Catch–quota matching allowances balance economic and ecological targets in a fishery managed by individual transferable quota

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Fishers with individual catch quota, but limited control over the mix of species caught, depend on trade and catch–quota balancing allowances to fully utilize their quota without discarding. However, these allowances can theoretically lead to overfishing if total allowable catches (TACs) are consistently exceeded. This study investigates usage of balancing allowances by the Icelandic demersal fleet over 2001–2017, for over 1,900 vessels. When a vessel's demersal catch exceeds owned and leased quota for a given species, the gap can be bridged by borrowing quota from the subsequent fishing period or transforming unutilized quota in other species, restricted by limits. Conversely, excess quota can be saved or transformed into quota for species where there is a shortfall. We found evidence that balancing behavior is frequently similar across the fleet. Transformations are consistent with indicators of a general quota shortage and potential for arbitrage caused by differences in conversion ratios used for transformation and lease prices. Larger companies contribute more to these patterns. Nevertheless, TAC overages are generally modest especially in recent years—key reasons appear to be the tightening of vessel transformation limits and the central role of Atlantic cod, which is the main target species but cannot be persistently overfished due to a specific prohibition on positive transformations into the species. These results show how the tailored design of the Icelandic catch–quota balancing system has helped in balancing economic and ecological goals of management. We suggest policy changes that could further reduce ecological risks, e.g., prioritizing between-year transfers over transformations.

catch–quota balancing | fisheries management | incentives

Harvesters in mixed-species individual quota fisheries (IQs or, if transferable, ITQs) potentially face a dilemma; what to do if they run out of quota in one species before they have used up remaining quota in other species (1, 2). One possible response, continuing to fish but discarding excess catch, has negative consequences and is now prohibited in many fisheries (3, 4). Purchasing additional quota can help but is sometimes not possible: If trade is prohibited for broader reasons (5), a particular quota is scarce due to a systemwide imbalance (6, 7), or frictional trading costs are high. Then harvesters may have to choose between illegal discarding and forfeiting unused quota. For these reasons, catch–quota balancing mechanisms have been introduced in a number of fisheries (8). Despite their limited track record, balancing mechanisms are likely to play an increasingly important role in fisheries management due to proliferation of ITQ systems (9) and discard bans (4), climate change-driven perturbation of marine ecosystems (10, 11), as well as the low amount of catch compared to quota in several mixed ITQ systems and the resulting loss of potential catch value (12, 13).

Catch–quota balancing mechanisms include banking (i.e., transfer of quota between periods; Fig. 1), transformation (i.e., exchange of quota in one species for quota in another species), and surrender (2, 8) (i.e., catch in excess of quota is "sold" at a prescribed price to the fishery manager). These mechanisms give harvesters limited flexibility to balance quota to catch after fishing. Experience of catch–quota balancing mechanisms has been mixed; while banking is common and has been positively associated with stock status across fisheries (5), transformation has been introduced and later abandoned in Canada and New Zealand due to concerns about overfishing (8) but survived, with modifications, in Iceland (14). A chief concern regarding these mechanisms is that they allow for implicit quota exchange rates (between quota in different periods or species), which may not be aligned with the equivalent exchange rates in quota markets. Where the quota exchange rates implied by balancing mechanisms differ from market exchange rates, harvesters will have an incentive to use balancing (15) to exploit the differences, effectively engaging in arbitrage (16). Such incentives are of concern to fishery managers because they are systematic, potentially causing larger gaps between harvest and total allowable catch (TAC). This does not necessarily mean that all instances of systematic behavior must be due to arbitrage; they may also be due to species for which there is a general quota shortage, for instance when, for rebuilding purposes, quota are set at low levels compared to actual biomass (if such species are caught together with target species, they can constrain the amount of catch of target species and function as so-called "choke"

Significance

The trend toward individual quota and discard bans presents a challenge for mixed fisheries: how to avoid widespread underutilization of quota due to choking effects of individual species for which quota is exhausted. Iceland's demersal fishery has met this challenge using the most elaborate set of balancing mechanisms in the world. We investigated the performance of the Icelandic system and find pervasive incentives inherent in the system's design. The absence of persistent overfishing of individual stocks is attributed to limits that have been tightened over time and are very strict for the primary target species. These results highlight the potential for balancing mechanisms to facilitate sustainable exploitation of distinct interconnected resources and the importance of adapting implementation to local circumstances.

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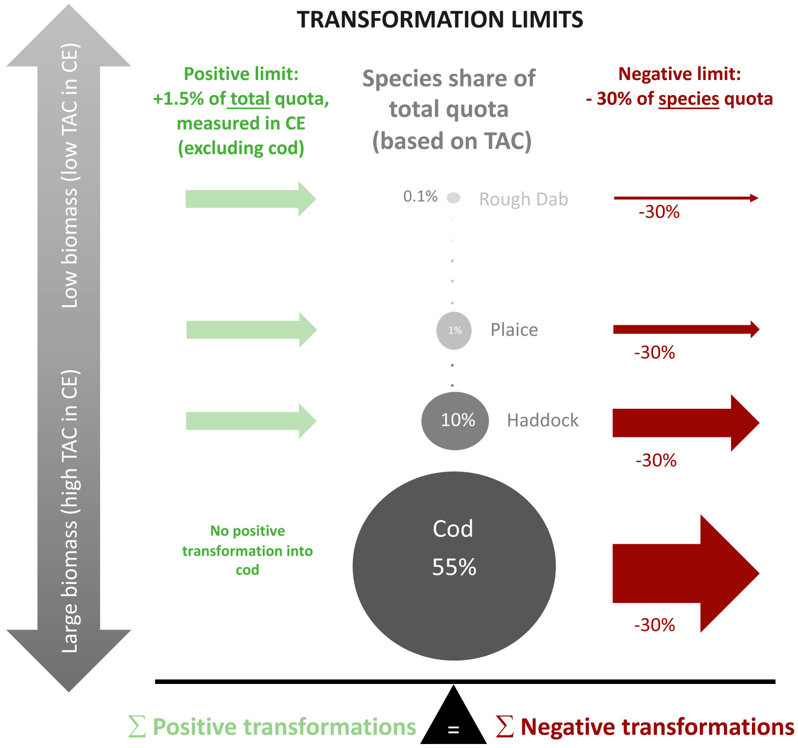

Fig. 1. Transformation and banking limits in the Iceland ITQ system. Positive (light green)/negative (red) limits restrict increases (decreases) in the permitted catch of the relevant species in the current period. Total cod equivalents (CEs) (units converting species quota to the same unit based on last year's price relative to cod) are summed across species before applying the 1.5% positive transformation and 5% total transformation limits; all others are applied as percentages of the originating species quota. The arrows are scaled relative to the total percentage of CE of the relevant species. The left-hand side of the figure shows how transformation limits are designed asymmetrically; the positive limits are based on a vessel's total CE quota, aggregated across species, which is the same for all species, while the negative limits are based on quota in the relevant species. This means that the overall fleetwide limit on positive transformations can potentially be several times TAC for low biomass species (it is 75 times TAC for common dab) but will be small relative to TAC for high biomass species and may be further constrained by the limited "supply" of negative transformations from low biomass species.

species). The distinction between drivers, a general quota shortage as opposed to arbitrage, is important because the latter can be sufficient to be the cause of persistent overfishing while the same is not true for the former.

The Icelandic ITQ-managed mixed demersal fishery is a suitable system for investigating catch–quota balancing behavior due to its use of all of the above-mentioned mechanisms (Fig. 1) as well as quota trade over an extended period, and the availability of detailed vessel- and company-level data. Previous analysis of aggregate balancing outcomes found that TAC overages were modest and did not occur consistently in any species from 2001 to 2013 (14). The current study extends this research, using a complete dataset of individual catch–quota balancing of over 1,900 vessels between 2001 and 2017, to explore the extent to which balancing behavior cancels out at the fleet level and if the pattern of behavior is consistent with hypothesized incentives and constraints. We would expect unpredictable local variation in catch to lead to balancing behavior that cancels out substantially at the fleet level, whereas systemwide constraints or incentives would be more likely to result in similar, seemingly systematic, behavior across vessels. We investigate both banking and transformation behavior, although we place greater emphasis on the latter mechanism since it can theoretically lead to persistent and significant overfishing of particular species. In contrast, the long-term risk from bringing quota forward is relatively low since the maximum amount is limited relative to annual quota and the impact is therefore diluted over longer time periods. The Icelandic ITQ system also allows for surrender of catch, but the associated volumes for demersal species are low, equating to 0.5% of total demersal quota between 2002 and 2017 (*SI Appendix*, Table S3), and have therefore been excluded from the analysis.

We began by investigating the extent to which balancing behavior (i.e., positive and negative flows) was similar across vessels for each species–year combination. In order to quantify behavioral similarity in balancing, we created a standardized index of the overall directionality of balancing adjustments, defined as D_s for species s and calculated as follows:

$$D_S = \frac{\sum_i^I P_{si} - \sum_i^I N_{si}}{\sum_i^I P_{si} + \sum_i^I N_{si}}, \qquad [1]$$

where P_s is the positive quota adjustment for vessel i (0 when negative), and N_s is the negative quota adjustment for vessel i (0 when positive). This index takes values between −1 and +1; the former implies that transformation or banking are purely negative, the latter that transformation or banking are purely positive, while 0 indicates equal volumes of positive and negative flows. The directionality index was calculated separately for quota transformed and quota banked at the end of each year.

We then used a regression model to examine the drivers of the directionality of transformations (we refer to this model as the "transformation directionality model"). We developed quantitative proxy measures of proposed behavioral drivers, namely, the following: potential for arbitrage (*arbitrage potential*), the ability to target species (*targeting indicator*), as well as a systemwide quota shortage (*choke indicator*). The potential for arbitrage arises when the quota conversion rate set by the fishery manager differs from the conversion rate that can be achieved in the quota market, i.e., by simultaneously selling quota in one species and purchasing quota in other species (17). We defined a proxy for each species' *arbitrage potential* in a given fishing year based on the ratio between the average lease cost of quota and transformation cost (fixed by the fishery manager as the cod equivalent [CE] value from the previous fishing year). The ratio is then normalized, dividing it by the weighted average ratio across all species (excluding Atlantic cod) to yield the proxy. An *arbitrage potential* value of 1 corresponds to parity with a notional basket of the remaining species, while a value >1 implies that it would be cheaper to obtain the relevant species quota indirectly by leasing and then transforming quota in other species rather than leasing the desired species quota directly; a value <1 implies the converse. This proxy is only a rough indicator of arbitrage potential over the fishing year as it is based on comparing average lease prices across species, whereas arbitrage involves risk-free exploitation of contemporaneous price disparities (16). Harvesters' ability to exploit *arbitrage potential* opportunities is increased when they can proactively target species, which can be transformed into cheaply (or avoid species with a high transformation value), potentially exacerbating the risk of overfishing, i.e., we would expect an interaction effect between the ability to target species and their *arbitrage potential*. To assess this possible behavior, we created an indicator of species *targeting*, defined as the percentage of each species total annual catch occurring on trips where the species contributed at least two-thirds of trip catch (*SI Appendix*, *Supplementary Methods*) and interact this variable with *arbitrage potential*.

Similar behavior across vessels and a high arbitrage potential could be caused by a general shortage of quota in the relevant species ("choke" species) or by arbitrage potential. In order to distinguish the two phenomena, we included a species *choke indicator*, calculated as a binary presence/absence variable where a choke effect was considered present whenever the average lease price exceeded the average marginal catch value (defined as ex vessel price less estimated crew share, quota fee, and fuel cost) (1). We also included TAC in the transformation directionality model as larger TAC species are more likely to be targeted due to economies of scale (18) and therefore more likely to be species for larger positive transformation flows ("sink" species).

We also developed a set of multispecies and single-species regression models to investigate balancing behavior (banking and transformation) at the individual vessel level and the influence of different resource user characteristics, including company and vessel size, and permit type. We refer to these models as the "vessel-level" models (i.e., single-species and multispecies vessel-level models). We expected larger companies to more fully utilize the balancing mechanisms for arbitrage since they would have more management resources and potentially have more scope to alter the species mix, especially if they have multiple vessels. This study examines catch–quota balancing behavior at the vessel and company level.

The Icelandic system has been adjusted over time, particularly the limits for transformation and banking, most notably in 2011/2012 (more detail in *SI Appendix*). The main rule change reduced the limit on negative transformations from 100% of species quota held by each vessel to only 30%, and we included this change as a dummy variable in the vessel-level models to investigate whether this change was effective. We use the vessel-level models rather than the transformation directionality model as only a change in underlying transformation volume would be expected, which is not captured by the directionality index.

Results and Discussion

There is behavioral similarity in both transformation and banking as the directionality indices deviate strongly from zero (Fig. 2 *B* and *C*). A small set of species have predominantly negative transformations effectively acting as "source" of additional quota for other species. For example, transformations for both dab species were consistently below −0.5. Similarly, there are "sink" species for which the direction of transformation appears to be mostly positive (e.g., haddock being above 0.5 for all years after the rule change). For the majority of species, the transformation directionality varies from year to year. Directionality of banking was predominantly negative (i.e., saving quota to the next year, Fig. 2*C*), meaning that harvesters prefer to save quota rather than borrow it, which is a pattern also observed in other fisheries (8). This result suggests risk aversion on the part of harvesters in the face of uncertainty regarding future TAC levels and the potential for choke effects. Overall, catches in the Icelandic system have been relatively well-aligned with the TAC, and in 2017 on average 88% (82% when excluding all TAC overages) of TAC was caught in Iceland's mixed fisheries (Fig. 2*A*). This is high compared to the 30 to 60% of TAC caught in mixed fisheries that same year in the United States (13).

We found large variation in arbitrage potential and a clear difference between species (Fig. 2*D*), suggesting that it may often be more profitable for companies to use species transformations rather than using the lease market. A few species have consistently low arbitrage potential values (e.g., both dab species and Greenland halibut), implying that harvesters with surplus quota in these species would have an incentive to transform out of the quota rather than lease it out. In contrast, other species exhibit high *arbitrage potential*, albeit not for every year, indicating that transformation into these species may be more profitable than leasing them in. There were few choke observations in the Icelandic system: Atlantic cod was indicated as a choke species in all years and haddock and redfish in several years (Fig. 2*E*). The *targeting indicator* also displays large variability, both between species and years (Fig. 2*G*). It is important to notice that some species, for example monkfish, could be vulnerable species for the transformation system, as they show both relatively high values for *arbitrage potential* and the *targeting indicator* and a low TAC; TAC overages for monkfish are, however, modest (Fig. 2*A*).

Arbitrage potential was the strongest statistically significant predictor of directionality of transformations (Table 1), consistent with the hypothesis that harvesters respond to the incentives arising from misaligned transformation costs and lease prices. The *arbitrage potential* predictor was also positively associated with the catch: quota ratio in the multispecies vessel-level model as well as 8 out of 14 individual-species vessel-level models (Fig. 3). Contextual evidence exists to support these findings. For example, several source species have material amounts of unused quota that are effectively forfeited (*SI Appendix*, Fig. S3), and it is logical to expect the owners of this quota to have fully utilized opportunities to transform quota of these species into more valuable species, as predicted by theory (19, 20). We find circumstantial evidence that transformations may sometimes be driving quota trade, with an average of 54% of negative transformation volume occurring when the quota was first leased in and then transformed (*SI Appendix*, Table S5)—with this ratio reaching 70% for some species.

On the other hand, we found that the *choke indicator* does not significantly predict directionality of transformations, which suggests that the alternative explanation that general quota shortages would drive up both transformation and relative lease prices is less supported, strengthening the case for arbitrage-driven behavior. In the vessel-level models, we found that the choke indicator also showed no significant effect in the multispecies model as well as most of the individual-species models, with the exception of a higher catch-to-quota ratio for redfish and common dab in choke years and a negative effect on the catch-to-quota ratio for ling (Fig. 3). The effects for the *choke indicator* should be read with caution, however; it could be that the presence/absence indicator is too coarse to capture a gradual shift in case a species turns out to be a choke during the fishing year (as lease prices may rise throughout the year). For redfish, it seems that *arbitrage potential*

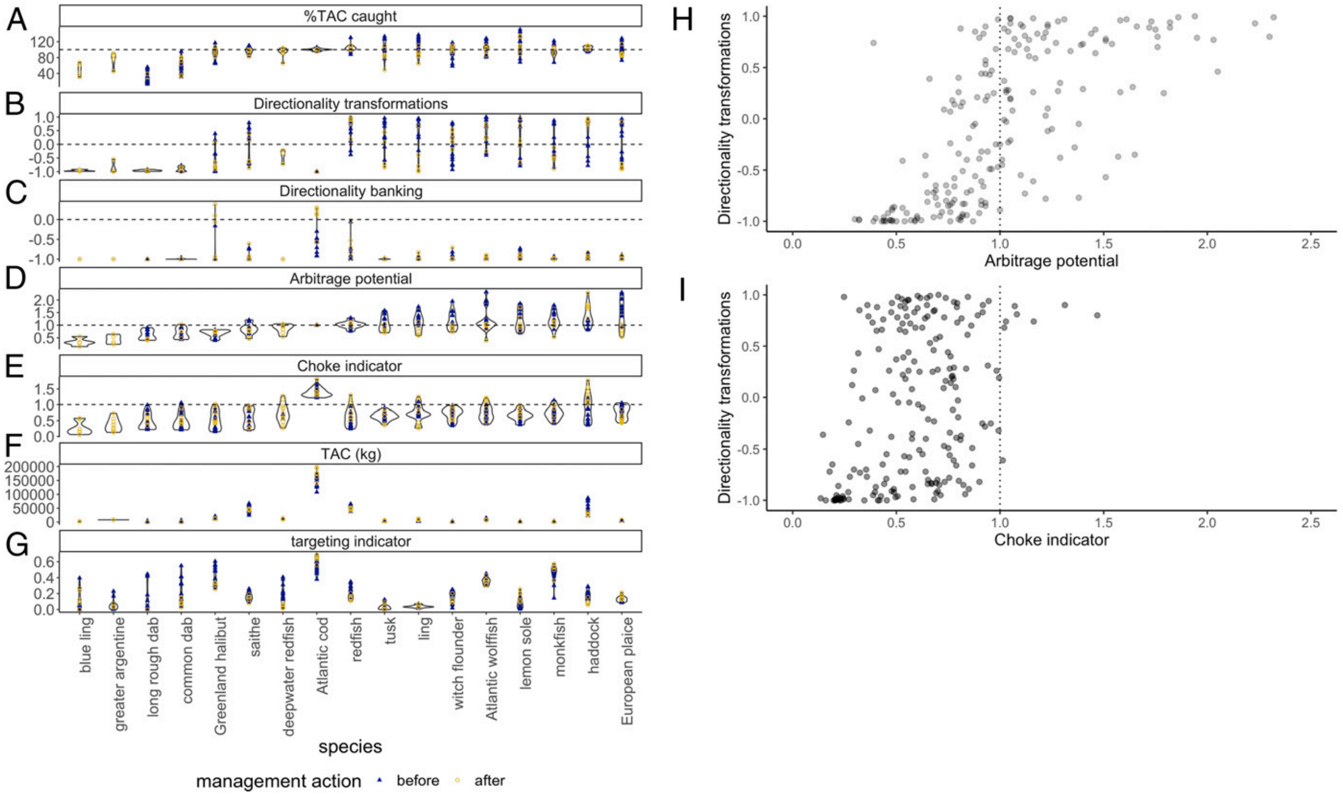

Fig. 2. Variables and indicators for the Icelandic catch–quota balancing system. (*A*) %TAC caught; (*B*) directionality of transformations: positive values indicate transformations into the species and negative values indicate transformations out of the species; (*C*) directionality of banking: positive values indicate borrowing from next year and negative values indicate saving to next year; (*D*) arbitrage potential: a value <1 means that it would be cheaper to lease quota in the corresponding species and then transform into a basket of the other species rather than lease quota for the basket directly; a value >1 implies the inverse; (*E*) choke indicator: >1 indicates that the cost of leasing quota exceeds landed value, net of fishermen's catch share; (*F*) TAC in kilos of gutted fish; (*G*) targeting indicator; (*H*) directionality of transformations as a function of arbitrage potential (excluding Atlantic cod); and (*I*) directionality of transformations as a function of choke indicator (excluding Atlantic cod). The blue triangles indicate observations before the rule change in 2011/2012, which limited flexibility in transformation usage, while the yellow points indicate observations after the rule change. Species are organized from lowest to highest mean values for *arbitrage potential*. Note that a few species have fewer observations as they were added later to the species transformation system (blue ling, greater argentine, and deep-sea redfish). For each species in *A*–*G*, the violin plot indicating the data frequency of distribution is also plotted.

and *choke indicator* act together, with different fishers possibly responding differently to ecological and economic signals. The way this could be explained is that, for example, a fishing company may run out of redfish quota and is forced to pay a high price, while another fishing company may be using species transformations to cover their redfish catch while simultaneously leasing out redfish quota. Moreover, including the cost of fuel is an important assumption when calculating the choke indicator as we assume that fuel is expended on the species mix and not for target species only; our results, however, are largely robust to this assumption as shown in a sensitivity analysis (*SI Appendix*). It could be that the low number of choke observations for small biomass species in Iceland are related to the asymmetry of the transformation limits (Fig. 1); these limits are hardly ever met by individual vessels for small biomass species but more frequently so for haddock and redfish especially after the management changes in 2011/2012 (*SI Appendix*, Table S8).

Atlantic cod may be the ultimate choke species in the Icelandic demersal quota system as we found that the average cod quota lease price exceeded estimated marginal value (average ex-vessel price adjusted for crew share, quota fee, and fuel cost) in all years. Moreover, the catch–quota balance for cod is nearly perfectly aligned for the majority of vessels (*SI Appendix*, Fig. S2). Atlantic cod is by far the most abundant demersal species and contributes the majority of the catch value of the Icelandic demersal fleet, so that each company would need to own some cod quota to run a demersal fishing operation, but it is the only species for which quota cannot be increased via transformation. We found that the vast majority of demersal trips and catch contain Atlantic cod (*SI Appendix*, Fig. S4) and Atlantic cod is at times actively avoided by vessels in the Icelandic fleet (21). Positive species transformations for many species will thus be limited due to the choke effect of cod, and the choke effect of cod may explain the high level of quota saving observed for many species, while borrowing is observed for cod (Fig. 2*C*). Ultimately, if cod quota is exhausted, then there is no incentive to transform into species for which the amount of cod is the limiting factor. This is an observation that needs to be considered if fisheries managers consider translating mechanisms from the Icelandic context to other fisheries (4), especially in an ecosystem where such a large economically important species is absent.

The results also show that directionality of transformations is predictable from TAC, which could be because larger quantities of fish may be cheaper to process and distribute (Table 1). We find that transformations tend to reduce catch of low TAC species and increase catch of high TAC species, for example redfish and haddock (*SI Appendix*, Fig. S3). Since the legal limits are more constraining for transformations into high TAC species (Fig. 1), the tendency to transform into high TAC species reduces the ecological risks associated with species transformation. However, a small negative effect for TAC is shown for six of the single species models, which may indicate companies needed to rely less

Table 1. Directionality of transformations model with fractional logit estimates of the contribution of each of the predictor variables, SEs, *z* values, and probabilities

Predictor	Estimate	SE	*z* value	Pr(>|*z*|)
Arbitrage potential	1.47	0.21	7.14	**<0.001**
Choke indicator (dummy variable)	−0.17	0.44	0.38	0.70
TAC	0.99	0.29	3.41	**<0.001**
Targeting indicator	−0.09	0.14	−0.63	0.53
Targeting indicator * arbitrage potential	−0.21	0.15	−1.35	0.18
Cox and Snell's $R^2 = 0.27$				
Nagelkerke's $R^2 = 0.58$				

It can be observed that *arbitrage potential* and total allowable catch (TAC) are the most important predictors of transformation directionality with a positive effect. P-values significant at the < 0.05 level are printed in bold. Predictor variables that were included are as follows (continuous variables are indicated as c; dummy variables as d; ranges are specified): 1) *arbitrage potential* (lease price over CE conversion ratio, normalized; c {95.7; 176.8}); 2) *choke indicator* (lease price rises above ex-vessel price plus marginal costs; d {choke observation, no choke observation}); 3) TAC (c {176; 86980}); 4) targeting indicator, percent catch of a species for which a species is two-thirds of the catch (c {0;1}).

on balancing mechanisms in high TAC years for those particular species, possibly indicating a general quota shortage in lower TAC years.

Contrary to our expectations, the interaction between the *targeting indicator* and *arbitrage potential* had no effect in predicting directionality of transformations (Table 1), but it did show a small positive effect in the multispecies vessel-level model and in five of the species' vessel-level models (Fig. 3). Some species (e.g., European plaice, redfish, and lemon sole) are thus predicted to have increased catches when both the *targeting indicator* and *arbitrage potential* have high values, indicating that for those species arbitrage opportunities increase when the species is more targetable. However, we also found a negative interaction effect in five of the single-species vessel-level models, which may be caused by increased lease prices due to choke effects rather than *arbitrage potential*. If species are highly targetable, they may also be easier to avoid. In a scenario where lease prices rise due to choking effects, the ability to avoid such species can result in lower catches.

Larger companies rely more on the transformation system and possibly make more use of the potential for arbitrage as there was a small positive effect of total demersal quota holdings in the multispecies vessel-level model and in 6 out of 14 single-species vessel-level models (Fig. 3). Moreover, boats with a small boat permit type (using either only hook and line gear or smaller than 10 gross tonnage) had less catch per quota than larger boats for most species, indicating more missed fishing opportunities, which is also demonstrated by larger amounts of unused quota for this fleet segment (*SI Appendix*, Fig. S5), as well as less transformation and banking activity in several species (*SI Appendix*, Fig. S6). Only for Greenland halibut is the small boat permit predicted to have more catch per quota on average, this is because Greenland halibut is a major source species for the larger boat permit (*SI Appendix*, Fig. S6).

The management action in 2011/2012 resulted in negative changes in catch–quota balance for the sink species Atlantic wolffish, ling, and monkfish (Fig. 3), as well as a large positive change for Greenland halibut, which acted as a main source species. Therefore, the management action appears to have been effective across a variety of species. This is also reflected in the fact that large TAC overages became less common after the management action, with the only overages above 10% of TAC occurring for lemon sole (Fig. 2*A*).

Several of our results have important policy implications. First, the arbitrage incentive that arises from species quota transformation ratios that are not aligned with quota markets should be considered when fisheries managers consider the implementation of such mechanisms e.g., in the context of the common fisheries policy in the European Union (4). Such incentives could result in systematic overfishing especially in cases where a highly constraining factor/species such as the Atlantic cod in the Icelandic case is absent. Second, we showed that fishers tend to save quota rather than borrow from the next year, but that companies at the same time use species transformations to cover catch in the same species as is saved. This is possible because balancing is done at the vessel and not at the company level. Simple policy changes could be 1) to allow companies to use species transformations to cover catches only if they have already borrowed the maximum amount from the next year, and 2) to balance catch to quota at the company level rather than the vessel level. In this way, a large amount of species transformations could have been avoided. For instance, 53.3% of positive haddock transformations could have been avoided if balancing was done at the company level or if banking was prioritized over transformations (*SI Appendix*, Table S6). In addition, the limit for transformation into each species is based on total vessel quota across species (Fig. 1). This design feature is particularly risky for profitable small biomass species as total CE holdings can be several times their TAC; it would thus be prudent to add a species-specific limit for positive transformations, as is already the case in Iceland for negative transformations.

Beyond fisheries, ITQ balancing mechanisms such as those studied here could be a template for new approaches to sustainable governance that respect multiple interconnected planetary boundaries to resource utilization and pollution, while recognizing the potential for marginal trade-offs to improve cost effectiveness (22). This approach, which may be described as "flexibility within limits," allows for partial substitutability between different forms of natural capital and can therefore be viewed as a compromise between strong and weak forms of sustainability (23, 24).

In conclusion, with the recent modifications to the catch–quota balancing system in 2011/2012 and additional slight adjustments, catch–quota balancing mechanisms could balance socioeconomic benefits for fishers harvesting uncertain and interconnected natural resources with ecological risks of overexploitation. Our conclusions, however, are very much bound to the Icelandic context where one highly abundant and strictly managed stock, Atlantic cod, may drive much of the observed behavior. We advise managers to consider this important role of cod when considering application of the Icelandic catch–quota balancing system to other ecosystems. Other mixed-fisheries ITQ systems may have a similar ubiquitous and economically important species (12, 25) and could benefit from Iceland's experiences with the balancing system. Arbitrage opportunities were nonetheless observed, which in the absence of restraining factors could result in ecological risks, especially for valuable low biomass species.

Materials and Methods

We obtained data on catches, quota, and lease values and company characteristics from the Fishery Directorate (www.fiskistofa.is/) (26) and ex-vessel prices from Statistics Iceland (https://hagstofa.is/) (27).

The *targeting indicator* was calculated by computing the fraction of catch for each species where the species was at least two-thirds of the catch. As an indication of company size, we summarized the companies' holdings in all demersal species multiplied by the respective species' CE value.

The directionality index was predicted using a fractional logit model (28) and species-level predictors using the following equation:

$$D_{s,t} = 2*\left(E_{s,t} + P_{s,t} + M_t + F_t + \varepsilon_t\right) - 0.5 \qquad [2]$$

where $D_{s,t}$ is the mean predicted directionality at time t for species s, $E_{s,t}$ is a matrix of ecological fixed effects (*targeting indicator* and TAC), $P_{s,t}$ is a

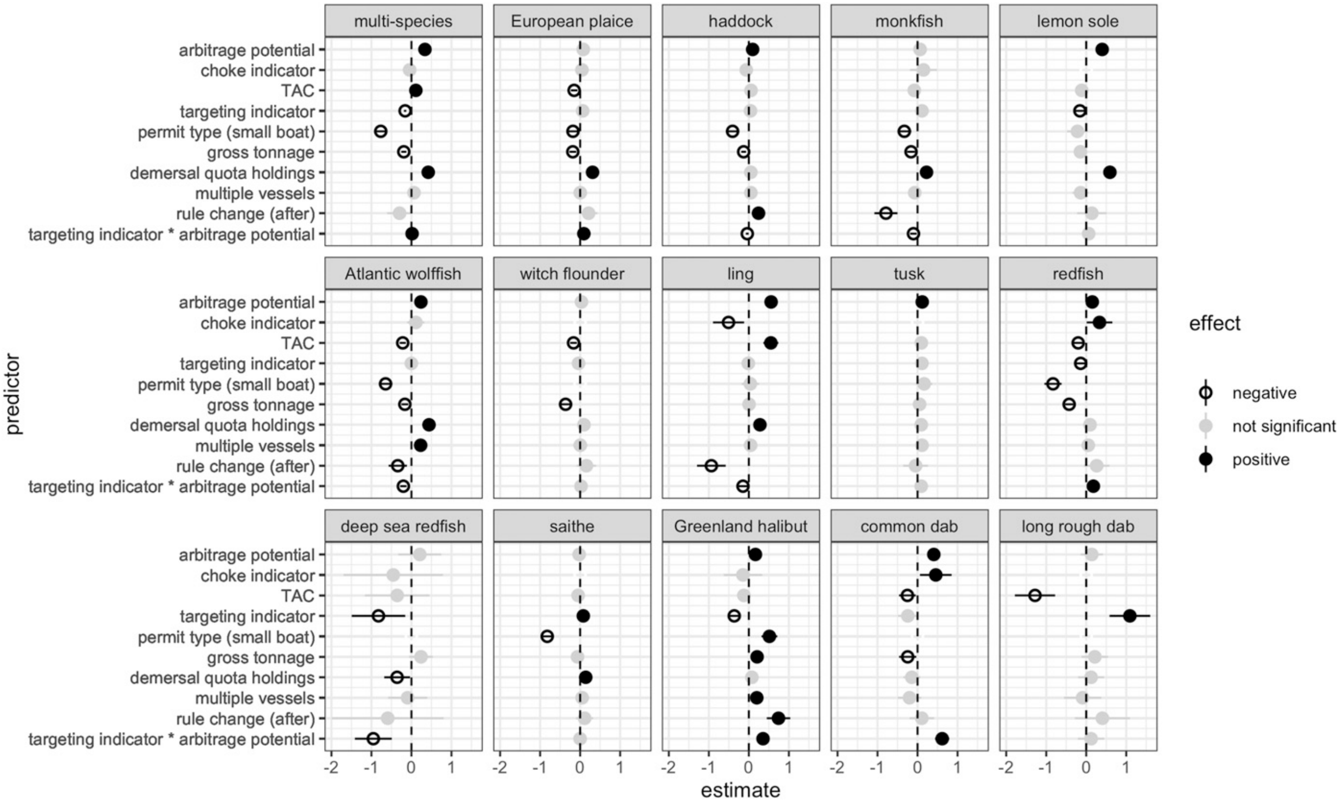

Fig. 3. Effect size for predictors predicting catch/quota in multispecies and single-species models, except Atlantic cod and a few species with too few observations. Effect size is represented by the location of the dots in the estimate values range along with 95% CIs. When CIs cross the dotted line at 0, the predictor variable is considered not significant (note that because there is a large amount of data underlying the figure the CI is often very narrow and not visible in the figure). The exponent of the effect size is the predicted increase in catch/quota for each unit increase in the predictor variable (e.g., on average for all species the ratio of catch/quota is predicted to increase with 1.4 with an increase of 1 in arbitrage potential, all else being equal). Predictor variables that were included are as follows (continuous variables are indicated as c, dummy variables as d, ranges are specified): 1) *arbitrage potential* (lease price over CE conversion ratio, normalized; c {95.7; 176.8}); 2) *choke indicator* (lease price rises above ex-vessel price plus marginal costs; d {choke observation, no choke observation}); 3) total allowable catch (TAC) (c {176; 86980}); 4) targeting indicator, percent catch of a species for which a species is two-thirds of the catch (c {0;1}); 5) a variable that represents the two main fleet segments (d {small boats with passive gear, larger boats with mostly active gear}); 6) the gross tonnage of the vessel (c {1; 7682}); 7) the amount of demersal quota held by the company operating the vessel (c {0;40568493}); 8) whether the company operating the vessels has multiple vessels (d {single vessel, multiple vessels}); 9) the management adjustments (rule change) (d {2011/2012 and prior, after 2011/2012}); as well as 10) the interaction effect for the *targeting indicator* and the *arbitrage potential*. The small-boat permit variable is not included for species that were not caught by small boats, and the choke indicator is not included for species that were never indicated as a choke species. Observations with negative allowed catch amounts (caused by borrowing and having only a small amount or no allocated quota) were excluded, representing 0.4% of catches of the Icelandic demersal fleet.

matrix of economic time- and species-specific fixed effects (*choke indicator* and *arbitrage potential*), and F_t is a dummy variable for the fishing year. We used the Newey–West estimator to calculate SEs, which is robust in the presence of autocorrelation. We chose to use a fractional logit as the directionality values are bounded between −1 and 1; to meet the requirements for the fractional logit model, we divided directionality values by 2 and added 0.5 so that values occur on a continuous interval of 0 to 1.

The individual level models were set up using the following equation assuming a gamma distribution and using a log link:

$$\mu_{i,s,t} = Q * E^{E_{s,t} + P_{s,t} + S_{i,t} + R_i + R_s + \varepsilon_{i,s,t}} \qquad [3]$$

where $\mu_{i,s,t}$ is the predicted mean catch of vessel i at time t in species s, $Q_{i,s,t}$ is quota of vessel i at time t in species s, $S_{i,t}$ is a matrix of vessel and time-fixed effects, R_i are the vessel random effects, and R_s are the species random effects. The model is offset by the amount of quota, and therefore predicts the ratio between mean predicted catch and quota (μ/Q). Autocorrelation in the time-series was controlled for using a first-order autoregressive model. In all models, we standardized predictor variables to have a mean of 0 and a SD of 1.

Data Availability. Anonymized data have been deposited in GitHub, https://github.com/maartje-oostdijk/quota-balancing.

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