied. Finally, high-grading was present in at least five fisheries with TAC management. The exact number cannot be inferred from the literature because not all studies exactly specify the management system, while even national annual quota are sometimes subdivided and made available to individual vessels by e.g. producer organisations. High-grading was not always related to fisheries management, even if extensive management was in place: the literature review resulted in seven papers that explicitly mentioned high-grading because of market condition. Four studies mentioned the constraining hold of the vessel to be a driver for high-grading (Pikitch et al. 1988; Neher 1994; Olbers and Fennessy 2007; Kristofersson and Rickertsen 2009). Lower price categories are high-graded, most often the smaller individuals. However, high-grading of larger individuals is also observed. Most of the observations on high-grading in the literature represent commercial fisheries using a wide range of gears. One paper explicitly studied and mentioned the existence of high-grading in recreational angling.

A second search was done for over-quota discarding, using the query 'TITLE-ABS-KEY (((("over-quota" OR "overquota") OR "individual quotas" OR ("individual" AND "quotas" AND "strategy") OR (discard* AND ("minimum landings size" OR "minimum legal length" OR "commercial species" OR "legislation"))) AND (fish*))'. The resulting papers were treated similar to the high-grading literature review. However, from the 314 papers resulting from this query, we found only five papers where over-quota discarding could be unequivocally inferred. Those papers where wording was sufficiently strong to suggest discarding of marketable fish after quota were exhausted are collated in Table 2. Some of these papers were also included in the high-grading observations. Many papers are not included in Table 2, because the discarding that resulted from constraining quotas can either be high-grading or over-quota discarding (e.g. Richards 1994; Baelde 2001; Brewer 2011; Cullis-Suzuki et al. 2012; Catchpole et al. 2014; Mace et al. 2014).

To summarise, the literature review shows that high-grading is reported from all over the world in a broad range of fisheries, although the number of reports with empirical evidence is small. High-grading occurs in fisheries that are restricted in landing their

Table 1 Summary of global high-grading papers reviewed

	References	Methodology	Management system	Gear	Main species	Area	Observation
1	MacDonald et al. (2014)*	On-board observers	Annual TACs	Twin trawl, Scottish seine	*Lepidorhombus whiffiagonis*	Shetland Islands, Scotland	Discards are predominantly above the minimum landing size. Discarding of megrim is on average 20 % by number of the total megrim catch in 2012
2	Keskin et al. (2014)	On-board observers	Closed areas and seasons, size limits	Bottom trawl	*Merluccius merluccius* *Mullus barbatus*	North-eastern Aegean Sea	Only 6 % of *M. barbatus* landed from the shallow shelf was < MLS, while 10 % of discarded specimens were > MLS
3	Feekings et al. (2013)	On-board observers	Size limits, mesh size regulations, TACs, seasonal closures	Bottom trawl	*Gadus morhua* *Platichthys flesus* *Pleuronectes platessa* *Limanda limanda*	Baltic Sea	Discarding > MLS occurs, and market price had a weak but significant effect on discard rates > MLS
4	Madsen et al. (2013)	On-board observers	Size limits, mesh size regulations, TACs	Bottom trawl	*Pleuronectes platessa*	Denmark (North Sea)	A considerable portion of the discards is comprised of individuals over MLS. This is most likely a result of catch restrictions
5	Hara (2013)*	Interviews	ITQs and licensing limits	?	*Sardinops sagax* *Engraulis encrasicolus*	West coast of South Africa	High-grading is influenced by minimum size of sardine suitable for canning and processing capacity of factories
6	Kraak et al. (2013)	Interviews	TACs, size limits, mesh size regulations	Bottom trawl, seines	*Gadus morhua* *Melanogrammus aeglefinus* *Merlangius merlangus* *Pollachius virens*	North Sea, West of Scotland, English Channel,	12 out of 14 respondents indicated they had discarded fish, cod and other species, as a result of the EU cod recovery plan, "(for example by high-grading)"
7	Tsagarakis et al. (2012)	On-board observers	Licensing limits, temporal and spatial closures, Mesh size regulations, size limits	Purse seine	*Sardina pilchardus* *Engraulis encrasicholus* *Scomber japonicas* *Boops boops*	Aegean and eastern Ionian Seas	The lengths at which 50 % of the individuals were discarded was > MLS for bogue and round sardinella
8	Bochenek et al. (2012)*	Interviews and on-board observers	Legal bag and size limits	Recreational angling	*Paralichthys dentatus*	Northeast coast of USA	16 % of anglers answered affirmatively when asked if they ever high-graded while 3.4 % reported high-grading during the previous fishing season
9	Feekings et al. (2012)*	On-board observers	Seasonal quotas and ITQs, size limits, mesh size regulations	Bottom trawl	*Gadus morhua* *Pleuronectes platessa* *Nephrops norvegicus*	Denmark (Kattegat)	Up to 1.9 cod and 14.2 plaice $\geq$ MLS were discarded per hour on average. Plaice discarding $\geq$ MLS was highest during quarter 1, indicating high-grading

Table 1 continued

	References	Methodology	Management system	Gear	Main species	Area	Observation
10	Depestele et al. (2011)*	On-board observers	Landings per Trip (LPT), size limits, mesh size regulations	Beam trawl	*Solea solea Pleuronectes platessa Gadus morhua Merlangius merlangus*	Belgium (North Sea)	Substantial cod and whiting discarding above MLS during periods with stringent LPT limitations
11	Scott-Denton et al. (2011)	On-board observers	Individual fishing quota, size limits, gear restrictions	Bottom longline, vertical line	*Epinephelus morio Epinephelus flavolimbatus Lutjanus campechanus Rhomboplites aurorubens*	Gulf of Mexico	Of the red grouper ≥ legal minimum size, 62 % were kept, 26 % were released alive, 8 % were discarded dead, and 3 % discarded in an unknown condition
12	Bök et al. (2011)	On-board observers	Size limits, beam length restrictions, mesh size regulations	Beam trawl	*Merluccius merluccius Pomatomus saltatrix Trachurus trachurus*	Turkey (Sea of Marmara)	Not all the marketable species in the fishery were landed, partly because there is no market demand for small specimens
13	Cetinić et al. (2011)	On-board observers	mesh size regulations, gear restrictions	Boat seine	*Spicara smaris Atherina hepsetus Boops boops*	Eastern Adriatic	Although there is no minimum landing size for several species, they were usually classified according to length and larger specimens were generally retained
14	Ulleweit et al. (2010)	On-board observers	Mesh size regulations, gear restrictions, size limits	Trawls	*Scomber scombrus*	Southeast coast of Ireland	Results of the study show that in some cases mackerel larger than the MLS is discarded, as larger mackerel is of higher market value
15	Poos et al. (2010)*	Voluntary log books	Annual ITQs, size limits, mesh size regulations	Beam trawl	*Solea solea Pleuronectes platessa*	Netherlands (North Sea)	In several fishing trips discarding marketable plaice was reported. Fishers state that discarding occurs because of low quota and low fish price
16	Kristofersson and Rickertsen (2009)*	Difference between modelled catch and auction data	ITQs	Longline and gillnet	*Gadus morhua*	Iceland	Discarding percentages of small marketable fish for gillnetters and longliners are 4.7 and 2.7 %, respectively. High-grading occurs mostly because of hold constraints

Table 1 continued

	References	Methodology	Management system	Gear	Main species	Area	Observation
17	Hamon et al. (2009)	Catch and effort logbook data	ITQs; input restrictions, size limits,	Traps	*Jasus edwardsii*	Tasmania	Discarding of big lobsters (more than 2 kg) occurs because the beach price of those lobster is much lower than for any other size category, and this only occurred since 2004
18	Clark and Kahn (2009)	On-board observers	ITQ, Size limits	Gillnet	*Morone saxatilis Alosa sapidissima*	Delaware River and Bay (USA)	84 % of the discarded striped bass were the minimum legal length or longer. Fish prices were lower early in the season, providing incentive for fishers to hold off landing fish
19	Welch et al. (2008)*	On-board observer estimates and anecdotal reports	Total allowable commercial catch	Hook and line	*Plectropomus* spp.	Great Barrier Reef, Australia	Anecdotal reports from fishers suggested that the size beyond which high-grading would become important was around 2 kg
20	Borges et al. (2008)*	On-board observers	Annual TAC	Pelagic trawl	*Scombrus scombrus Trachurus trachurus*	European waters	There is evidence of high-grading mackerel early in the year, mainly around the minimum landing size
21	Olbers and Fennessy (2007)	On-board observers	?	Otter trawl	*Fenneropenaeus indicus Otolithes ruber*	Tugela Bank, KwaZulu-Natal	Large quantities of small-sized individuals of O. ruber are discarded at sea, because it is uneconomic to market them and they would take up freezer space
22	Barnard and Pengilly (2006)***	On-board observers	Size limits, TAC, quota shares, limited number of pots per boat	Pots	*Paralithodes camtschaticus*	Bristol Bay	High-grading occurred for legal sized males: while new-shell individuals are retained, males with old and very-old shells are discarded
23	Borges et al. (2006)	On-board observers	Size limits, annual quotas	Otter trawl, beam trawl, Scottish seine	*Merlangius merlangus Melanogrammus aeglefinus Lepidorhombus whiffiagonis Pleuronectes platessa*	Waters around Ireland	Whiting were discarded at markedly longer lengths than the established MLS (23 cm) before 2000 and discard ogives obtained for haddock and megrim are consistent with high-grading for some areas and fleets
24	Punt et al. (2006)	On board observers	ITQs, gear restrictions, closed areas	Trawls	*Macruronus novaezelandiae Seriolella brama*	South-eastern Australia	Discards of blue grenadier were always small fish (<60 cm) although not all fish <60 cm are discarded. Hence, years of high discards can be attributed largely to availability of small (and largely unmarketable) fish

Table 1 continued

	References	Methodology	Management system	Gear	Main species	Area	Observation
25	Sanchirico et al. (2006)**	Pers. Comm.	ITQs	Danish seines, trawls	Macruronus novaezelandiae Hoplostethus atlanticus Seriolella punctata	south-eastern Australia	Discarding occurs for a range of reasons, including lack of quota, high-grading, damage to fish, and weak markets for landings
26	Ter Hofstede and Dickey-Collas (2006)	On board observers	Size limits	Pelagic trawls	Sardinella aurita Sardinella maderensis Sardina pilchardus Scomber japonicus Trachurus trecae,	Mauritania	Discards consisted mainly of commercial sizes and species. When catches were high commercial fish of low abundance was discarded. Also if fish lost its quality it was discarded
27	Santojanni et al. (2005)**	On-board observers	?	Pelagic trawlers and purse-seines	Sardina pilchardus Engraulis encrasicolus	Adriatic Sea	In certain fleets, smaller sardines were often discarded while larger sardines were retained. Increased discarding of larger size classes at larger catches suggested a market driven incentive
28	Gray et al. (2005)	On-board observers	Size limits, mesh size limits	Gillnets	Mugil cephalus, Girella tricuspidata Acanthopagrus australis Platycephalus fuscus	New South Wales (Australia)	Discarding of species without size limits was length based with the smallest individuals mostly being discarded, but because of their low market value, this was often dependent on total catch
29	Machias et al. (2004)*	On-board observers	MLS-regulations and seasonal closures	Trawl	Trachurus mediterraneus Trachurus trachurus Pagellus erythrinus	Eastern–central Mediterranean Sea	For species with low commercial value the estimated L_{50} was higher than MLS. Lower market price resulted in higher discard sizes
30	Allain et al. (2003)	On-board observers	?	Trawl	Coryphaenoides rupestris	Off the West coast of the British Isles	In the absence of an MLS, discarded fish are smaller on average than landed fish
31	Gray and Kennelly (2003)*	On-board observers	Spatial and temporal closures, mesh size regulations, size limits	Beach-seine	Gerres subfasciatus Meuschenia trachylepis Meuschenia chinensis Sillago maculate Pelates sexlineatus	South-eastern Australia	Although there is no MLS for these species only the larger individuals were retained. These larger individuals were retained for sale to satisfy particular markets

Table 1 continued

	References	Methodology	Management system	Gear	Main species	Area	Observation
32	Rochet et al. (2002)*	On-board observers and self-sampling	MLS-regulations and mesh size regulations	Bottom trawl	Pleuronectes platessa, Gadus morhua, Merlangius merlangus, Lepidorhombus whiffiagonis	France (Celtic Sea)	For most species L_{50} was larger than the minimum legal landing size. The difference was generally small, but as large as 7–9 cm for hake and whiting
33	Gray (2002)**	On-board observers	MLS regulations, mesh size regulations, effort regulations	Gill nets	Liza argentea, Pseudocaranx dentex	Australia (New South Wales)	Discarding of L. argentea and P. dentex that have no MLS was size-based (and probably market driven), with only the larger individuals being retained for sale
34	Dewees (1998)*	Interviews	ITQs	Gill nets, longlines, Trawls, seines	?	New Zealand	In 1995, 25 % of the interviewees indicated high-grading was a problem of ITQs in New Zealand
35	Fujita et al. (1998)**	Anecdotal reports	ITQs,	Longlines	Anoplopoma fimbria, Hippoglossus stenolepis	British Columbia	Anecdotal reports indicate that there was not much evidence of high-grading in these fisheries during the first season managed under ITQs
36	Stratoudakis et al. (1998)*	On-board observers	Quotas, MLS-regulations and mesh size regulations	Bottom trawl and seines	Melanogrammus aeglefinus, Merlangius merlangus, Gadus morhua	UK (North Sea)	Haddock L_{50} was highest in a period when landings were close to quotas
37	Annala (1996)	Industry sources	ITQs	Inshore and deep-water fisheries	?	New Zealand	High-grading has occurred when a premium price is paid for fish of a certain size or quality and when small fish are discarded because of their unsuitability for processing
38	Neher (1994)	?	Individual quotas	Traps and longlines	Anoplopoma fimbria	Canadian continental shelf Pacific ocean	Year-round fishing has relaxed the pace of fishing, leading to less high-grading (cargo space is not so much at a premium)
39	Boyd and Dewees (1992)	?	ITQs	?	Chrysophrys auratus	New Zealand	High-grading at sea occurred, with lower-grade fish being dumped. Fishermen reasoned that if their catches were limited, they needed to fetch high prices for landed fish

Table 1 continued

	References	Methodology	Management system	Gear	Main species	Area	Observation
40	Lehmann and Degel (1991)**	On-board observers	quotas	Bottom trawl	*Pandalus borealis*	Greenland	Shrimp is discarded partly due to low quality and partly due to small size, in order to high-grade the catch
41	Muse and Schelle (1989)**	?	Individual quotas	Otter trawl	*Gadus morhua Pandalus borealis*	Gulf of St. Lawrence	Managers believe that there is some high-grading in the form of fishers making exploratory tows. Tows producing too many small fish are released and fishers move on. Managers do not appear to be concerned over this high-grading
42	Muse and Schelle (1989)**	?	Individual quotas	Trawls, gillnets, seines, and hooks and lines	*Sander vitreus*	Lake Erie	Markets were accustomed to using fish of 16–18 inches. When the stock composition changed the markets were not accustomed to larger fish of lower ex-vessel price. Those fish were consequently discarded
43	Muse and Schelle (1989)**	?	Individual quotas, capacity limitations	Gill nets and trap nets	*Salvelinus namaycush*	Wisconsin lake superior	The quotas are measured in numbers of fish while the price per kilo varies little among size classes, resulting in high-grading. Officials estimate that reported landings underestimate mortality by 30–50 % due to high-grading
44	Pikitch et al. (1988)**	On-board observers	Trip quotas	Groundfish trawl	*Anoplopoma fimbria*	USA	A significant fraction of the total discard was attributed to high-grading because processors paid a higher price for the larger fish than for smaller fish

L_{50} is the estimated length at which 50 % of the caught fish is discarded

* These papers explicitly mention the existence of high-grading in the fishery in the title or abstract

** These are references in papers resulting from the Scopus query

Table 2 Summary of global over-quota discarding papers reviewed

References	Methodology	Management system	Gear	Main species	Area	Observation
Kaplan et al. (2014)	?	TAC, bimonthly cumulative landings limits, spatial closures	Trawl	*Microstomus pacificus* *Anoplopoma fimbria*	US West coast	Captains could freely discard species for which they had exhausted their landings limit. Successive tightening of landings limits caused high regulatory discard rates
Baudron et al. (2010)	?	TACs	Longline, pair trawl	*Gadus morhua* *Melanogrammus aeglefinus* *Pollachius virens*	Faroe Islands	The TAC system resulted in extensive discarding when single-species quotas were filled
Clark and Kahn (2009)	On-board observers	ITQ, Size limits	Gillnet	*Morone saxatilis* *Alosa sapidissima*	Delaware River and Bay (USA)	If the netters reached their striped bass quota they discarded striped bass and kept other valuable species
Sanchirico et al. (2006)	Pers. Comm.	ITQs	Danish seines, trawls	*Macruronus novaezelandiae* *Hoplostethus atlanticus* *Seriolella punctata*	South-eastern Australia	Discarding occurs for a range of reasons, including lack of quota, high-grading, damage to fish, and weak markets for landings
Punt et al. (2006)	On board observers	ITQs, gear restrictions, closed areas	Trawls	*Macruronus novaezelandiae* *Seriolella brama*	South-eastern Australia	Years of high discards of blue warehou are related to operators having insufficient quota to cover catches

otal catch due to management, market or physical constraints. In the following sections, we will describe a conceptual model for quantifying high-grading and over-quota discarding.

Simulation model

In order to gain insight as to the mechanisms inducing high-grading and over-quota discarding behaviour, we used a dynamic-state variable model (DSVM; Houston and McNamara 1999; Clark and Mangel 2000). Dynamic state variable models have been applied in a variety of fisheries to analyse vessel fishing behaviour (Gillis et al. 1995; Poos et al. 2010; Dowling et al. 2012; Batsleer et al. 2013). In such models, the optimal annual strategy of fishing vessels operating in fisheries under individual quotas and in a stochastic environment is evaluated. Our model differs from earlier models in that: (1) it includes size structured fish catches, and (2) ex-vessel price by size class fluctuates over time. The utility function assumes that fishers are profit maximizers. Although other

incentives may play a role in decision making, there is empirical evidence for profit as a useful metric of utility (Robinson and Pascoe 1998).

We model bottom trawl fishers targeting three size-structured fish species (sole, plaice and cod), where catches are divided into market categories based on size (Table 3). The size classes have seasonally variable auction prices (Fig. 1). The size structure and species composition of the catch is thus an important determinant of the value of a catch. The expected catch rates of each species/size class combination is defined by probability distributions that are functions of fishing location and season, reflecting spatial and seasonal variations in abundance. Parameters describing the probability distributions are estimated from historic data.

In the model fishers maximise their annual net revenue[1] by making weekly decisions on (1) to go fishing or not; (2) fishing location; and (3) how much

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[1] i.e. the revenue minus variable costs, given that fixed costs do not impact short term decisions.

Table 3 Marketable size classes of the three target species

Size class	Plaice (cm)	Sole (cm)	Cod (cm)
1	>41	>38	>88
2	35–41	33–38	72–88
3	31–35	30–33	55–72
4	27–31	27–30	46–55
5		24–27	35–46

to discard given their annual landing quota and restrictions on discarding. A weekly time scale is chosen because most fishing trips last from Monday to

catches are discarded) or 2^{31} (all catches are landed) for each combination of species and size class. The catches are modelled as a random variable having a negative binomial distribution with a mean $m_{s,n,a,t}$ per area, week, species and size class, and a dispersion parameter per species r_s. The means and dispersion parameters are estimated from logbook data from the case study fleet. The probability $\lambda_{s,n}\left(l_{s,n}, d_{s,n}, a, t\right)$ of making a landings $l_{s,n}$ of amount χ is a function of the area choice in a given week, and the discarding decisions such that it has following cumulative distribution function

$$\lambda_{s,n}\left(l_{s,n} \leq \chi, d_{s,n}, a, t\right) = f\left(\chi; d_{s,n}, m_{s,n,a,t}, r_s\right)$$
$$= \begin{cases} \sum_{l_{s,n}=0}^{\chi} \left(\dfrac{r_s}{r_s + m_{s,n,a,t}}\right)^{r_s} \dfrac{\Gamma\left(r_s + l_{s,n}\right)}{l_{s,n}! \Gamma\left(l_{s,n}\right)} \left(\dfrac{m_{s,n,a,t}}{r_s + m_{s,n,a,t}}\right)^{l_{s,n}}, & \text{for} \quad 0 \leq \chi < d_{s,n} \\ 1, & \text{for} \quad \chi \geq d_{s,n} \end{cases} \quad (1)$$

Friday in the bottom trawl fishery that serves as a case-study (Rijnsdorp et al. 2011).

For simplicity we assume that there is one individual quota restricting a single species. In this case we chose plaice given observations of discarding of marketable plaice in the Dutch beam trawl fishery (Poos et al. 2010). Historically, the plaice quota constrained the fishery in the 1990s, leading to changes in the targeting behaviour of the fleet (Quirijns et al. 2008). The cumulative landings in weight of species s of the set of species S and size class n of N size classes is denoted by $L_{s,n}$. The cumulative landings in weight of the quota constrained species, that we define by $s = 1$, represents the state of the individual, denoted by L and equal to $\sum_N L_{1,n}$.

The landings are determined by the discarding decision and the catches which in turn depend on the spatial and temporal distribution of all size classes within the 3 species. Each week t individuals choose to visit fishing area a and to keep or discard any combination of the size classes caught of the different species. This behaviour is defined by a matrix d, of dimension S and N. Catches above $d_{s,n}$ are discarded. To limit the number of discarding options, the values of $d_{s,n}$ are restricted to 0 (all

where $\Gamma(\cdot)$ is the gamma function (Press et al. 2002). The optimal strategy in each week of the year, denoted by t depends on the cumulative landings of the quota species. These landings affect the possibility to continue fishing and land fish without exceeding the annual quota. The expected net revenue at the end of the year is linked to the choices in the preceding weeks through a value function between time t and the end of year T. The value function represents the maximum expected net revenue to be made between week t and the end of the year T and depends on the state of the individual L, the amount of quota U for the quota species, the fine per unit weight for exceeding the quota F, and is expressed as $V(L, U, F, t)$. Individuals exceeding their quota get a fine that depends on the quota overshoot. At the end of the year T, after all fishing has been completed, the value function $V(L, U, F, T)$ is defined by the fine of overshooting the quota

$$\Phi(L, U, F) = \begin{cases} 0, & L \leq U \\ -(L - U)F, & L > U \end{cases}. \quad (2)$$

For each week before T, the expected net revenue is determined by the value function, the weekly gross revenue and the costs of fishing.
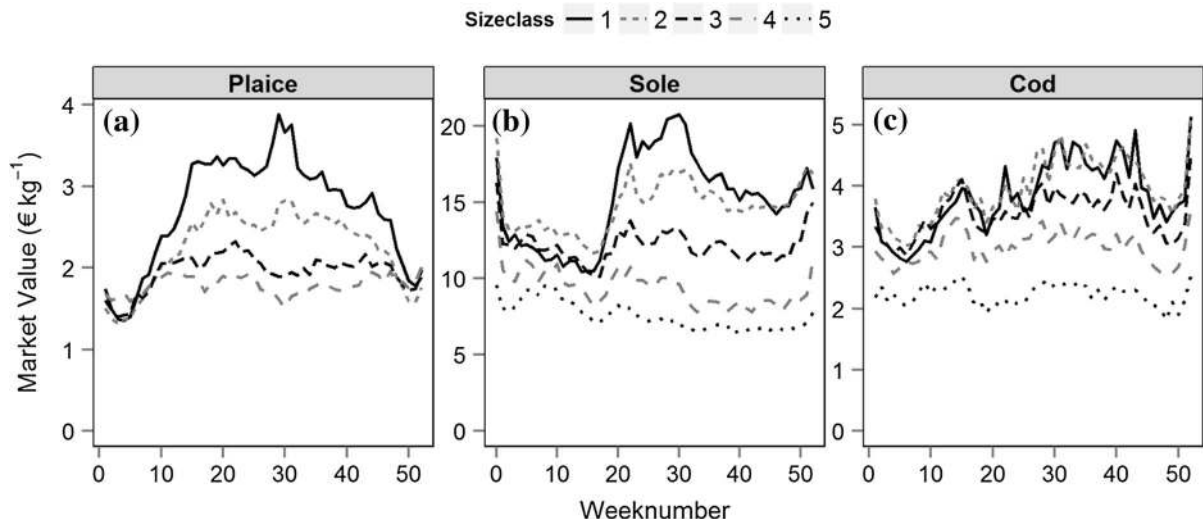
Fig. 1 Seasonal variation in the ex-vessel price of the five size classes of **a** plaice, **b** sole and **c** cod. Size classes are ordered from 1—large to 5—small (adapted from Rijnsdorp et al. 2012)

For all times t preceding T we use stochastic dynamic programming to find the optimal solution by backward iteration of the net expected revenue H from t to the end of the year considering the choices a and d and the state L at t and optimal choices in subsequent weeks

$$H(L, U, F, t; a, d) = R(a, d, t) * \kappa - C(a) \\ + \mathbb{E}_{a,d}[V(L', U, F, t + 1)], \quad (3)$$

where $R(a, d, t)$ is the expected direct contribution of the gross revenue that follows from the sales of fish in a week resulting from choices a and d, and the prices of fish in that week $p_{s,n}(t)$: $R(a, d, t) = \sum_S \sum_N \lambda_{s,n} (l_{s,n}, d_{s,n}, a, t) * l_{s,n} * p_{s,n}(t)$. The term κ represents a factor accounting for the additional revenue obtained from landing marketable species that are not explicitly modelled. The term $C(a)$ represents the variable costs in a week resulting from the choice of fishing area a. The term L' reflects the change of the state L resulting from the weekly landings for the quota species, $\sum_N l_{1,n}$. The term $\mathbb{E}_{a,d}[V(L', U, F, t + 1)]$ denotes the expected future value taken over all possible states resulting from choices a and d. The optimal choice is given by

$$V(L, U, F, t) = \max_{a,d}\{H(L, U, F, t; a, d)\}. \quad (4)$$

Hence, starting with $V(L, U, F, T) = \Phi(L, U, F)$ we can iterate backwards in time and find the optimal

choice in terms of location and discarding behaviour for all possible states, combining the net revenue obtained from the sale of fish and costs of a fishing trip and the effect of the annual fines when exceeding annual quota.

We explore high-grading and over-quota discarding decisions of conventional beam trawlers under a range of individual plaice quota (100–800 tonnes year^{-1}).

Case study data

Marketable catch and effort data by fishing trip are obtained from logbooks and individual sale slips for large Dutch beam trawl mixed fishery (>1500 hp). Restrictive TACs in recent years may bias port-based catch rate observations of marketable fish because of over-quota discarding and high-grading (Rijnsdorp et al. 2008; Poos et al. 2010). Therefore, log book data from 1970 to 1974 are used, a period where there were minimum mesh and landing sizes, but no TACs (Daan 1997). TACs were introduced only in 1975 for this fishery (Salz 1996). The data are collected on a trip by trip basis and include the landed weight of marketable fish by species and size category, fishing ground (ICES rectangle, ca. 30 × 30 nautical miles), fishing effort (hours fished), fishing gear, vessel length, and engine power. Data for plaice, sole and cod are analysed.
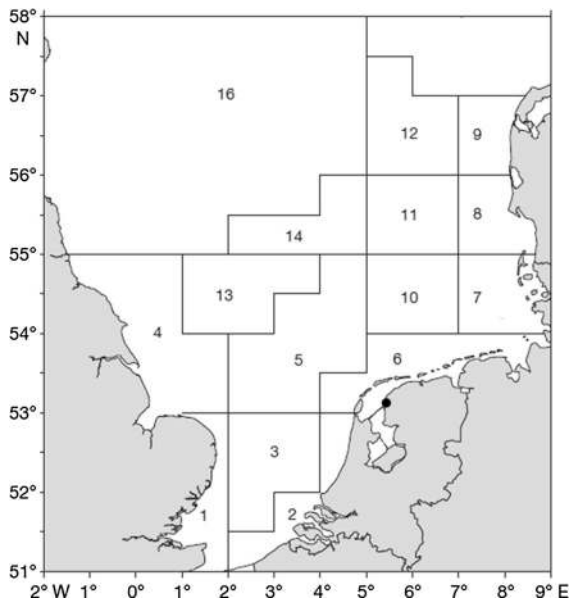
Fig. 2 Fishing areas, *black point* indicates the location of the fishing harbour used in the model

Fishing areas are defined by aggregating ICES rectangles, similar to (Rijnsdorp et al. 2012; Fig. 2). The large Dutch beam trawlers are prohibited from fishing in the Plaice Box (areas 6–9) and the 12 nautical mile zones (areas 1 and 2). These areas are excluded from further analysis. Fishing effort is determined by summing the fishing time and the travel time per week. The fishing time for large trawlers is estimated at 65 h per week based on the effort dataset. Travel time is calculated by taking the distance from the harbour of departure to each of the fishing grounds and assuming a steaming speed of 12 nautical miles h^{-1} (Poos et al. 2013).

Trawl catch rates

Seasonal catch rates per fishing area for the different size classes of plaice, sole, and cod in the beam trawl fleet are described using generalized additive models (GAM, Wood 2006). Catch rates are modelled using the weight of the catches (kg) from the logbooks per size class per fishing trip as a response variable while effort (h) is used as offset variable (Wood 2006). By using a negative binomial GAM with a logarithmic link function we allow over-dispersed data and zero-observations (Wood 2006; Zuur et al. 2009). The model to estimate catch by size class n and area a per week is applied to the data per species s:

$$m_{s,n,a,t} = a + gear + f_1(n,t|a) + \log(engine\ power) + f_2(sweek,n) + offset(\log(effort)),$$

$$(5)$$

where f_1 and f_2 are smooth functions based on a tensor product smoother (Wood 2006). The tensor product smoother $f_1(n, t|a)$ is based on a cubic regression spline for size class and a cyclic cubic regression spline for week by area. The cubic regression spline for week by area results in equal values and slopes at the beginning and end of the year (Wood 2006). The maximum degrees of freedom for both smoothing terms is limited (k = 4) to prevent over-fitting. The covariate *engine power* is the log-transformed horse power and is included because of its influence on the catch efficiency. The covariate *gear* is included to differentiate the catch efficiencies between the beam and otter trawl. The covariate *sweek* within the second smoothing term $f_2(sweek, n)$ is week number since the start of the data collection (1 January 1970) and captures the gradual changes in biomass for each size class over time as a result of recruitment and mortality. In addition to the estimates of the mean catches $m_{s,n,a,t}$ the model also returns the estimated dispersion parameter per species r_s. All analyses were done using the R statistical program (version 2.12.1; R Core Development Team 2013). The "mgcv 1.7-29" package was used for the GAM model for trawl catch rates (Wood 2011).

The GAM model is used to estimate the spatial and temporal patterns in catch rates (kg $week^{-1}$) for each size class of each target species in the period 1970–1974. To obtain values representative for the time period in which the economic data is collected, the predictions are rescaled with a factor calculated by dividing the mean of the absolute values of the spawning stock biomass (SSB) of 1970–1979 by the mean of the absolute values of the SSB of the past 10 years (2004–2013).

Economic data

The three species modelled represent 82 % of the gross revenue of the Dutch beam trawl fleet. Mean weekly market values for the marketable size classes are calculated from sale slip data from 2003 to 2007 (Fig. 1). The fine for overshooting the individual quota is set to 320 € kg^{-1}. Such a high fine ensures full compliance to the individual quotas in the model. Costs of discarding in terms of additional sorting time are assumed to be negligible.

Table 4 Variable costs of the beam trawl used in the simulation

Variable fishing costs	Value	Units
Fuel costs	6400	€ day^{-1}
Gear maintenance	347	€ day^{-1}
Landing costs	0.24	€ kg^{-1}
Employment costs	33	%
Other variable costs	0.05	

Information on the cost structure of large beam trawl vessels (2008–2010) is obtained from LEI (Agricultural Economic Research Institute). The variable costs represent about 75–80 % of the total annual costs and include fuel costs, gear maintenance costs, cost of handling and transportation of landings, crew shares and other variable costs, such as auction and harbour fees. Fuel costs depend on effort and fuel price and is estimated to be approximately €6400 day^{-1} (van Marlen et al. 2014). Gear maintenance cost is assumed

proportional to fishing effort, landing costs proportional to the total weight landed, and other variable costs proportional to the gross revenue. Crew shares are predominantly determined by an agreement between the owner and his crew. Crew share is calculated after fuel, handling and transportation costs are deducted from the gross revenue. Values used for variable costs in the simulation model are presented in Table 4.

Results

Trawl catch rates

The input data of the simulation model consists of the estimates of the weekly catch rates for the different size classes of plaice, sole and cod. Distinct seasonal patterns between the different size classes for each of the three target species are observed (Fig. 3). Large plaice (>31 cm, size classes 1, 2 and 3) exhibit a
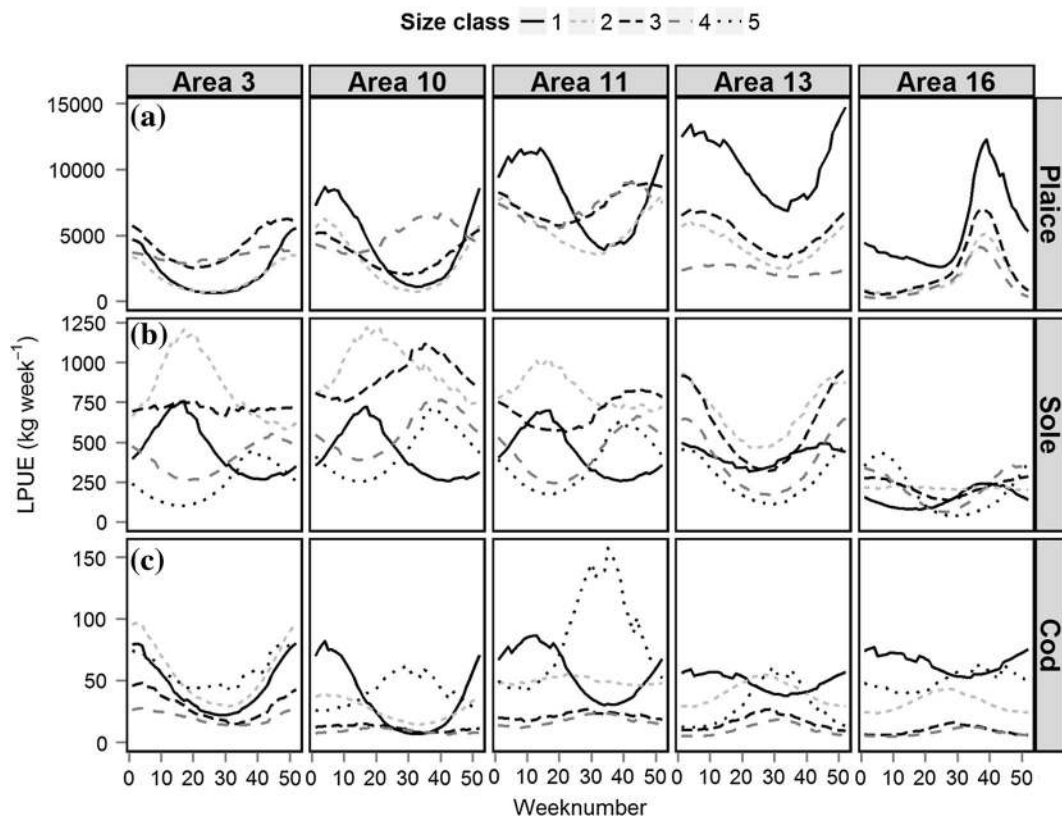

Fig. 3 Seasonal variations in the landings per unit of effort (LPUE kg week^{-1}) of the size classes of **a** plaice, **b** sole and **c** cod. Size classes are ordered from 1—large to 5—small
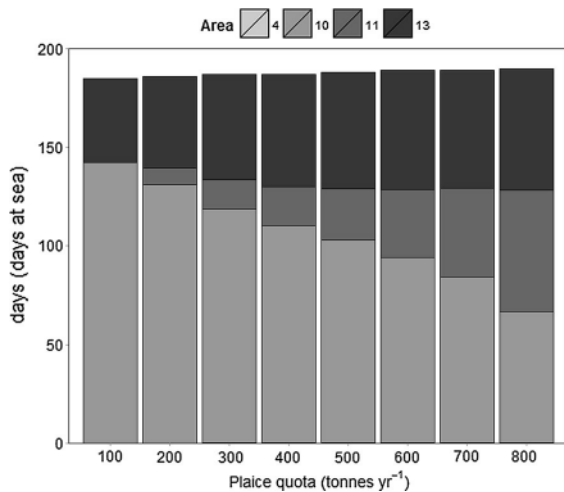
Fig. 4 Annual fishing effort (days at sea) and fishing areas selected as a function of the plaice quota for a beam trawler under a management regime where discarding is allowed. Area 4 is only selected for quotas >300 tonnes year^{-1}. The effort allocated to this area is extremely limited. The majority of effort is allocated to areas 10, 11, and 13

similar seasonal distribution in most areas with low catch rates during spring and summer and high catch rates in the winter months. The smallest marketable size class (27–31 cm, size class 4) exhibits the opposite pattern with higher catch rates in spring and summer and lower catch rates in winter months. In addition, the catchability of large plaice appears to be higher in the more central and northern areas of the North Sea (e.g. area 13, Southern Dogger Bank) compared to the more coastal areas (e.g. area 3, Southern Bight).

For sole, the catch rates of the larger size classes (>33 cm, size class 1 and 2) peak in winter and early spring, while the smaller size classes (size classes 3, 4, and 5) show a seasonal pattern, with a peak in summer and early autumn similar to that for smaller plaice. Sole catch rates are highest in the North Sea areas closer to the coast such as the Southern and German Bight (areas 3 and 10). Within the more central and northern areas of the North Sea catch rates are lower.

The highest catch rates of cod (all size classes) within the coastal areas (area 3, southern Bight) are observed in December and January. A different pattern emerges for the offshore areas such as the German Bight (area 10 and 11) where the catch rates of the smallest size class (35–46 cm) peak in late spring and summer while large cod (88+ cm) catch rates peak in

winter and early spring. These patterns although still present, level off in most northern areas such as the Dogger Bank and Central North Sea (area 13 and 16). Catch rates of intermediate size classes (3 and 4) of cod are consistently low throughout the year for all areas.

Simulation model

The catch rates for the different size classes of plaice, sole, and cod are used as input to the model, together with the cost structure for the different choices. The model is run for individual plaice quotas ranging from 100 to 800 tonnes. No publicly available information exists on the amount of individual quotas per vessel, hence we used the 2013 plaice landings of the fishing vessels of the Dutch harbor Urk as a proxy for individual quotas. The landings ranged between 160 and 795 tonnes per vessel, with a median of 629 tonnes. Runs are used to evaluate the effects of different landing ITQ levels on effort allocation, and discarding behavior.

Effort allocation

Increasing individual quota for the limiting species results in a very small increase in overall fishing effort per vessel. However, there is a substantial reallocation of fishing effort over the fishing areas (Fig. 4). A low individual quota results in a concentration of fishing effort in the German Bight (area 10) which is one of the areas open for fishing close to the harbor. As individual quotas increase, more effort is allocated to areas 11 and 13 at the expense of effort in area 10. This shift to northern fishing grounds can be explained by the availability of large plaice in those areas.

Catches of marketable fish

The marketable catches comprise landings and discards (over-quota and high-graded fish). Landings are perfectly controlled by the individual quota because fines for overshooting quota are much higher than the value of the extra catch and the risk of getting fined for overshooting is 100 % in the model. Discarding of marketable plaice occurs in two different ways: over-quota discarding, when quota is exhausted and discarding occurs for all size classes, and high-grading, when fishers have quota available and discard
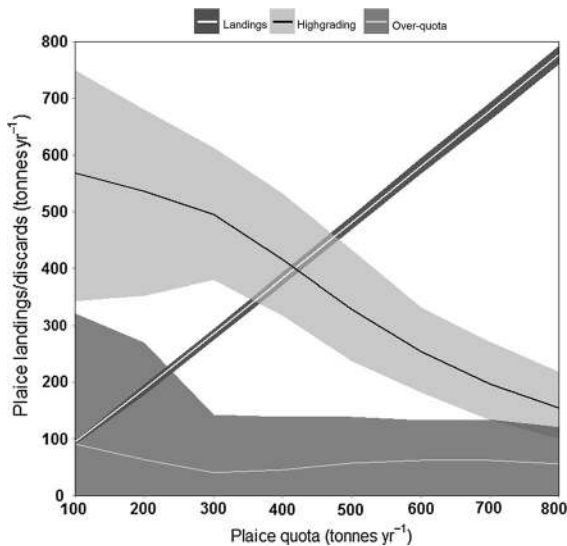
Fig. 5 Landings and discards (tonnes year^{-1}) of a beam trawler as a function of the plaice quota. Discards are distinguished between high-grading and over-quota discarding

certain size classes. The model results indicate that over-quota discarding is largely unaffected by the amount of quota available, while high-grading increases with a decreasing quota (Fig. 5).

All over-quota discarding occurs at the end of the year (Fig. 6). When more quota is available, fishers take more time to reach their quota limit and therefore

over-quota discarding occurs later in the year. In our case study system, there is substantial seasonal variation in the prices of the different size classes for the limiting species. At the beginning of the year prices for all size classes are lower than later in the year. In addition, larger fish generally fetch higher prices than smaller fish, except for the beginning of the year when the opposite is observed. As a result of the seasonal variability in prices, the highest amount of fish being high-graded is in the first weeks and at the end of the year when fish prices are low (Fig. 6). With low quota fishers will high-grade year-round. An increase in quota systematically reduces the occurrence of high-grading throughout the year. The decrease in high-grading first occurs in the middle of the year (price of fish is highest) and then at the end of the year.

The size distribution of the catches, landings and discards of marketable plaice is influenced by the amount of quota (Fig. 7). Each of these distributions depends on the allocation of effort to areas or weeks characterised by different size composition and the discarding choices made by the individual skippers. At high quota, there are relatively few discards of the smallest size classes. Reductions in quotas result in an increasing amount of small fish being high-graded. The relationship between the discarding of small fish and the quota is far from linear and results from the
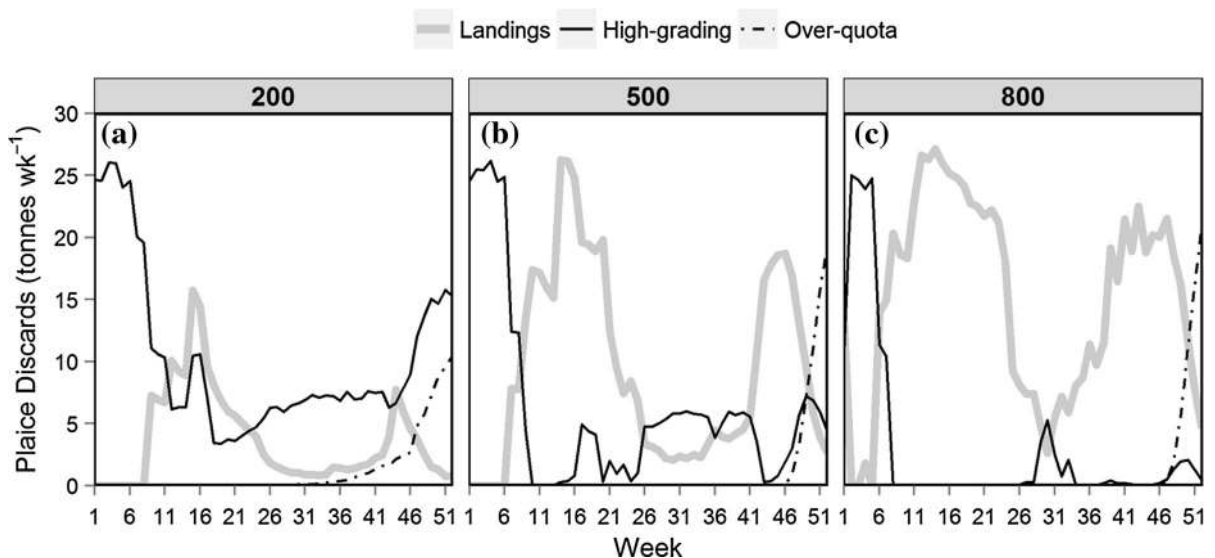

Fig. 6 Weekly landings and discards for a beam trawler at a plaice quota of **a** 200, **b** 500 and **c** 800 tonnes year^{-1}. High-grading and over-quota discarding are depicted separately
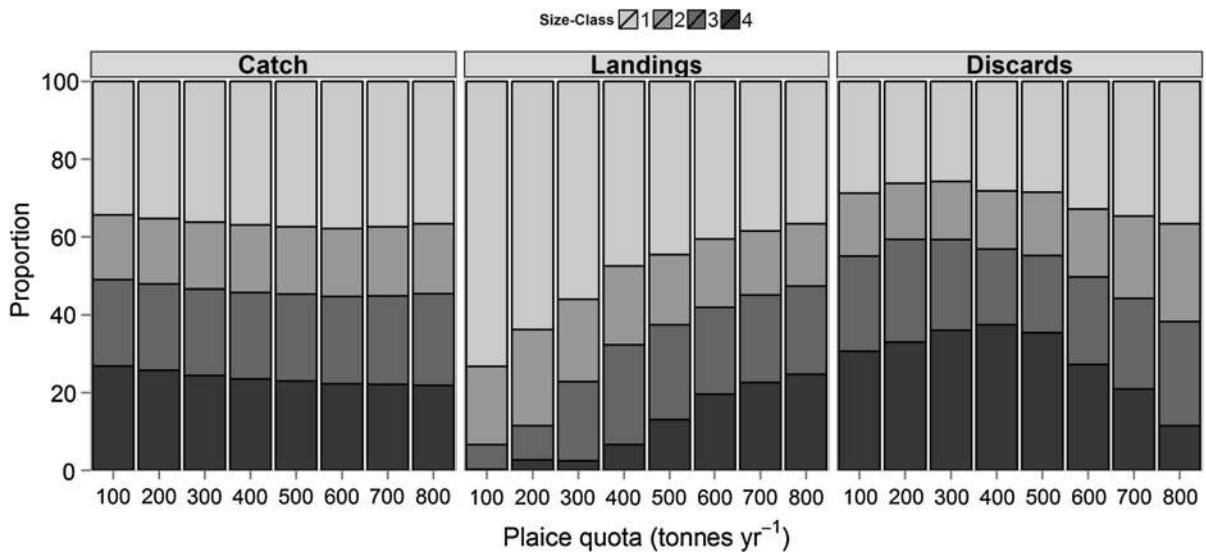
Fig. 7 Proportion of marketable size classes in the catch, landings and discards for a beam trawler as a function of plaice quota

Discussion

Having started with a broad query which produced 336 papers, our review of literature resulted in 44 papers describing observations of high-grading. Our findings that only 44 papers contained high-grading observations corroborates Boyd and Dewees (1992), who stated that even if high-grading is expected, it is difficult to detect and prove: on board observers may influence the fishing behaviour of skippers and reduce the probability of detection (Liggins et al. 1997; Benoît and Allard 2009). Despite this problem, the positive reports reviewed shows that high-grading occurs worldwide in both pelagic and demersal fisheries, in fisheries with and without ITQs, in commercial and recreational fisheries, and in single-species and mixed fisheries. In all these fisheries, we expect differences in utility among different size classes of fish (Zimmermann and Heino 2013) or among different periods within the quota planning horizon (Rijnsdorp et al. 2012), being one of the prerequisites for high-grading (Branch et al. 2006). We expect the incentive to high-grade to depend on

interplay between the seasonal differences in availability and ex-vessel price of the different market categories.

the price differential among the different size classes (Kingsley 2002).

Most of the fisheries in which high-grading was observed are mixed fisheries managed under individual catch quota systems. This is not surprising given that individual quotas allow individuals to maximise the economic return on their quota by high-grading the cheaper parts of the catch and increasing the average return per unit quota (Gillis et al. 1995; Squires and Kirkley 1995). These fisheries allow individual fishers to plan the use of their quota, being it on an annual, trip or other time-period. The mixed nature of the fishery allows income from a fishery even if parts of the limiting quota species are discarded. Meanwhile, discarding of undersized fish may also occur in mixed fisheries if minimum size limits of different species and mesh size regulations do not match (Daan 1997).

Our review suggests that high-grading often occurs because of quota constraints. For example, in the North Sea, megrim (*Lepidorhombus whiffiagonis*) is high-graded and the likelihood of this species being discarded decreases significantly with increasing quota (Macdonald et al. 2014). Likewise, the amount of high-grading for cod in the North Sea by Belgian fishers decreased nearly linearly with trip quota (Depestele et al. 2011). Elsewhere, high-grading is suggested as a problem of limiting individual quota (Dewees 1989, 1998). In a few cases, market

conditions were pinpointed as the important driving force for high-grading. This difference in the frequency of occurrence could suggest that fisheries strive to find markets for as much of their catch as possible.

We found substantially fewer papers that described observations of over-quota discarding than those describing observations of high-grading. This could be due to several reasons. First, high-grading can occur for reasons of constraining quota or market conditions, while over-quota discarding only occurs because of limiting quota. Second, we decided to only include papers where the wording unequivocally indicated that discarding occurred after quotas were depleted. Finally, we expect that fishers will use price differences in market classes and fishing seasons to high-grade their catches, rather than discard the entire catch including the high-valued market categories at the end of the year.

The dynamic state variable model simulates a mixed fishery under individual quota constraints with a price differential among different size classes. Seasonal and size variations of the prices result in the discarding of specific size classes if quota are restrictive. Importantly, the model results indicate that the amount of high-grading is sensitive to the amount of quota, while over-quota discarding is almost constant irrespective of the quota level. The reason for this difference is that high-grading is the result of fishers planning their use of available quota. Over-quota discarding is the result of the stochastic nature of the catches which prevents fishers from planning their catches perfectly. Hence, we hypothesize that the amount of over quota discarding is a function of the variability in the catch rates. In an environment with price differences among size classes or seasons, over-quota discarding will decrease with decreasing uncertainty in catch rates.

By incorporating size structure in the resources, seasonally variable catch rates and fish prices we have improved the ability to explore the consequences of quota management on the discarding of marketable size classes compared to earlier studies (e.g. Gillis et al. 1995; Poos et al. 2010; Batsleer et al. 2013). Some simplifying assumptions, however, still remain. In our study, six assumptions are relevant. First, we assume that individual fishers maximize their economic performance while fully complying with management regulations. Non-compliance to quota

regulations would result in a lower amount of high-grading and over-quota discarding if fish are landed illegally. Second, the model ignores quota leasing. Such quota leasing could reduce high-grading and over-quota discarding if fishers who are forced to discard can buy quota from vessels with excess quota because of low catch rates. This quota leasing would not occur in situations with low quota when all vessels are constrained by the quota, or in situations with high quota when no vessels are constrained. Third, the model does not incorporate any frequency or density dependent effects, such as exploitation and interference competition, which may negatively affect catch rates (Rijnsdorp et al. 2000; Gillis 2003), or price formation (as in e.g. Dowling et al. 2012). Fourth, only three target species (i.e. plaice, sole and cod) are included in our model of which only plaice has a catch quota affecting the behavior of a fisher while in reality, sole and cod are also managed by quota. In addition, location choice may also be affected by the availability of other components of the mixed fishery such as turbot (*Scophthalmus maxima*) and brill (*Scophthalmus rhombus*; Gillis et al. 2008). Fifth, we assume that the hold capacity does not constrain the landings within a fishing trip. Finally, the model assumes that the proportional catch of different size categories is fixed within each area and season. In reality, the fishers may have the additional behavioral flexibility of changing the proportional catches of different size categories by changing the mesh size of the gear. However, in our case study the effect of changing the mesh size is substantially different for the different species. Increasing the mesh size has a much stronger effect on the catches of the more valuable sole than it has for plaice, because of the difference in shape between the two species (Van Beek et al. 1983).

Our model shows that fishers can respond to changes in individual quota by reallocation of effort and discarding part of their marketable catch. These results are in line with previous studies showing the adaptability of fishers in a mixed fishery to reallocate effort in space and time thereby optimizing their catch composition relative to the size of the quota (Poos et al. 2010; Batsleer et al. 2013). Our model results indicate that substantial high-grading may occur at the beginning of the year, long before quota are exhausted as a result of seasonal variation in the price of plaice. During the spawning period, the price of the larger size classes of plaice is relatively low as compared to the

smaller size classes due to the presence of a large gonad and a lower meat quality of spawning fish (van Overzee and Rijnsdorp 2015). High-grading also occurs during other parts of the year, in particular in late summer and autumn when a new year class recruits to the fishery and the high catch rate of the smallest size class coincide with a relatively low price compared to the larger size classes. The amount of over-quota discarding is more limited and by definition concentrated at the end of the year. This over-quota discarding is the result of the uncertainty in the catch rates, preventing individuals from optimizing the use of quota by high-grading alone.

In the model, individual landing quotas are strictly enforced by means of high fines while high-grading is allowed. In reality, high-grading is prohibited in the North Sea since 2009. To test whether a ban on high-grading can be enforced effectively, we estimated the number of observed infringements from the campaign results of the joint deployment plan of the European Fisheries Control Agency (EFCA). All campaign results in terms of number of on board inspections, number of infringements of fisheries conservation measures, and the nature of the infringement are published on the EFCA website. Based on the reports from the period 2009–2012, it seems that inspections in the North Sea rarely detect high-grading: The 3000 inspections carried out, recorded approximately 350 infringements, of which only one was related to high-grading (EFCA 2014). Although this could indicate high-grading in these fisheries occurs rarely, we infer that it reflects the difficulty of detection because (1) high-grading can only be detected by fishery inspectors when fishers are caught in action and (2) the time needed to process the catch on board is relatively short.

To our knowledge, our study is the first to model discarding of marketable fish while explicitly distinguishing between high-grading and over-quota discarding. Given the difficulties in obtaining reliable estimates of the amount of marketable fish that is discarded, modelling studies can provide the urgently required insight as to the quantity, the age and size structure as well as the conditions when this may be expected. This insight may guide inspection agencies to manage their inspection effort. More importantly, the insight as to the quantity as well as the size or age-structure of the discarded catch will allow fisheries scientists to explore the accuracy of their assessment

of the stock (Harley et al. 2000; Dickey-Collas et al. 2007; Heery and Berkson 2009; Pawlowski and Lorance 2009) and the quality of the scientific advice (Daan 1997; Rijnsdorp et al. 2007; Ulrich et al. 2011).

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