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

Maartje Oostdijk,a,b,1 Conor Byrne,c Gunnar Stefánsson,d Maria J. Santos,e,f, and Pamela J. Woodsg

*aDepartment of Life and Environmental Sciences, University of Iceland, 101 Reykjavik, Iceland; bDepartment of Physical Geography, Stockholm University, 114 19 Stockholm, Sweden; cDepartment of Environment and Natural Resources, University of Iceland, 101 Reykjavik, Iceland; dScience Institution, University of Iceland, 107 Reykjavik, Iceland; eUniversity Research Priority Program in Global Change and Biodiversity, University of Zurich, 8057 Zurich, Switzerland; fDepartment of Geography, University of Zurich, 8057 Zurich, Switzerland; and gDemersal Division, Marine and Freshwater Research Institute, 220 Hafnafjörður, Iceland

Edited by Nils Chr. Stenseth, University of Oslo, Oslo, Norway, and approved August 13, 2020 (received for review April 29, 2020)

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.

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 systemic 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”...
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:

$$D_s = \frac{\sum_i P_{ui} - \sum_i N_{ui}}{\sum_i P_{ui} + \sum_i N_{ui}}$$

[1]

where $P_{ui}$ is the positive quota adjustment for vessel $i$ (0 when negative), and $N_{ui}$ 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, species).
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 contemporary 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 directional 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 the balancing mechanisms for arbitrage since they would have more management resources and potentially have more scope to in these species would have an incentive to transform out of the quota thus 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. 2E). The targeting indicator also displays large variability, both between species and years (Fig. 2G). 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. 24).

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...
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, 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. 2C). 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
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 and in five of the species overages became less common after the management action, with Greenland halibut, which acted as a main source species. Therefore, ling, and monkfish (Fig. 3), as well as a large positive change for changes in catch targeting indicator and arbitrage potential

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)).

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 indicator 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:

$$D_{st} = 2 \times (E_{st} + P_{st} + M_t + F_t + e_st) - 0.5 \quad [2]$$

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

### 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 $R^2 = 0.58$        |          |     |         |          |
matrix of economic time- and species-specific fixed effects (choke indicator and arbitrage potential), and \( R_i \) 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:

\[
\mu_{i,s,t} = \frac{Q_i}{s} + E_{s,t} + R_i + S_{i,s} + R_{i,s} + \varepsilon_{i,s,t}
\]

where \( \mu_{i,s,t} \) is the predicted mean catch of vessel \( i \) at time \( t \) in species \( s \), \( Q_i \) is quota of vessel \( i \) at time \( t \) in species \( s \), \( S_{i,s} \) is a matrix of vessel and time-fixed effects, \( R_i \) are the vessel random effects, and \( R_{i,s} \) 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 \( (\mu_i/Q) \). 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/quotabalancing.

ACKNOWLEDGMENTS. We thank Pórrstein Hilmarsson from Directorate of Fisheries for supplying us with data and information. We thank Svétlana Markovic for giving us insights into the balancing system. We thank Hafn Hróvarsdóttir for helping us construct a database of the Icelandic fleet. We thank Laura Eslier, Sveinn Aagnarsson, Brynhildur Davíðsdóttir, and three anonymous reviewers for helpful comments on an earlier version. M.O. has received funding from the European Union’s Horizon 2020 Research and Innovation Programme under the Marie Skłodowska-Curie Grant Agreement 657153 and University of Iceland Empskip Fund under Project 1538-1533105. C.B. has received funding from the project GreenMAR, Green Growth Based on Marine Resources: Ecological and Socio-Economic Constraints, funded by Nordforsk, Project 61582.

1. D. S. Holland, Making cents out of barter data from the British Columbia groundfish ITQ market. Mar. Resour. Econ. 28, 311–330 (2013).
2. D. Squires et al., Individual transferable quotas in multispecies fisheries. Mar. Policy 22, 135–159 (1998).
3. R. Goni, Ecosystem effects of marine fisheries: An overview. Ocean Coast. Manage. 40, 37–64 (1998).
4. M. Harte, R. Tiller, G. Kailis, M. Burden, Countering a climate of instability: The future of relative stability under the Common Fisheries Policy. ICES J. Mar. Sci. 76, 1951–1958 (2019).
5. M. C. Melnychuk et al., Which design elements of individual quota fisheries help to achieve management objectives? Fish Fish. 17, 126–142 (2016).
6. D. S. Holland et al., US catch share markets: A review of data availability and impediments to transparent markets. Mar. Policy 57, 103–110 (2015).
7. A. Dobeson, The wrong fish: Maneuvering the boundaries of market-based resource management. J. Cult. Econ. 11, 110–124 (2018).
8. J. N. Sanchirico, D. Holland, K. Quigley, M. Fina, Catch-quota balancing in multispecies individual fishing quotas. Mar. Policy 30, 1257–1277 (2015).
9. P. J. Woods, D. S. Holland, G. Marteinsdottir, A. E. Punt, How a catch-quota balancing system can go wrong: An evaluation of the species quota transformation provisions in the Icelandic multispecies demersal fishery. ICES J. Mar. Sci. 72, 733–740 (2015).
10. P. J. Woods, D. S. Holland, A. E. Punt, Evaluating the benefits and risks of species-transformation provisions in multispecies IFQ fisheries with joint production. ICES J. Mar. Sci. 73, 1764–1773 (2016).
11. Marine Research Institute, “State of marine stocks in Icelandic waters 2014/2015 and prospects for the quota year 2015/2016” (Marine Research Institute, 2015).
12. R. G. Newell et al., Asset pricing in created markets. Am. J. Agric. Econ. 89, 259–272 (2007).
13. N. L. Klaer, D. C. Smith, Determining primary and companion species in a multi-species fishery: Implications for tac setting. Mar. Policy 36, 606–612 (2012).
14. R. U. Ayres, On the practical limits to substitution. Ecol. Econ. 61, 115–128 (2007).
15. E. Guazzo, J. M. Wooldridge, Econometric methods for fractional response variables with an application to 401(k) plan participation rates. J. Appl. Econ. 11, 619–632 (1996).