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Evolution of effort and the efficacy of input controls in controlling fishing mortality in the Icelandic female lumpsucker (*Cyclopterus lumpus*) gillnet fishery

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ABSTRACT

The female lumpsucker (*Cyclopterus lumpus*) gillnet fishery in Iceland has been managed exclusively through input controls for several decades. The present study assessed how different components of total effort have changed from 1985 to 2024 and how different components of effort influenced an estimate of relative fishing mortality (F_{proxy}). F_{proxy} could be predicted from a combination of the number of boats participating in fishery, the average number of gillnets hauled per day, the average number of fishing days utilised in the season and an index of under/over estimation of the biomass index. Time period was also included in the model as there was a change in the catch per unit effort (CPUE) at a given level of biomass index from 2004 to 2005 when limits on the number of fishing days pre boat was introduced. The number of boats with a licence to participate in the fishery currently exceeds the capacity of the fishery, thus if the number of boats were to rise to historical highs, then F_{proxy} would rise above the management target. Total catch is primarily managed through the number of consecutive days a boat can fish for, however, the number of boats has a greater impact on fishing mortality than the number of fishing days. We present a model which can predict F_{proxy} for a given level of effort, but this requires the number of boats which will participate in the fishery to be known. In terms of maintaining fishing mortality within sustainable limits, the effort system could be considered to be successful. However, the management of this fishery is now changing to an output-controlled fishery, but the experience from this fishery serves as a good model for other fisheries where management systems have a limited capacity to control catch.

1. Introduction

To limit fishing mortality on a fish stock, a management strategy will normally be put in place which will involve input and (or) output controls. Input controls are concerned with limiting fishing effort e.g. number or size of fishing boats, length of fishing seasons or regulations on mesh size. Output controls are primarily an implementation of a total allowable catch (TAC).

When managing a fishery through input controls, it is essential to have a comprehensive understanding of how effort is evolving within the fishery (Eigaard et al., 2011). It is also necessary to have a good understanding of how changes in different aspects of effort impact catch rates. However, what exactly constitutes fishing effort is difficult to gauge and will be dependent on the biology of the target species and the type(s) of fishing gear used. Some important aspects may be difficult to quantify such as knowledge and experience of the captain (Squires and Kirkley, 2011) and some descriptors not traditionally measured, which have substantial impacts on catch rates, may change over time leading to technological creep (Marchal et al., 2007). Changes in the distribution of the target species within and between years can impact the relationship between catch and effort, which can be further complicated if the fleet is also mobile and can move between areas of varying abundance (Rijnsdorp et al., 2006).

In Iceland, fisheries are primarily managed by means of output controls with the exception of the female lumpsucker (*Cyclopterus lumpus*) gillnet fishery (hereafter referred to as lumpsucker fishery) which has been managed using input controls for several decades. These input controls have evolved over time (Kennedy et al., 2019), but at the time of writing, it has been decided to alter the management to output controls. This fishery primarily targets female fish for their roe. Under the input-controlled management system, to legally target lumpsucker, a boat required a lumpsucker licence which was open to all boats < 12 GT up until 1990. In 1991, regulations were introduced which ceased vessel entry and no new licences have been issued since, thus capping the

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number of boats which could participate in the fishery. For a new boat to enter the fishery, a licence must be transferred from another boat. For some vessels which participate in the lumpsucker fishery, this is the only commercial fishery they are involved in, others participate in the coastal jig fishery in the summer (Gunnlaugsson et al., 2021), while others own quota which they utilise at other times of the year. Not all vessels which have a lumpsucker licence participate in the fishery each year, with varying levels of participation each year.

Up until 2004, the regulations of the lumpsucker fishery mainly concerned the size of the boats, mesh size, number of gillnets and the timing of the fishing season. In 2005, the fishers were faced with difficult market conditions so, at the request of the National Association of Small Boat Owners, limitations were placed on the length of time each boat could fish for within the fishing season by the Directorate of Fisheries. This was primarily aimed at reducing the supply of roe. Before commencing fishing in a particular year (typically in March-April), a boat must select a management area (Fig. 1) in which they can fish and cannot fish in another area during that year (Inner Breiðafjörður is part of Area B but fishing is not permitted there until 20th May each year). The fishery primarily takes place at depths < 50 m depth (Kennedy and Sigurdsson, 2024) around the coast of Iceland except for the south coast where effort and landings are limited (Fig. 1).

The catch of lumpsucker during the Iceland spring groundfish survey, which covers the continental shelf around Iceland, is used to calculate a relative biomass index which reflects the change in biomass of lumpsucker over time (Kennedy and Jónsson, 2017). Using total landings from the fishery, a proxy of fishing mortality is calculated (F_{proxy}) (landings/biomass index) (Kennedy et al., 2021). In 2011 (for the 2012 fishery), the Marine Research Institute (Iceland) (now the Marine and Freshwater Research Institute) began offering advice on a TAC for the lumpsucker fishery (MRI, 2011). The TAC advice is derived from an advisory rule (Kennedy et al., 2021) which is based upon maintaining F_{proxy} at 0.75 (F_{target}) or below which is regarded as being consistent with long term maximum sustainable yield (MSY). While there were several input controls on this fishery (number of gillnets, size of boats etc.), the Directorate of Fisheries primarily relied upon the limit on the number of days each boat could fish for in order to maintain F_{proxy} below 0.75. The number of days was set at the beginning of the season and adjusted annually according to a forecast (which was based upon input from the industry) of the number of boats which would participate in the fishery for that year. However, there was no explicit method to translate the recommended TAC to number of fishing days and was primarily based upon past performance of the fishery and input from the industry.

Fishing mortality of a population is, generally, positively correlated with fishing effort (García-Carreras et al., 2015) thus it is logical that limiting effort will limit fishing mortality. However, effort can take on different forms which can influence fishing mortality to different degrees. If gillnets are considered, then total net days (total number of all nets used in the fishery * number of fishing days) may be considered a reasonable measure of effort. However, all net days may not be equal. The ability of the net to catch fish may be affected by soak time (Hamley, 1975) and (or) the relative distribution of net days between the length of the fishing period and number of boats. The aim of the present study is to assess how different measures of fishing effort have changed over time in the lumpsucker fishery in Iceland. We also investigate how changes in effort can impact fishing mortality (measured as F_{proxy}) and how effective the current management practice of limiting the number of fishing days of each boat is in limiting the total catch below the advised TAC. Even though this fishery will now be managed using output controls, this fishery offers a wealth of data which can give insight how an input controlled fishery can function and serve as an example for managers of other small scale fisheries to draw upon.

2. Materials and methods

2.1. Sources of data

Historical landings of female lumpsucker were estimated from two sources, National Association of Small Boat Owners (1985–2007) and Directorate of Fisheries (2008–2024). Landings data from National Association of Small Boat Owners was in the form of barrels of roe produced as reported by boat owners, which is converted to landings of whole lumpsucker using an established formula (Kennedy and Jónsson, 2017). Landings data from the Directorate of Fisheries was from direct measurements of the weight of either ungutted lumpsucker or lumpsucker roe, measured by persons accredited by the Directorate of Fisheries. The landings of roe were converted to weight of ungutted

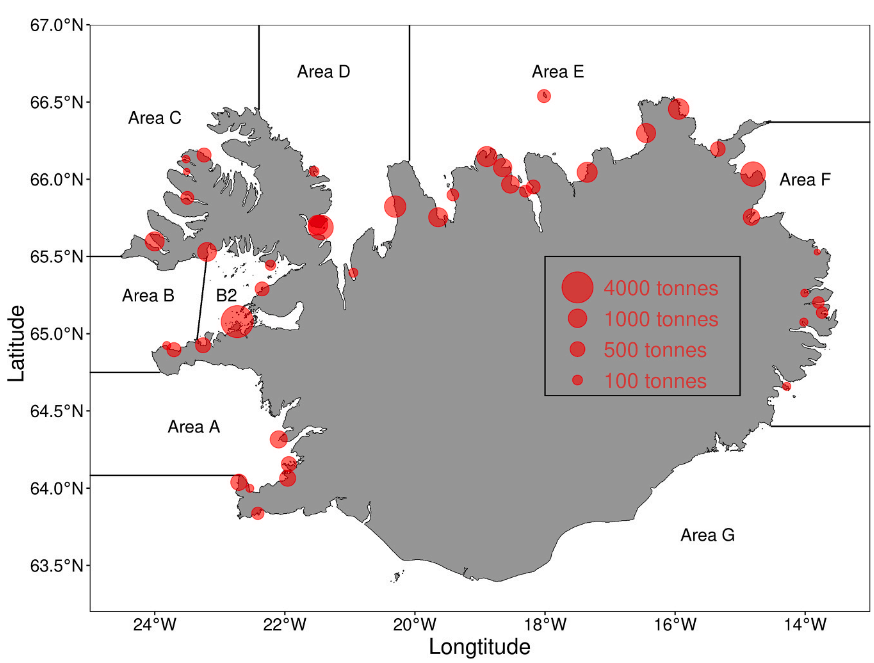

Fig. 1. Average quantity and location of female lumpsucker landings in Iceland between 2019 and 2024. The seven lumpsucker management areas are shown with B2 referring to inner Breiðafjörður.

lumpsucker by multiplying the weight by 3.28 (see details in Kennedy and Jónsson (2017).

The biomass index is estimated from the Icelandic Spring Groundfish Survey which gives a relative index of the female portion of the spawning stock biomass of lumpsucker around Iceland; details of this biomass index can be found in Kennedy and Jónsson (2017). An index of relative fishing mortality was estimated for female lumpsucker using Eq. 1.

$$F_{proxy} = \frac{landings}{biomass\ index} \tag{1}$$

Several measures of effort were considered; the number of boats which partake in the fishery each year, the size of the boats (gross tonnage), the duration of the fishing period of each boat, the average number of gillnets hauled on each fishing trip and the average soak time of the gillnets. The number of boats participating in the fishery was taken from two sources. From 1985–1997, the number of boats was assumed to equal the number of logbooks submitted each year. The submission of a logbook is mandatory for boats which participate in the fishery. From 1998, the number of boats which participated in the fishery was available from the Directorate of Fisheries.

The usual procedure for a boat participating in the lumpsucker fishery is it will lay all their gillnets during the first day of fishing. A fishing trip is defined as the boat hauling a portion of the gillnets and landing the catch. Maximum soak time is stipulated in the regulations; this was 6 nights from 1985 to 2011, 4 nights from 2012 to 2019 and 3 nights from 2020. A typical fishing pattern is that a vessel would haul around one half of their gillnets every 2–3 nights, depending on the regulated soak time. This pattern could be affected by weather and the volume of catches. The number of gillnets hauled on each trip is recorded in the logbooks for the whole period (1985–2024). The average number of gillnets hauled per trip was calculated by taking an average of all hauls from each year. Before 2012, fishers could use nets of 110 m or 220 m, nets with a length of 220 m counted as two nets within the regulations but recorded as one long net in the logbooks. However, there were some irregularities in the logbook data, thus net numbers were not adjusted to account for the use of long nets. After 2016, the distinction between long and short nets was no longer reported in the logbooks so for consistency through the years, it is assumed that the proportion using long nets was similar over time. Preliminary examination of the data showed that for 1980–2016, average CPUE calculated for each year while adjusting for long and short nets was correlated with CPUE when not accounting for net length.

The fishing period for each boat (the number of days they had gillnets in the water) was calculated. This was estimated for each year using logbook data (1985–2007) and landings data from the Directorate of Fisheries (2008–2024). For 1985–2007, the number of days between the date of the first entry minus 6 days (to account for the initial soak time) and the last entry in the logbooks was considered the length of the fishing period. For 2008–2024, the first day of fishing was the first day which their licence was valid for that year (boats could not begin fishing before that day, and with a limited number of fishing days it is reasonable to assume they began as soon as possible), and the final day was the final landing of that year. The average fishing period for each year was calculated using this data. How the catch of each vessel changed through its fishing period and how the start date of a fishing vessel affected the total catch over the fishing season was examined.

By rearranging the basic catch equation for CPUE (Eq. 2), an index of effort was calculated (Eq. 3) (Kennedy and Jónsson, 2017). The catch per unit effort (CPUE) of the fishery was calculated using logbooks from the fishery. The methods for calculation of CPUE of the fishery and the effort index are documented in Kennedy and Jónsson (2017) but is briefly summarised here. For each fishing trip detailed in the logbooks, CPUE was calculated as the catch of lumpsucker for that trip, divided by the total number of gillnets hauled in that trip. The CPUE for each year was calculated as the average CPUE of all fishing trips for all boats for that year.

$$catch\ per\ unit\ effort\ (CPUE) = \frac{catch}{effort} \tag{2}$$

$$effort\ index = \frac{total\ catch}{average\ CPUE\ of\ fishery} \tag{3}$$

This index of effort is used to track effort in the annual stock assessment of lumpsucker (Kennedy et al., 2021). While CPUE of the fishery is positively correlated with the biomass index, it is negatively correlated with effort itself (Kennedy and Jónsson, 2017), which is a common feature in fisheries. If CPUE is lower or higher than expected for a given biomass index it would be an indication that the biomass index was over or underestimated, or could be an indicator of varying catchability. Using this principle, the residuals from the linear model (formula 1)

$$CPUE = Biomass\ index + \log(effort) + time\ period \qquad \text{(formula 1)}$$

were used as an index of under/over estimation of abundance and is referred to as the residual index throughout the manuscript. Time period was included due to bias in the residuals over time (see results) and consisted of two time periods; 1985–2004 and 2005–2024.

2.2. Data analysis

Data was analysed using R version 4.2.2 (R Core Team, 2022). Factors influencing the effort index and F_{proxy} were investigated using general linear models (GLM's), with a Gaussian distribution, and variables chosen for the model were based upon data availability and theoretical considerations i.e. what could reasonably be believed to influence F_{proxy}. In the GLM models, it was assumed that there was a linear response between the predictor and response variables and that the residuals were normally distributed. These assumptions were tested by plotting residuals against predicted values and normality was tested using QQ plots. Factors chosen were number of fishing boats which took part in the fishery (N_b), average number of days fished (N_f), average number of nets hauled per fishing trip (N_{nets}), residual index (res) and stipulated maximum soak time (st). All combinations of the model, including the full model (formulas 2 & 3), were trialed and the model with the lowest Akaike information criterion (AIC) being considered the best.

$$F_{proxy} = N_b + N_f + N_{nets} + res + period + soak\ time \qquad \text{(formula 2)}$$

$$effort\ index = N_b + N_f + N_{nets} + res + period + soak\ time \qquad \text{(formula 3)}$$

The best model for F_{proxy} was evaluated using Leave-one-out Cross Validation in the R package "caret" (Kuhn, 2008), whereby, one data point is omitted, and the model is trained on the remaining data. The model is then used to predict the omitted data point, the whole process is then repeated for each data point. The probability of maintaining F_{proxy} below 0.75 was estimated by calculating prediction intervals using the 'stats' package in R. The sensitivity of F_{proxy} to changes in the values of each variable in the model was visualized using the 'visreg' package in R (Breheny and Burchett, 2017). As a demonstration on how the number of boats taking part in the fishery would be expected to affect the F_{proxy}, three scenarios were considered which consisted of three different values for the number of fishing days. The values of fishing days were 32, 40 and 45 days (chosen to represent typical values for the number of fishing days set in recent years) where 97 % (the maximum average value for the period 1985–2024) of the fishing time was utilised, and the resultant F_{proxy} was estimated using the model mentioned above for 150–360 boats which approximately reflects the range of in the number of boats which took part in the fishery between 1998 and 2024. Average number of nets hauled was set at the average of the previous 6 years (68 nets) while soak was set at 3 days to reflect current regulations, and residual index was set at 0. The number of days that each boat could fish for, for the recent maximum number of boats (363) which participated in the fishery between 1998 and 2024, while maintaining a reasonable chance of maintaining F_{proxy} below 0.75 was examined. The effect of change in the regulations for the maximum number of nets in 2013 on F_{proxy} was predicted. This change in regulation altered the maximum number nets from 100 nets per crew member with a maximum of 300 per boat to a maximum of 200 per boat irrespective of the number of crew. This was subsequently altered in 2014 to a maximum of 7500 m of nets as measured by the headline.

3. Results

3.1. Developments in the population and fishery

Landings of whole lumpsucker has varied over time (1985–2024), ranging from ~2500 to almost 10 000 tonnes (Fig. 2). The biomass index was highest over time in the 1980's and lowest in the 1990's (Fig. 2). F_{proxy} varied from 0.29 to 1.35 (Fig. 2). Between 1985 and 1997, there was an average of 360 (min = 234, max = 447) fishing boats targeting lumpsucker (Fig. 3). This decreased to an average of 241 (min = 128, max = 363) between 1998 and 2024. The average number of gillnets checked per fishing trip increased over time (Fig. 3). Both the average 'actual' fishing period and the maximum allowed fishing period have decreased over time (Fig. 3). As the maximum allowed fishing period decreased, the proportion of the fishing period utilised increased (linear regression, n = 30, r^2=0.91, $p < 0.001$, Fig. 3) with a range from 35 to 82 and 60–97 % in period 1985–2005 and 2006–2024. Average soak time was relatively constant between 1985 and 2011, it then decreased between 2011 and 2013, and again from 2019 to 2020, with both decreases coinciding with the change in the regulations stipulating the maximum soak time (Fig. 3). The size of the boats participating in the lumpsucker fishery increased continuously between 1992 and 2024 from an average gross tonnage of 5.87–9.84 (Fig. 3).

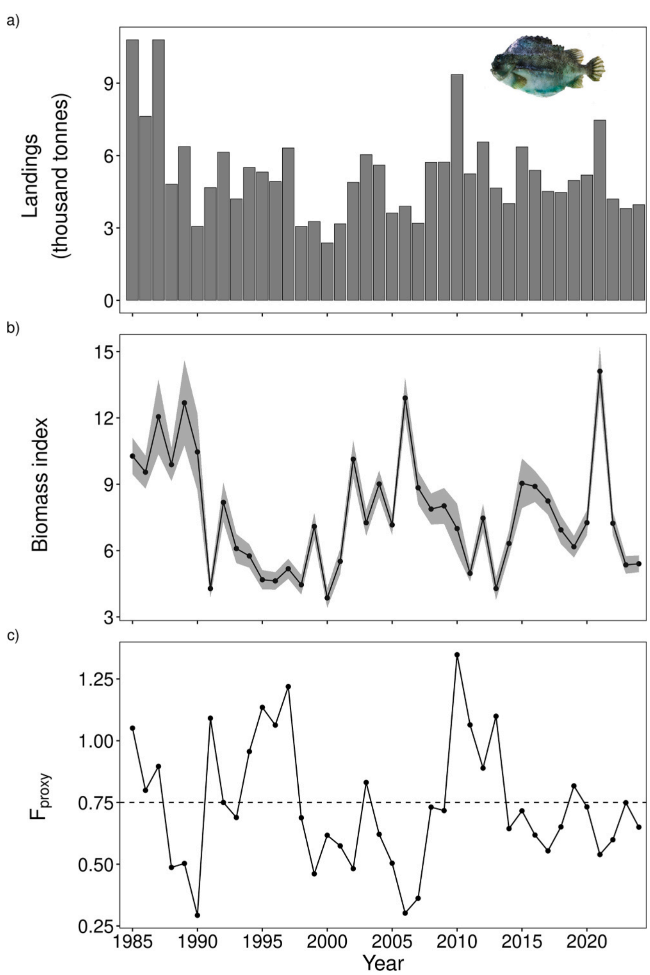

Fig. 2. (a) Landings of female lumpsucker in Iceland, (b) biomass index from the Icelandic spring groundfish survey and (c) changes in $F_{proxy,}$ from 1985 to 2024. The dashed line indicates F_{target}, 0.75. Image insert shows female lumpsucker.

The effort index generally decreased over time with an average of 4.76 and 2.21 during 1985–1997 and 1998–2024 respectively (Fig. 3). The effort index was positively correlated with number of boats, average number of gillnets and average number of fishing days and was negatively correlated with soak time (GLM, n = 40, r^2=0.90, $p < 0.001$) (Table 1). When boat size was applied to a subset of the data (1992–2024), boat size was not significant (GLM, $p > 0.05$).

Catch was relatively constant through the fishing period of each boat with no obvious increase or decrease in catches (Supplementary Fig. 1). However, boats which began fishing later in the season tended to have a lower total catch than boats which began earlier in the season apart from boats which fished within Breiðafjörður (Supplementary Fig. 2). CPUE was positively correlated with biomass index and negatively correlated with effort with a significant difference between the time period 1985–2005 and 2006–2024 (Linear regression; $r^2 = 0.83$, $p < 0.0001$) (Fig. 4). The change in the relationship between 1985 and 2005 and 2006–2024 was identified from the residuals from the linear model (formula 4)

$$CPUE = biomassindex + \log(effort) \quad \text{(formula 4)}$$

which were predominately negative from 1985 to 2005 and predominately positive from 2006 to 2024 (Fig. 4). The switch from a predominately negative to predominately positive residuals indicate that the relationship between CPUE and biomass index changed between these two time periods, adding time period as a factor removed the effect on the residuals (Fig. 4). There was a consistent negative linear correlation between log(CPUE) and log(soak time) between years i.e. lumpsucker gillnets catch the most fish in their first night with their catch efficiency decreasing with longer soak times (Supplementary Fig. 3).

3.2. F_{proxy}

For the different models used to predict F_{proxy}, RMSE and AIC was lowest when the number of boats, average number of fishing days, average number of gillnets hauled per day, residuals from the model predicting CPUE and time period were included (Fig. 5; Table 2; Supplementary Table 4). Sensitivity analysis of each variable showed a positive correlation between predicted F_{proxy} and the number of boats, number of fishing days, average number of nets and the residual index (Supplementary Fig. 4). F_{proxy} was predicted to be higher during time-period 2005–2024 than 1980–2004 when all other variables were held constant (Supplementary Fig. 4). The majority of the values of the residual index varied between −4 and 4. Moving from a residual index of −4–4 would result in an increase of 0.19 for predicted F_{proxy} (Supplementary Fig. 4). Using Leave-one-out Cross Validation for the best model, the model predictions generally followed the actual F_{proxy} and correctly predicted when F_{proxy} would be above or below F_{target} (0.75) 75 % of the time. In the effort simulation using the aforementioned GLM model, for a fishing period of 32 fishing days, in order to keep F_{proxy} at or below 0.75, a maximum of 241 boats could participate in the fishery (Fig. 6). At 40 and 45 days, boat numbers would need to be constrained below 215 and 198 respectively. The model predicts that increasing the number of boats has a greater effect on F_{proxy} than doubling the number of days e.g. in a scenario with 150 boats and 30 days, F_{proxy} would be 0.56, increasing the number of days to 60 gives an F_{proxy} of 0.77 whereas increasing the number of boats to 300 gives an

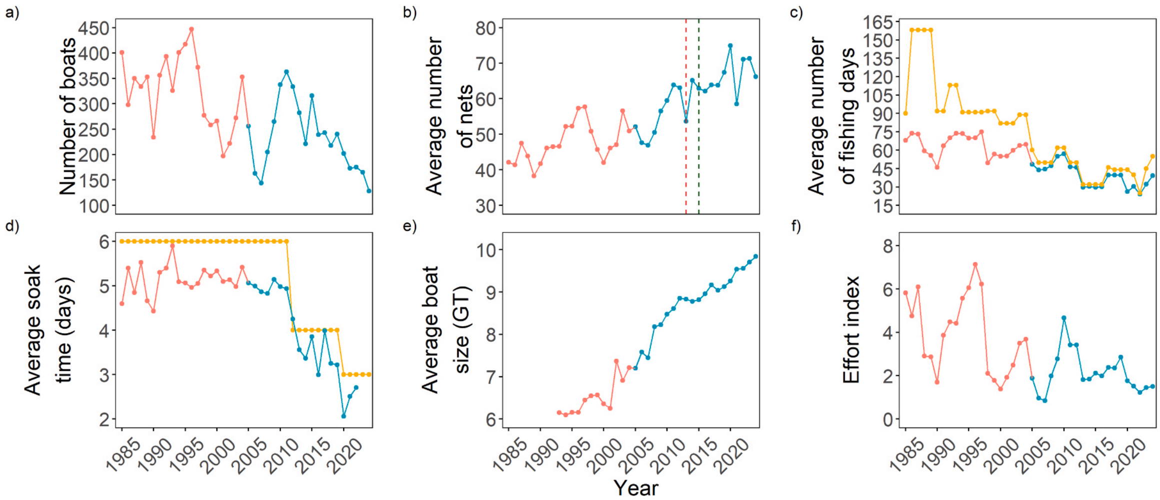

Fig. 3. (a) The number of boats participating in the female lumpsucker (Cylopterus lumpus) fishery, (b) average number of gillnets hauled per landing, (c) average fishing period of the fleet (red/blue line) and maximum allowed fishing period (yellow line), (d) average soak time of the gillnets from logbooks (red/blue line) and maximum allowed soak time (yellow line), (e) average size of boats participating in the fishery and (f) effort index, from 1985 to 2024. Dashed lines indicate when maximum number of gillnets was reduced from 300 to 200 (red) and when maximum number of gillnets was changed to maximum total length (green). Colour represents the two time periods utilized in the GLM (see results)1985–2004 (red) and 2005–2024 (blue).

Table 1
Summary statistics of general linear model of various measures of effort on the effort index from CPUE and landings data. N_{boats} = number of boats, N_{nets} = number of gillnets hauled per trip, and N_{days} = average number of fishing days.

term	estimate	std.error	statistic	p_value
Intercept	−5.2014	1.3413	−3.88	< 0.001
N_{Boats}	0.0103	0.0015	7.01	< 0.0001
N_{nets}	0.0495	0.0148	3.34	< 0.01
Soak time	−0.3451	0.1538	−2.24	< 0.05
N_{days}	0.0869	0.0111	7.84	< 0.0001

F_{proxy} of 0.86. The model predicted that when the number of boats was at the recent maximum of 369 boats with the average number of gillnets hauled per day for 2019–2024, that it would not be possible to maintain F_{proxy} below 0.75 with any number of days. This is unrealistic and the failure of the model is probably due to extrapolations beyond the data as the number of observations with high number of boats together with high number of gillnets was limited.

The change in regulations in 2013 led to a decrease in the average number of gillnets hauled from 63 to 54. The model predicts that this would have led to a decrease of 13 % in F_{proxy} when using values specific for 2013 (boats = 282, soak time = 4 days, average fishing period = 29.7 days). The actual F_{proxy} in 2013 was 1.06, if this had indeed been decreased by 13 % due to the change in the regulations regarding the number of gillnets, then had this change not been implemented, then the F_{proxy} would have been 1.22 which is equivalent to an additional catch of 686 tonnes.

4. Setting number of fishing days

By rearranging the GLM model (formula 2, Table 2), it can be used, together with the number of boats that will participate in the fishery, to estimate the maximum number of fishing days that will achieve F_{target} (Eq. 4)

$$N_d = \frac{F_{target} - (-0.88 + 0.002 * N_b + 0.0108 * N_{nets} + 0.024 * resid + 0.176)}{0.007} * \frac{1}{0.97} \quad (4)$$

Assuming no changes in regulations, average values from the previous 5 years can be used for the average number of gillnets hauled. The value of 0.97 refers to the assumption that 97 % of the fishing days are utilised.

5. Discussion

The lumpsucker fishery in Iceland has been constantly changing regarding effort over the past three decades with a move towards larger boats, hauling a greater number of gillnets per fishing trip but fish for a shorter period (due to regulations). To maintain F_{proxy} below F_{target} (0.75), fishing effort needs to be constrained. While there are limitations on the total length of gillnets and the number of fishing days, a significant source of variation in the effort is the number of boats which participate in the fishery each year. While there is a limit on the number of licences, there is a considerable degree of latent effort; at the time of writing (2024) there were 429 boats with a lumpsucker licence, however, since 1998, the greatest number of licences utilised within any one year was 363. If all 429 licences were to be utilised within one year (which would be unprecedented) this would far exceed the capacity of the fishery (i.e. F_{proxy} would likely exceed F_{target}). At the recent maximum (363), under recent developments in the number of gillnets hauled per day, it is unclear how many days fishing could be carried out while maintaining F_{proxy} below 0.75, but it would likely be so few that it would be uneconomical.

The biomass index from the spring groundfish survey is currently taken into account when the number of fishing days for a season is being considered. However, assuming the biomass is above the historical minimum, then this value plays only a minimal role when deciding upon the number of fishing days as F_{target} is constant between years. With the increase in CPUE with the biomass index, a constant level of effort between years will take a similar proportion of the population irrespective of the biomass index, which will equate to an increase or decrease in landings in line with changes in the biomass index. However, the number of fishing days needs to be adjusted in accordance with the number of boats that participate in a particular year to maintain a constant level of effort between years. Under the current system, this is not possible as the number of boats which will participate is unknown prior to the commencement of the fishery. There is substantial variation in the number of boats which participate in the fishery each year, and this has a strong effect on the resultant F_{proxy}. Thus, in order to optimize

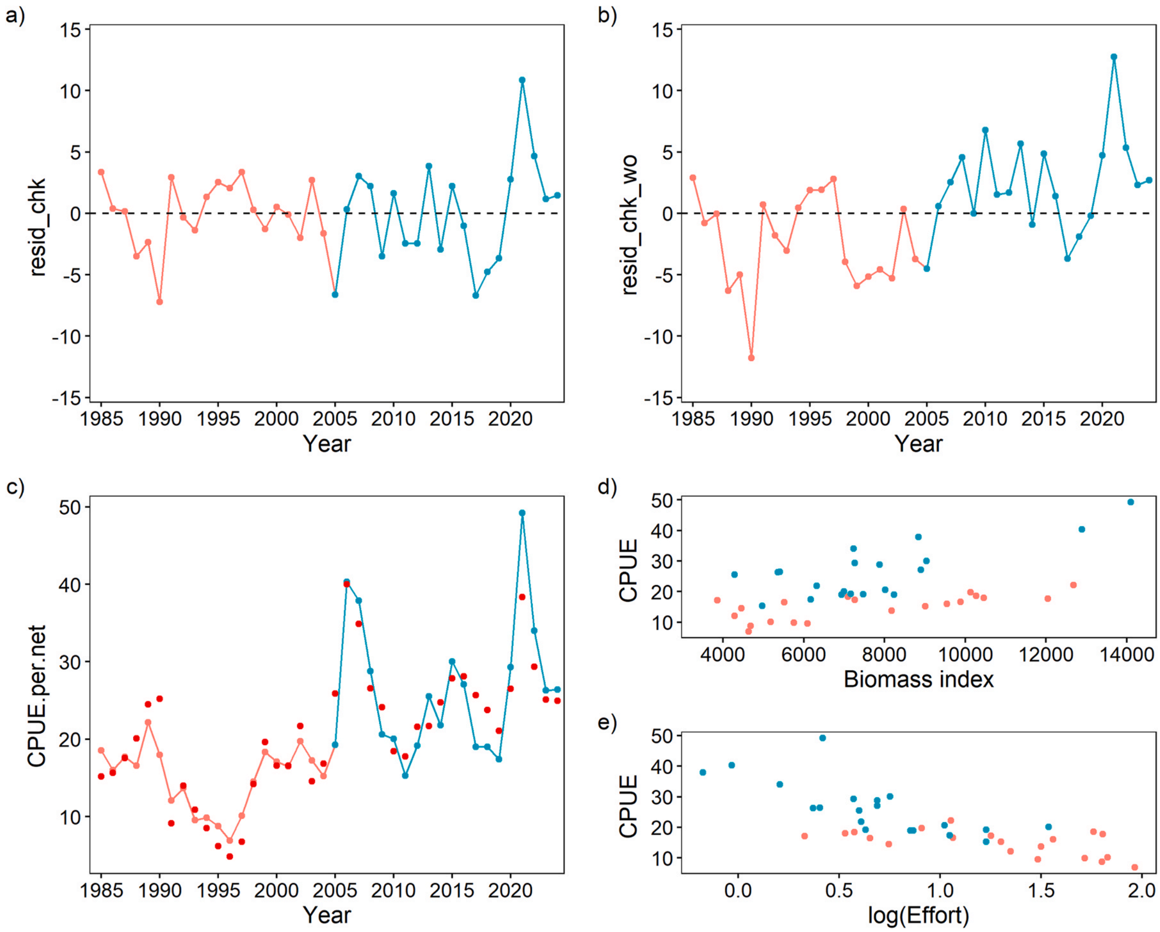

Fig. 4. Residuals from the linear model CPUE = biomass index + log(effort) + time period when time period was (a) included and (b) not included in the model, (c) change in CPUE over time (black line) together with predicted values from the linear model (red points), (d) raw values of biomass index versus CPUE and (e) log transformed effort versus CPUE. Colour represents time period 1980–2004 (blue) and 2005–2024 (red).

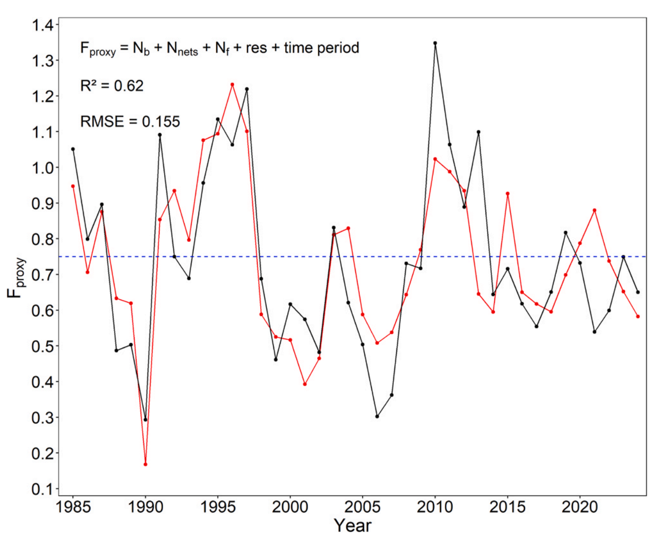

Fig. 5. Predicted F_{proxy} using Leave-one-out Cross Validation (red line) over time for female lumpsucker (Cyclopterus lumpus) (Table 1) and actual F_{proxy} (black line). The model used for the predictions is shown along with R^2 and RMSE. N_b = number of boats, N_{nets} = average number of gillnets hauled per trip, N_f = number of fishing days, res = residual index.

Table 2
Summary statistics of general linear model of various measures of effort on F_{proxy}. N_{boats} = number of boats, N_{nets} = number of gillnets hauled per trip, and N_{days} = average number of fishing days.

term	estimate	std.error	statistic	p_value
Intercept	−0.8759	0.2409	−3.64	< 0.001
N_{Boats}	0.0020	0.0004	5.21	< 0.0001
N_{nets}	0.0108	0.0035	3.14	< 0.01
Residual index	0.0242	0.0063	3.84	< 0.001
N_{days}	0.0073	0.0029	2.50	< 0.05
Time period	0.1760	0.0827	2.13	< 0.05

the fishery in terms of utilization of the recommended TAC, the number of boats which will participate in the fishery should be known before the fishery begins for that year. If the number of boats is lower than expected, then there will be under-utilisation of the recommended TAC, however, if substantially more boats participate than expected, this would increase the F_{proxy} beyond the F_{target}.

An important shortfall in the prediction of F_{proxy} is the lack of real-time information on the residual index which is a significant predictor of the resultant F_{proxy}. The residual index is likely an indicator of over/under estimation of the biomass index and(or) variations in catchability. Given the size of the effect of the residual index on F_{proxy}, precise estimation of F_{proxy} before the fishing season begins could prove challenging with the actual F_{proxy} likely to be up to approximately ± 0.10 of the estimated value in most years (but could occasionally exceed this) when using a presumed value of zero. There are however two alternative

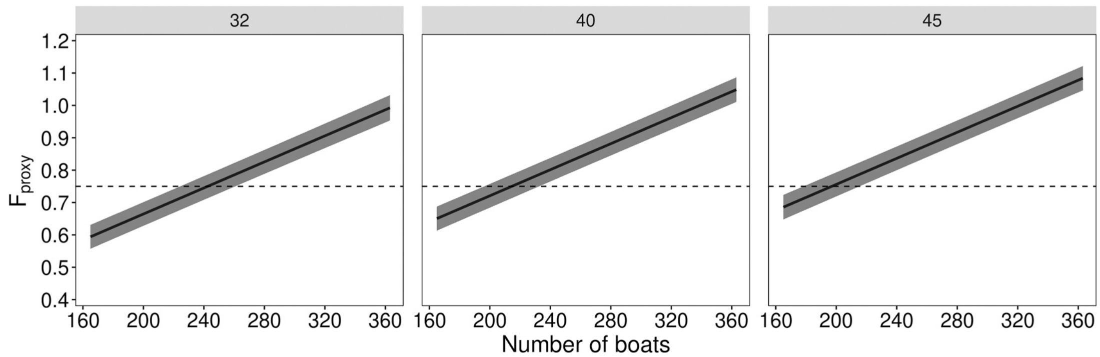

Fig. 6. F_{proxy} versus number of boats for a fishing period of 32, 40 and 45 with boats utilising 97 % of the fishing period as predicted by the GLM model (Table 2). Twenty percent prediction limits are shown.

methods that could be used to deal with this situation. One possibility is to allow the fishery to proceed with the desired level of effort that would lead to an estimated F_{proxy} of 0.75 with the assumption of no over/under estimation and constant catchability. This will lead to F_{proxy} being lower or higher than the target F_{proxy} in particular years depending on the actual situation of that year, but over the long term, average F_{proxy} should approach 0.75. Allowing the fishery to proceed is the strategy taken in Iceland from 2012 to 2019. An alternative approach is to monitor the progression of the fishery. Landings in Iceland are known in real time so if an F_{proxy} of 0.75 is likely to be exceeded, the fishery can be closed, or could be extended if final landings are expected to fall significantly short of F_{target}. This strategy was taken in Iceland from 2020 to 2024 with the fishery being closed early in 2020 when the catches were much higher than expected given the biomass index of that year. This strategy ensures that F_{proxy} never exceeds 0.75 but it results in an olympic fishery as the fishers are aware the fishery could be closed early creating an incentive to begin fishing early.

The lumpsucker population in Iceland spawns over many months with the fishery selecting for fish which are very close to spawning due to the migratory behaviour of lumpsuckers as they approach spawning (Kennedy, 2018). The current understanding is that lumpsucker resides outside of the main fishing areas in areas of deeper water while their ovaries develop for spawning. They then migrate to shallow water to spawn and it is then that they become vulnerable to fishing (Kennedy, 2018). The lack of any discernible decrease in catches of individual boats through the fishing period suggests that there is no localised depletion of fish. This indicates there is a frequent influx of fish from outside the fishing area which agrees with the current understanding. However, the reason for the boats which begin earlier having greater catches for the season is unclear but it may be that boats which begin earlier get the best fishing spots.

With increasing soak time, the catch per night of the gillnets decreased, as seen by the negative correlation between soak time and catch per day; this is a well-documented characteristic of gillnets (Hansen et al., 1998; Minns and Hurley, 1988; Olin et al., 2004). As lumpsucker gillnets are set in shallow water (<50 m), they tend to become entangled with seaweed which will decrease their efficiency. In addition, Atlantic cod (*Gadus morhua*), a frequent bycatch species in the lumpsucker fishery, tend to roll up the net which also decreases its effectiveness. Soak time was negatively correlated with effort and in 2012, maximum soak time was decreased from 6 to 4 days, and then to 3 days in 2020. The aim of this decrease in soak time was to reduce discarding of cod which quickly dies and decomposes after becoming entangled in gillnets, this contrasts with lumpsucker which can survive in a gillnet for several days (Kennedy et al., 2016). With this reduction in soak time, the gillnets are cleared of catch and seaweed more frequently which will increase their effectiveness. This decrease in soak time effectively increased the effort but it appears the increase was not sufficient to significantly influence F_{proxy}. This could be in part due to the data in the logbooks concerning soaktime being observational and lacking a systematic investigation into its effect on catch. It is often the case that when catches are expected to be high, the gillnets are hauled earlier, which will alter the correlation between soak time and catches.

In 2013, the total number of gillnets allowed by each boat was reduced from a maximum of 100 per crew member with a maximum of 300 per boat to a maximum of 200 per boat irrespective of the number of crew. The aim of this regulation was to reduce the total effort within the fishery. The number of gillnets hauled per trip decreased in 2013 by ~10 nets (15 %) compared to the previous year with an estimated reduction in F_{proxy} of 13 %. Given that the regulation cut the maximum number of gillnets by a third, why was the decrease in gillnets hauled per day not much lower? It may have been that many boats were not using the maximum number of gillnets or, it could have been that boats with only 1 crew member increased their number of gillnets. Unfortunately, data was not available to truly understand the effects of this change in the regulations.

The present study highlights how total effort should be carefully considered in a gillnet fishery. More gillnets in the water or greater soak time does not necessarily equate to increased effort or increased mortality, in fact this can have the opposite effect. By having fewer gillnets, these nets can be hauled, cleared of fish and debris and reset, more often. Thus, the total fishing power of each net over the entire fishing period will be greater. This essentially means that for a given fishing period, shorter soak time between haulings will result in the net being hauled more often within the fishing period and so higher effort.

The index of fishing effort (landings/CPUE) is the current metric utilised to track changes in effort over time in the stock assessment of lumpsucker in Iceland. Given that the measures of effort considered within the present study explains 90 % of the variance in the effort index over time gives confidence that the method gives a reasonable indicator of effort over time. This level of explanatory power indicates that the majority of the effort in this fishery is captured with just four variables; number of boats, number of gillnets hauled per trip, soak time and average number of fishing days. However, the need for the inclusion of time period suggests there was a significant change in the fishery which affected CPUE. This increase in CPUE at a given level of effort coincided with the introduction, in 2006, of a limit on the number of fishing days per boat. This limit was requested by the fishers themselves to limit catches and maintain price, however, the mechanism behind it which led to the increase in CPUE is unclear.

It is interesting to contrast the lumpsucker fishery with other fisheries which have a history of input controls but differing results in terms of their success in constraining effort/total catch. The Faroe Islands demersal fishery has been managed using an effort quota (EQ) system since 1996, but this system is considered a failure due to the poor state of the cod and haddock (*Melanogrammus aeglefinus*) stocks and that the fleet is largely unprofitable (Danielsen and Agnarsson, 2018). The Faroe Island demersal fishery is a multispecies fishery with a fleet consisting of different sized vessels utilising different gears. As a result, the relationship between fishing effort and fishing mortality is unclear and technological creep has altered this relationship over time (Eigaard et al., 2011). This contrasts with the lumpsucker fishery which targets a single species, with a single gear type and exclusively by small coastal vessels. The use of input controls was considered efficient in managing latent effort and constraining catches in the Australian rock lobster (*Panulirus cygnus*) fishery, which also targets a single species with a single gear type (Penn et al., 2015). There were interesting similarities in the management system between the Australian rock lobster fishery and Icelandic lumpsucker fishery including a limited entry system and limits on the total effort each boat could employ (i.e. number of pots per 10 m of boat length and total length of gillnets for the rock lobster and lumpsucker fishery respectively), both fisheries also had an indicator of abundance of the target species which they could use as a basis for management. The Australian rock lobster fishery did eventually switch to output controls in the form of a TAC to improve economic efficiency.

In 2024, the Icelandic government decided to change the management of the lumpsucker fishery from input to an output-controlled fishery for economic reasons, similar to that for the Australian rock lobster (Penn et al., 2015). With this move away from input controls, the findings of the current study are unlikely to be tested. However, the study demonstrates that small scale fisheries can be managed successfully using input controls to limit fishing mortality when an index of abundance is available. The lumpsucker population in Iceland, while it does fluctuate from year to year, does not show any signs of long-term decline. This points to the success of the management system, but declining participation in the fishery is likely to also have played a role. There is a substantial amount of data available for the lumpsucker fishery in comparison with many other small-scale fisheries and for a fishery which has been managed as an input controlled fishery for multiple decades. This will present an interesting study in the coming years after the quota system has been implemented.

CRediT authorship contribution statement

James Kennedy: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of Competing Interest

I have nothing to declare.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.rsma.2025.104105.

Data availability

Data will be made available on request.

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