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# Decarbonizing Fisheries Through Ensuring Healthy Stock Status

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## ABSTRACT

Industrial capture fisheries depend on fossil fuels, which tend to dominate both greenhouse gas emissions and operational costs of this form of seafood production. Improving energy efficiency is, in addition to shifting to alternative fuels, a crucial path towards decarbonizing fisheries. Theory suggests that healthy stocks, i.e., with higher density, should require less fuel to harvest when fishing effort and catches are correlated. This is a situation generally observed in bottom trawl fisheries. Rebuilding stocks could thus represent an important pathway for decarbonization. By analysing available time series data on fuel use intensity (FUI), fleet size and fish price in 13 European and U.S. bottom trawl fisheries, we find empirical evidence that lower FUI is associated with higher stock abundance. Lower FUI is also observed for catches with lower fish prices and with reductions in fleet size. Results suggest that rebuilding fish stocks by setting and following sustainable harvest limits combined with balancing fishing capacity with resource availability can be one part of a decarbonization strategy. However, economic incentives such as fish price and subsidies are counterproductive. Combined, this suggests that energy use and carbon emissions be considered as key fisheries management objectives. The sparse data availability of fuel use in fisheries also points to the need for standardised collection programs to allow for further research for improved understanding as well as monitoring progress towards societal objectives.

## 1 | Introduction

Capture fisheries, and particularly industrial fisheries, depend extensively on fossil fuels for vessel propulsion and other onboard processes. This use typically dominates the greenhouse gas (GHG) emission profile, or carbon footprint, of the full value chain of seafood products (Parker et al. 2018; Winther et al. 2020). Fuel cost is also an important component of operating costs which makes fisheries' profitability sensitive to fuel price increases (Guillen et al. 2023; Prellezo et al. 2024). Combined, the urgency to curb GHG emissions and recent spikes in fuel prices due to geopolitical conflicts have accelerated interest in the decarbonization of fisheries. In this endeavour, it is vital to begin improving energy efficiency of fishing operations to the extent possible, regardless of the primary fuel used for vessel operations (Ziegler and Hornborg 2023).

Efforts to understand and improve the energy efficiency of industrial fisheries date to at least the mid-1970s (Wiviott and Matthews 1975; Rawitscher and Mayer 1977; Lorentzen 1978). Though early work to improve energy efficiency often pursued technical interventions, it is now evident that reducing the fuel use intensity (FUI) of a fishery, typically expressed as a the volume of fuel combusted per unit mass of landings, can be achieved through multiple pathways and the result is the sum of all measures taken (Bastardie, Hornborg, Ziegler, et al. 2022; Ziegler and Hornborg 2023; De Vet et al. 2024). Reduction opportunities for a single fisher active in a specific fishery (defined by target species and fishing gear) exist in operational or technological changes. Examples of operational components include reduced steaming speed, and increased level of skipper and crew skill (Ruttan and Tyedmers 2007; Bastardie, Feary, Kell, et al. 2022), while technological changes include improvements in engines, ship design, hull maintenance, and development or refinement of gears to improve efficiency and reduce hull and gear drag in the water (e.g., Basurko et al. 2013, Sala et al. 2022). Studies that have explored the relative importance of potential drivers of FUI over time have, however, found that technological interventions typically have not been a main driver for improvements in energy efficiencies within a fishery (Hilmarsdóttir et al. 2024; Jafarzadeh et al. 2016). Rather, changes in FUI within fisheries have to a larger extent been attributed to fishery management actions—i.e., reducing overcapacity, stopping the “race to fish” and increasing the abundance of fish stocks, e.g., (Parker and Tyedmers 2015; Byrne et al. 2021).

A recent theoretical study (Guillen et al. 2025) suggested that both reducing fleet size and increase stock abundance should reduce fuel use by increasing stock abundance, while subsidies should increase it. Empirical analyses have to date only provided piecemeal information on the potential scale of improvements in fuel use efficiency from improved stock status in individual fisheries and only weak correlations between stock status and fuel use intensity have been found (Byrne et al. 2021; Bastardie, Feary, Brunel, et al. 2022). Although theory supports the notion of “more abundant fish, more fuel-efficient to fish” when comparing a fishery at two different points in time and in different conditions (Farmery et al. 2014; Hornborg and Smith 2020), other factors such as ex-vessel price of fish may also be of importance. Crustacean fisheries are for example often highly energy-intensive as the high value of the landings may sustain high fuel expenditures (Bastardie, Hornborg, Ziegler, et al. 2022). Further, fishing practices may differ as a function of the behaviour of the target species, where for example pelagic fisheries with purse seines often exhibit remarkably low variability in fuel use intensity (Parker et al. 2015) even though the stock status and absolute abundance of animals targeted with purse seines are likely to differ substantially. An explanatory factor may be that purse seiners target species that form schools, making the link weaker between time spent fishing and the resulting fuel use intensity of landings compared to bottom trawl fisheries that generally target demersal species occurring at lower and more uniform densities.

Bottom trawl fisheries contribute nearly a quarter of global marine landings and are highly variable in fuel use intensity (Parker and Tyedmers 2015; Cashion et al. 2018). This observed variability can be attributed to the species targeted (Parker and Tyedmers 2015), ex-vessel price (Bastardie, Hornborg, Ziegler, et al. 2022), and fishing capacity in terms of fleet size (Ziegler et al. 2016). Fisheries for demersal species, often using demersal trawls, also dominate global GHG emissions from capture fisheries (Parker et al. 2018). Consequently, identifying which factors primarily determine FUI of bottom trawling is an important endeavour for supporting the decarbonization of fisheries, and also improves our understanding of the extent to which high abundance may support energy efficient fisheries.

Here we assemble available time series data on bottom trawl fisheries in different regions. We evaluate the (extent that there is a) relationship between FUI and stock status, fishing capacity as represented by number of vessels, and ex-vessel price. The study is limited to bottom trawl fisheries for groundfish (gadoids and flatfish), motivated by their importance in global fisheries emissions, high variability in FUI between bottom trawl fisheries, similar stock dynamics, and data availability.

## 2 | Methods

### 2.1 | Case Study Identification and Selection

Our initial search for case studies targeted different time series of data on FUI for bottom trawl groundfish fisheries using the Fisheries and Energy Use Database (FEUD) database (Parker and Tyedmers 2015), our collective experience and knowledge of other publicly accessible datasets, and literature searches using combinations of search terms such as “bottom trawl”, “fuel”, “FUI” and “carbon.” Inclusion criteria were: at least 2 years of vessel-specific or fleet-wide total fuel use and species-specific landings data were available for trawl fisheries targeting primarily finfish species; there was no significant change to fleet definition over time (by consultation with local experts); outlier values did not indicate potential errors; fuel use values were not unreasonably high or low relative to global averages; and stock status was possible to obtain for at least 60% of all landings by the fleet. Effort was made to include case studies covering a range of geographical regions, fisheries management systems, and stock status.

Case study data sets included demersal trawl fisheries in various countries in Europe and North America (Table 1). Few records on FUI exist for other regions except for Oceania, where no fishery was identified that targeted finfish with bottom trawls and met our criteria (Parker and Tyedmers 2015). One dataset was included despite only having a single year of data: an Italian demersal trawl fishery in the Mediterranean. This was motivated from having high-precision data on fuel use intensity, a clear definition of target species, and occurring in a region where stock status is typically known to be poor, providing greater overall contrast in relative biomass values.

### 2.2 | Data Sources and Treatment

#### 2.2.1 | Fuel Use

For each case study, we compiled data on the annual fuel use (L) and total live weight catch for the same year (tonnes) to obtain annual FUI. Table S1 shows the source of fuel use for each case study. Annual FUI for each year and mean FUI over the time series in each case study appears in Table S2. One exception was the Dutch 40+ beam trawl where for several years a portion of the fleet was using pulse fishing (using electric currents to draw fish into the net), which reduced fuel use. To maintain

**TABLE 1** | Attributes of groundfish bottom trawl case study fisheries included in analyses.

| Case study | Fishing area | Main species | Fishing gear | Vessel size | Management system | Years |
|---|---|---|---|---|---|---|
| Dutch 24–40 beam trawl | NE Atlantic | Plaice, Sole, Dab | Beam trawl | 24–40 m | Individual quotas[a] | 2008–2021 |
| Dutch 40+ beam trawl | NE Atlantic | Plaice, Sole, Dab | Beam trawl | 40+ m | Individual quotas[a] | 2008–2021 |
| Germany | North Sea | Saithe, Cod, Herring | Trawl | NA | Individual quotas[a] | 2008–2021 |
| Iceland Danish seine | N Atlantic | Cod, Plaice, Haddock, Saithe, Redfish, Ling, Greenland halibut | Danish seine | NA | IVQ or ITQ[b] | 1982–1997 |
| Iceland decked trawl | N Atlantic | Cod, Plaice, Haddock, Saithe, Redfish, Ling, Greenland halibut | Trawl | NA | IVQ or ITQ[b] | 1982–1997 |
| Iceland freezer | N Atlantic | Cod, Haddock, Saithe, Redfish, Ling, Greenland halibut | Trawl | NA | IVQ or ITQ[b] | 1997–2018 |
| Iceland fresh | N Atlantic | Cod, Haddock, Saithe, Redfish, Ling, Greenland halibut | Trawl | NA | IVQ or ITQ[b] | 1997–2018 |
| Iceland trawl | N Atlantic | Cod, Plaice, Haddock, Saithe, Redfish, Ling, Greenland halibut | Trawl | NA | IVQ or ITQ[b] | 1982–1997 |
| Italy | N Adriatic | Sole, Sepia, Murex | Beam trawl | 24–40 m | Mainly effort controls[c] | 2019 |
| Norway | NE Atlantic | Cod, Saithe, Haddock | Trawl | NA | TAC or IVQ[d] | 1980–2017 |
| US Bering sea bottom trawl | Bering Sea | Yellowfin sole, Pacific cod | Trawl | 40+ m | Cooperatives[e] | 2008–2020 |
| US West Coast deepwater trawl | NE Pacific | Widow rockfish Petrale sole, Lingcod, Yellowtail rockfish | Trawl | 15–30 m | ITQ | 2009–2018 |
| US West coast shallow trawl | NE Pacific | Dover sole, Thornyhead, Sablefish | Trawl | 15–30 m | ITQ | 2009–2016 |

[a]Quotas set by EU allocated to vessels and producer organisations, and managed collectively within producer organisations.
[b]Individual vessel quotas between 1984 and 1989; individual transferable quotas beginning in 1990.
[c]Sole—primary tool effort control, also partially under EU TACs; Sepia and Murex—managed nationally through effort limitations, gear restrictions, and spatial closures.
[d]Fleet-wide TACs between 1980 and 1983; individual vessel quotas beginning in 1984.
[e]Allocation of quotas by company within cooperatives.

consistency in this data set we calculated what the fuel use without pulse would have been during those years based on the differential fuel use between pulse trawling and normal beam trawls, and the proportion of effort that was pulse trawling.

#### 2.2.2 | Catch Composition

All case study fisheries catch multiple species. When information on total catch volumes or catch of individual species targeted by each case study fishery was lacking, we compiled this information from a range of databases and agency publications as described in Table S1. The species considered in assessing stock status constituted 80% or more of the total catch, with the exception of the Iceland Danish seine which was 60%, and the Dutch 24–40 beam trawl which was 69%.

#### 2.2.3 | Stock Status

Stock status, i.e., estimated biomass relative to a target reference point for biomass expressed as a decimal fraction or multiple, were assembled for individual stocks targeted by each case study fishery and matched with landed volumes of the stock. These estimates were taken from stock assessments available from either ICES databases, the RAM Legacy Stock Assessment Database (RAMLDB), or the General Commission for the Mediterranean (GCFM) as shown in Table S1. Catch-weighted mean stock status estimates for each fishery are reported in Table S2. Management agencies in different fishery jurisdictions may have different target reference points which can result in differences in absolute stock abundances between fisheries, e.g., if the fishery is under a Maximum Sustainable Yield or Maximum Economic Yield regime (Hornborg and Smith 2020). This may complicate comparisons in FUI between case study fisheries. Where the case study fisheries operate, reference points are typically a proxy for the biomass level providing long-term maximum sustainable yield, making this issue less problematic. Further, the same reference point (usually from the most recent stock assessment) is used for all years for any given stock in the analysis and may thus be used to inform our assessment of the role of stock status as a driver of FUI for the case study fishery.

#### 2.2.4 | Price

Time series of fish ex-vessel prices were estimated for individual stocks. Estimates were drawn from national and regional datasets where available, and where not available were predicted using a regression model that accounted for taxonomy, region, and macroeconomic covariates (Melnychuk et al. in prep). Inflation-adjusted real prices were estimated from 1950 to 2016 and standardised to U.S. dollars in 2015. For each fishery and stock, we used the observed real price for the middle year of the time series, where possible corresponding to the same stock for which stock status was drawn. If observed prices were not available for the same stock, they were drawn from the geographically nearest stock of the same species. If the observed real price was unavailable, we then used the model-predicted real price for the corresponding species and region. Catch-weighted mean prices are reported for each fishery in Table 2.

#### 2.2.5 | Vessel Numbers

Where available, time series of vessel numbers for each fishery were assembled, with mean values listed in Table 2, taken from various sources listed in Table S1. For older datasets, vessel numbers were not available which led to separate analyses either including or not including vessel count data (See Statistical analyses). For our analyses including vessel counts, the number of vessels in each case study was scaled relative to the maximum number of vessels across its time series. We could find no time series data splitting the Iceland freezer and fresh fleets, so we used the total combined number and assigned them to the fresh fleet which constitutes the majority of the catch.

### 2.3 | Calculations

Fuel use intensity for fishery $f$ in year $y$ ($FUI_{f,y}$) was calculated as the total fuel volume used divided by the total live weight landed across all species reported by the fishery.

At the mixed-species fishery level, stock status combines individual statuses from multiple stocks. Combined stock status for fishery $f$ in year $y$ ($S_{f,y}$) was calculated as a weighted sum of ($R_{f,y,s}$) (the biomass of each individual stock $s$ in year $y$ relative to the reference point for stock $s$), weighted by the proportion of the total fishery catch that over all years came from stock $s$ ($W_{f,s}$). This was done so that if a stock was depleted and no longer constituted a significant portion of the catch, its poor status would still be reflected in our overall measure of stock status.

$$S_{f,y} = \sum_{s} R_{f,y,s} W_{f,s} \quad (1)$$

$$W_{f,s} = \frac{\sum_{y} C_{f,y,s}}{\sum_{y,s} C_{f,y,s}} \quad (2)$$

In calculating this weighting term, $C_{f,y,s}$ is the catch of stock $s$ in year $y$ in fishery $f$. This differed from the approach used to represent average price for each fishery, where only a single year (the time series midpoint) for each stock was drawn before applying the same weighting term $W_{f,s}$ to estimate average price for the fishery. This was because price varied little from year to year, but status in some cases varied considerably and we were especially interested in how changes in stock status may impact FUI.

For analyses, we rescaled the number of vessels in the fishery, $N_{f,y}$, to the maximum across years for that fishery:

$$N^{*}_{f,y} = \frac{N_{f,y}}{max(N_{f,y})} \quad (3)$$

### 2.4 | Statistical Analysis

We examined fluctuations in FUI in relation to changes in stock status, fishing capacity (relative number of vessels) and price. Our design allowed for case study-specific temporal trends in FUI to allow for potential changes from technological innovation, species distribution movement or other external factors. The number of vessels operating in each year in a fishery could only be determined

**TABLE 2** | Average values for fuel use, stock status, fleet size and ex-vessel price for each case study.

| Case study | Average FUI (L/t) | FUI range | Average stock status | Status range | Average number vessels | Vessel range | Average price (USD/t) |
|---|---|---|---|---|---|---|---|
| Dutch 24–40 beam trawl | 2074 | 1196-3057 | 1.59 | 1.21–1.97 | 28.5 | 24–35 | 3444 |
| Dutch 40+ beam trawl | 2976 | 2417-3494 | 1.57 | 1.20–1.95 | 58.8 | 52–64 | 3627 |
| Germany | 532 | 155–1145 | 1.95 | 1.53–2.27 | NA | NA | 1432 |
| Iceland Danish seine | 542 | 363–659 | 0.90 | 0.70–1.07 | NA | NA | 2487 |
| Iceland decked trawl | 591 | 458–684 | 1.00 | 0.74–1.28 | NA | NA | 2578 |
| Iceland freezer | 463 | 286–626 | 1.26 | 0.77–1.89 | NA | NA | 2563 |
| Iceland fresh | 609 | 385–865 | 1.24 | 0.73–1.89 | 58.2 | 43–76 | 2563 |
| Iceland trawl | 424 | 340–519 | 1.09 | 0.84–1.42 | NA | NA | 2371 |
| Italy | 5418 | 5418-5418 | 0.74 | 0.74–0.74 | NA | NA | 8.29 |
| Norway | 522 | 296–791 | 1.33 | 0.39–3.49 | NA | NA | 2289 |
| US Bering Sea bottom trawl | 137 | 122–154 | 1.96 | 1.63–2.10 | 19.5 | 18–22 | 555 |
| US West Coast deepwater trawl | 211 | 160–290 | 2.54 | 2.51–2.60 | 64.0 | 49–108 | 2321 |
| US West Coast shallow trawl | 245 | 180–440 | 1.51 | 1.19–1.84 | 51.3 | 36–89 | 2177 |

for seven case studies, as indicated in Table 2. We thus first analysed the full data set excluding a vessel effect (called 'AllCases'), and then analysed a second, smaller, dataset which included only records with a known number of vessels (called 'WithVessel').

We formulated two linear mixed-effects models (using 'AllCases' and 'WithVessel') using the R function 'lmer' in the package 'lme4', in both cases with annually-varying log(FUI) as the dependent variable. Predictor variables treated as fixed effects included: log(-Price) (the middle year of the corresponding time series); weighted average stock status relative to the target reference point (annually varying); calendar year (rescaled to years since 1979, so 1980 is 1, etc.); an overall intercept; and, for the 'WithVessel' analysis, the scaled number of vessels in the fishery. Random effects were also incorporated. Random intercepts allowed for variability in FUI among individual case studies, with offsets from the overall intercept constrained to follow a normal distribution. Random slopes of calendar year allowed for trends in FUI over time to also vary among case studies, where offsets from the overall fixed effect coefficient for calendar year were constrained to follow a normal distribution.

## 3 | Results

Fuel use intensity (FUI), stock status and number of vessels all varied among case study fisheries as well as over time (Figure 1; Table 2). Four of the case studies that began in the 1980s (Norway, Dutch 40+ beam trawl, Iceland Danish seine and Iceland decked trawl) showed no real trend in FUI until about 2010 when FUI for most cases began to decline. Other case studies with only more recent data available had either much lower or much higher FUI (note log scale in Figure 1). The relative variability of FUI, i.e., the ratio of the highest value to the lowest value within a case study's time series, was smallest for the Bering Sea fishery at 1.3 and largest at 7.4 for the German trawl fishery, with most other cases between 1.3 and 2.5. Many of the case studies with several decades of stock status estimates showed an improvement in stock status over time from around or below the target ratio of 1 in earlier years to above the target in more recent years. The relative variability in weighted average stock status values within a case study's time series was smallest for the U.S. deepwater trawl fishery, at 1.04, and largest for the Norwegian case study, at 8.88. All case studies with available data for vessel counts showed a decline in the number of vessels, ranging from 20% to 60% relative to the number of vessels fishing at the start of the available time series, with some declines steeper than others (Figure 1). Average fish ex-vessel prices ranged from a low of $555 per mt in the Bering Sea fishery to a high of $8290 in the Italian fishery (Table 2).

Across case studies, average FUI was positively related to middle-year fish ex-vessel price, and negatively related to weighted average stock status (Figure 2). For most case studies, weighted average stock status values were above the management target for biomass.

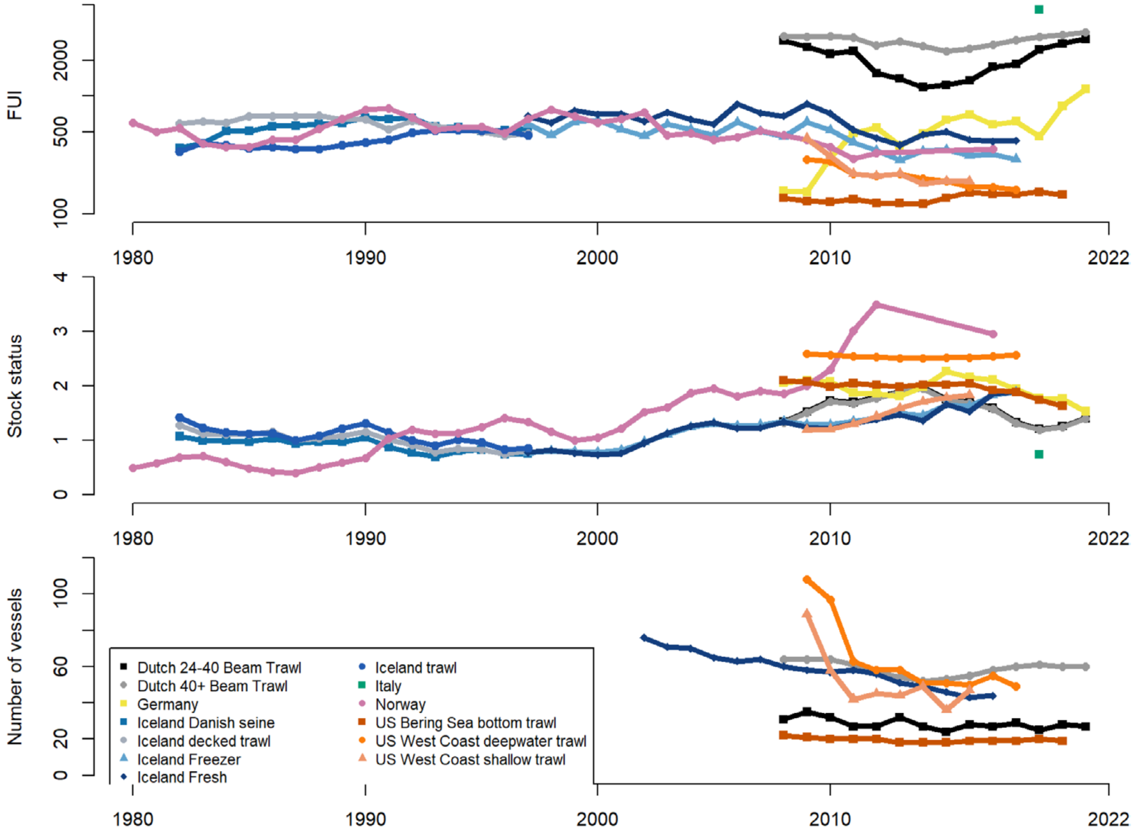


**FIGURE 1** | Fuel use intensity (FUI; plotted on log scale), weighted mean stock status and number of vessels by year for each case study.

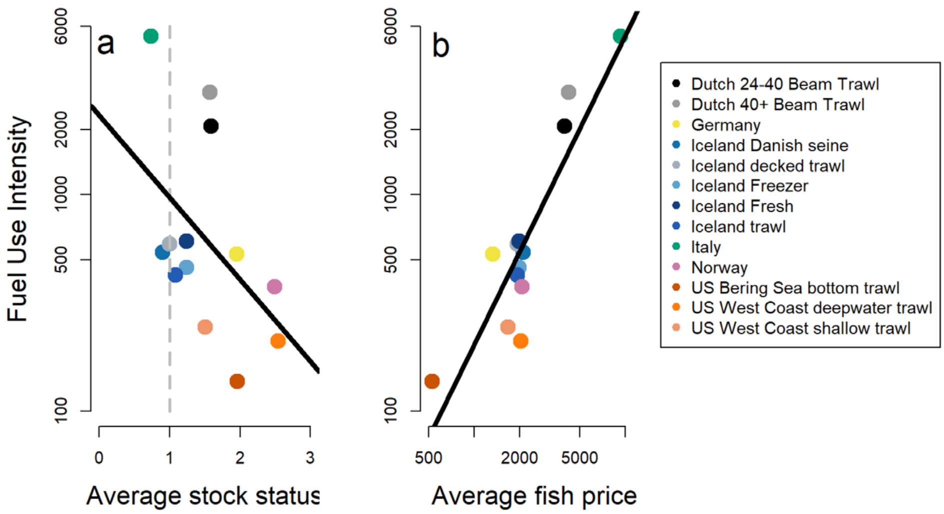


**FIGURE 2** | Relationships between average fuel use intensity and: Weighted average stock status (panel a); or average fish price (panel b). Fuel use intensity and fish price are shown on log scale. Data points are individual case studies. Solid lines show least-squares best fits. Dashed line at stock status = 1 represents the typical management target.

Within case studies, most cases showed a simultaneous increase in stock status, decrease in FUI, and where available, a decline in number of vessels. The most informative datasets in terms of the relationship between FUI and weighted mean stock status were the two Dutch beam trawl fisheries where FUI decreased and then increased corresponding to a period of increasing and then decreasing stock status (Figure 3). This pattern is far more informative than the other examples which typically had little contrast in stock status, or at best an increasing trend in stock status and a decline in FUI. Seven of the case studies showed a general decline in FUI with increasing stock status, while one (Iceland decked trawl 1977–1999) showed the opposite trend. There was little real contrast in stock status for most case studies, most obviously in the U.S. West Coast deepwater trawl case, but also in the Iceland Danish seine and Iceland decked trawl fisheries, which had only narrow ranges of stock status values throughout the period with

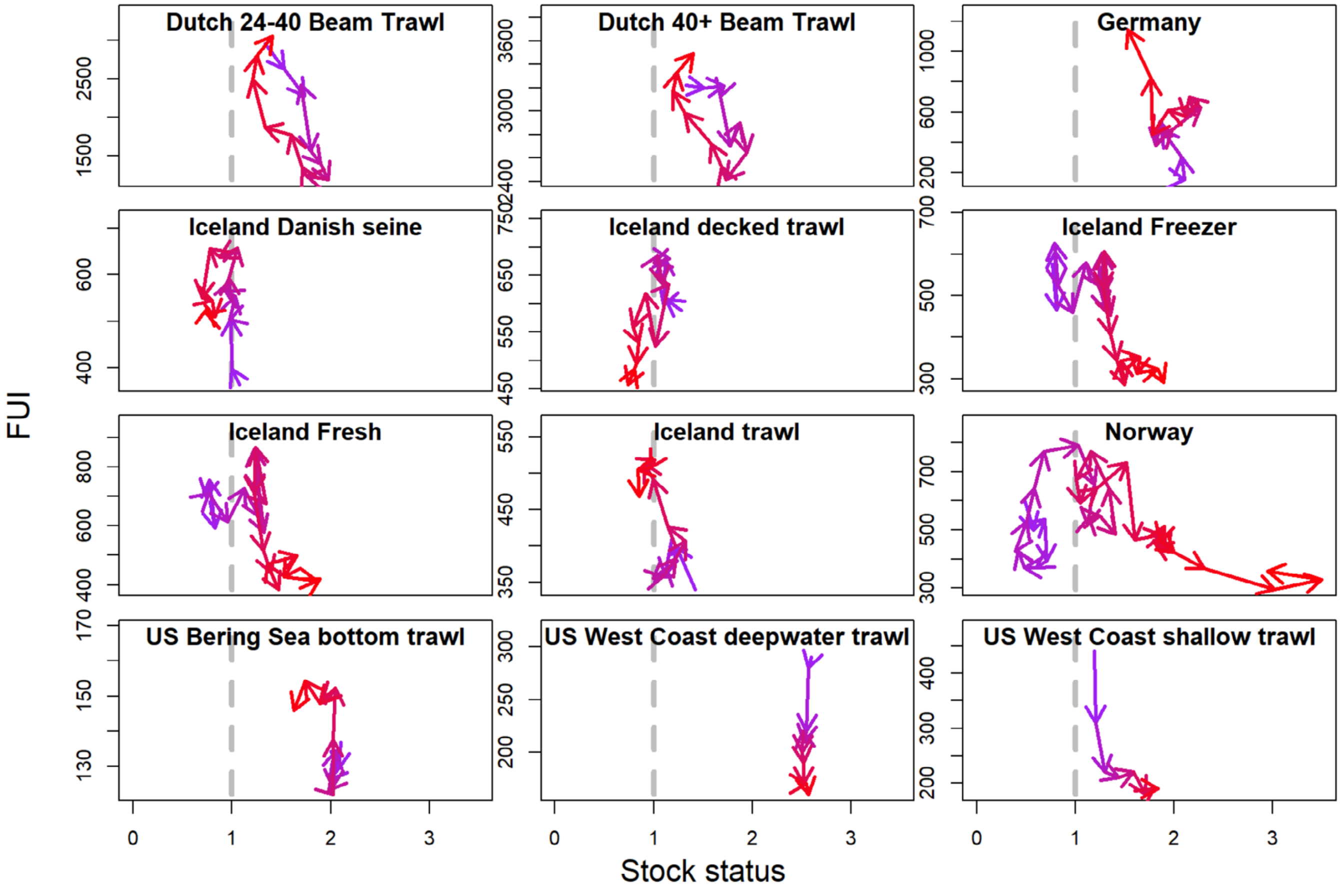


**FIGURE 3** | Phase plots of trends in weighted mean stock status and FUI for each case study. Arrows point from earlier (purple) to later (red) years within each time series. Note that the scale of vertical axes varies by panel. Dashed lines at stock status = 1 represent the typical management target.

available data. Half of the case studies had no biomass estimates that were below the target biomass level, while the other half had at least some years of below-target biomass levels (Figure 3). The Norwegian fishery had the greatest range of weighted average stock status levels, and a pattern of increasing FUI in early years followed by decreasing FUI in more recent years.

### 3.1 | Effects of Stock Status, Vessel Numbers, and Price

Fixed effects results are reported in Table 3, representing 13 case studies for the 'AllCases' analysis and seven case studies for the 'WithVessel' analysis. Intercept estimates are of little interest as these are sensitive to scaling and transformations of other predictor variables. In both analyses, a strong negative association between FUI and stock status was identified ($t < -8.2$), supporting the time-averaged pattern seen in Figure 2a. A positive, statistically significant relationship between FUI and ex-vessel price was also observed in both analyses, supporting Figure 2b. In the 'AllCases' analysis, the negative relationship with calendar year was statistically significant, indicating a general decline in log-transformed FUI over time (about 1.5% per year on average). However, in the 'WithVessel' analysis with vessel data available for a subset of the case studies, no effect of calendar year was observed (Table 3). Instead, a positive relationship between FUI and scaled number of vessels was observed, suggesting that the observed relationship between FUI and calendar year in the 'AllCases' analysis may be a surrogate for the missing data for number of vessels.

No strong correlations between fixed effect parameters were observed, except between the overall intercept and log ex-vessel price, as well as, in the 'WithVessel' analysis, a correlation of −0.65 between scaled vessel numbers and calendar year. Estimates of random effect variance hyperparameters reveal moderate variability among case studies. Estimates for the random intercepts among case studies were $\sigma^2 = 0.0916$ for 'AllCases' and $\sigma^2 = 0.214$ for 'WithVessel', with conditional modes reflecting the variability in FUI among case studies seen in the top panel of Figure 1. These hyperparameter estimates were similar in magnitude to residual variances of $\sigma^2 = 0.0268$ and $\sigma^2 = 0.0245$, respectively. Estimates for the random slopes around the overall calendar year relationship were instead negligible for both analyses ($\sigma^2 = 0.000118$ and $\sigma^2 = 0.000044$, respectively), suggesting little variability among case studies in the overall trend over time.

Fitted models were used to predict FUI for a typical case study fishery under different combinations of predictor variable values. Predicted FUI at low values of stock status are approximately 3-fold greater than at high values of stock status (Figure 4). Similarly, predicted FUI at the higher selected ex-vessel price are approximately 3-fold greater than at the lower selected ex-vessel price. The relative variability in predicted FUI was somewhat smaller over the range of relative fleet sizes considered, approximately 1.5-fold between the highest and lowest relative fleet sizes. An improvement in stock status from 1 to 1.5 could lead to a reduction in FUI of 25%. If this increase in stock status is combined with a reduction in number of vessel by 30% (corresponds to 0.7 in Figure 4 bottom panels), FUI could be decreased by 31%.

## 4 | Discussion

The case studies examined provide empirical evidence that in bottom trawl fisheries, (i) higher fish stock abundance generally leads to lower fuel use (as measured by FUI), (ii) fisheries with higher prices of target species tend to have higher FUI, and (iii) decrease in fleet size is associated with decreases in FUI. Some unexplained exceptions to these general rules exist, perhaps reflecting that FUI depends on more factors than just the three considered here. We chose to focus exclusively on bottom trawl fisheries for groundfish to eliminate some of the potentially confounding factors, but there was still considerable variability in FUI among case study fisheries. Still, the implications of this analysis are that FUI reductions may be achieved in part from management measures (i.e., improving the status of stocks and reducing the number of vessels), while FUI reductions associated with the price of fish are driven by market mechanisms and largely outside the control of either managers or industry. Thus, a single fisher may arguably be caught in between these driving forces—coping with rising fuel prices while being constrained by market prices for fish, only being able to make operational changes or technological investments within what is permitted in the given management regime.

In terms of representativeness of the case study fisheries, average fuel use intensity (FUI) ranged from a low of 137 L/t (Bering Sea bottom trawl fishery) to a high of 5148 L/t (Italian fishery in the Adriatic), thus spanning most of the range of reported FUI for fisheries generally (Parker and Tyedmers 2015). Further, the Bering Sea fishery had the lowest price and second highest average stock status of all the cases, while the Italian fishery had the highest price and the worst stock status (Figure 2). Apart from the Italian and Dutch case studies, the average FUI of fisheries examined here was under 500 L/t. This is well below the average reported for bottom trawls of roughly 2000 L/t, making most of the fisheries analysed among the least fuel intensive bottom trawl fisheries. The higher FUI in the Dutch case studies may

**TABLE 3** | Model results of the 'AllCases' and WithVessels' analyses. Fixed effect coefficient estimates, standard errors, and *t*-values are shown for associations between predictor variables and log-transformed FUI.

| Analysis | Variable | Estimate | Std error | *t*-value |
|---|---|---|---|---|
| AllCases | Intercept | −3.03 | 1.94 | −1.56 |
| | Log price | 1.45 | 0.25 | 5.80 |
| | Stock status | −0.59 | 0.10 | −6.18 |
| | Year | −0.02 | 0.01 | −2.58 |
| WithVessel | Intercept | −4.08 | 2.29 | −1.77 |
| | Log price | 1.42 | 0.29 | 4.18 |
| | Number of vessels | 0.81 | 0.22 | 3.70 |
| | Stock status | −0.53 | 0.10 | −5.33 |
| | Year | 0.00 | 0.01 | −0.40 |


**FIGURE 4** | Predicted FUI under different combinations of stock status, ex-vessel price, and fleet size (or fleet size data absent). Predictions are based on fitted models for 'AllCases' (top panels) and 'WithVessel' (lower panels) datasets. Ex-vessel prices of $3500 USD/t (left panels) and $1500 USD/t (right panels) represent high and low levels typically observed (Table 2). Colour represents different relative fleet sizes in lower panels, while upper panels do not include vessel counts among the predictor variables.

originate from the fact that these fisheries use beam trawls, a gear category with higher FUI compared to other types of bottom trawls and Danish seine (Thrane 2004). The Italian fishery targeted flatfish, representing fisheries in the higher range of FUI compared to other finfish fisheries (Gephart et al. 2021).

Concerning representativeness of stock status for the case study fisheries, time period and length of time series differed. The weighted average stock status ranged from 0.70 in the Italian fishery (1 year of data) to 2.54 in the U.S. West Coast deepwater trawl fishery (12 years of data). Over time, stock status varied to different extents, but few fisheries targeted stocks with low stock status values in any year of their available time series. Within the fisheries considered, 44 species/year combinations had stock status estimates below 0.5. However, being mixed stock fisheries, a stock with poorer status is averaged with stocks of better status. Depending on volumes caught, some signals of overfishing may thus not be picked up. For instance, the time series for the German trawl fishery includes landings of cod and herring stocks that today are severely depleted and have catch advice of 0 t. The FUI for this fishery shows a dramatic increase, but average stock status is less alarming (Figures 1 and 3).

We had relatively little data at stock status below $B_{MSY}$ and those showed no indication that increasing status led to lower FUI. Only the Norwegian data had a major increase in stock status from a low starting point and FUI went up. The Italian data set was a single observation but at the lowest average stock status and highest FUI.

### 4.1 | Theory and Previous Findings—Lessons Learnt for the Three Factors Analysed

If catch per unit effort (CPUE) determines FUI, and CPUE is dependent upon stock status, the relationship between stock status and FUI is relatively simple (Hornborg and Smith 2020). In general, there is a positive correlation between fish stock abundance and CPUE (Hilborn and Walters 1992; Harley et al. 2001), although exceptions exist for certain gear types and target species (Hoyle et al. 2024). The general negative relationship we found between FUI and stock status indicates a correlation for bottom trawl fisheries, and is consistent with earlier studies (e.g., (Ziegler and Hornborg 2014)). However, the result is not universal given the trend in the Iceland decked trawl fishery data. Such an exception is also supported by previous studies (Bastardie, Hornborg, Ziegler, et al. 2022), indicating potential influence of other factors that merits further investigations.

A positive relationship between fish price and FUI should be expected given that fuel costs frequently represent a significant fraction of total fishing costs. With a higher value of the product, the increased fuel use and associated costs may be sustained. Fisheries for small pelagic species consistently have the lowest FUI, while fisheries for crustaceans have the highest (Parker and Tyedmers 2015), correlating with the typical price of these groups.

There are a number of reasons that we might expect fleet size reductions to reduce FUI. First is interference competition. When there are fewer vessels there is less competition for prime fishing locations. A second reason is fleet rationalisation which can result from either government run or facilitated effort reduction by paying vessels to leave the fishery (Holland et al. 1999), or formation of cooperatives in which fishing companies agree on how to share catch and then only operate the minimum number of vessels to achieve their combined allocated catch (Felthoven 2002). A natural dynamic of fleet rationalisation is for less efficient vessels to be retired, while more efficient vessels remain active. This was the case for all three U.S. fishery case studies. While there are more attributes of efficiency in vessels than just fuel use, more efficient vessels are generally going to be characterised by higher CPUE and lower operating cost, both of which would lead us to expect decreased FUI with rationalisation.

### 4.2 | Other Influential Factors Not Considered

This analysis focused on various bottom trawl fisheries to minimise confounding factors among which gear type may be the most prominent (Parker and Tyedmers 2015). When considering other gear types, surrounding nets such as purse seines have lower FUI than methods like pots, traps and hook and line gears that capture less fish per days fishing. Trawling practices are, however, more complex. On the one hand, they generally catch higher volumes than pots, traps and hook and line, but they also tow fishing gear through the water which is a more energy-intensive practice than use of passive gear types. There is also a considerable difference in FUI between bottom trawls and pelagic trawls, the latter typically benefiting from avoiding the increased resistance and related fuel use of being dragged along the bottom, while also often capturing schooling species, both of which result in lower FUI. Correlations between FUI and stock status may also be stronger for fisheries that are more selective for one or a few stocks, compared to highly mixed fisheries, which applies for both bottom trawl fisheries and other gear categories.

Davie et al. (2015) evaluated factors in fuel use including vessel gear, vessel size and fuel price. Bastardie et al. (2010) concentrated on spatial allocation of fishing and reducing FUI by fishing closer to port. This however also depends on fish behaviour. Scherrer et al. (2024) for example showed that the FUI of the Norwegian fishery doubled when fishers were forced to catch the fish in the Norwegian EEZ instead of the UK EEZ, due to unfavourable schooling behaviour.

### 4.3 | Perspectives for the Energy Transition of Fisheries

There is considerable discussion related to decarbonizing fishing fleets through switching to methanol, ammonia or electrical power (Koričan et al. 2023; Díaz-Secades 2024; Sønnervik et al. 2024), but these technologies could take decades to become economic and transition the fleets. All alternative fuels known so far have a lower energy density than marine diesel fuel, which means that larger volumes are required to provide the same amount of energy. Since storage volume on fishing vessels is strongly limited, it is critical that the energy requirements are minimised, which can be achieved by increasing the fuel efficiency *before* shifting to alternative fuels. The analysis presented here suggests that FUI of many fisheries could be markedly decreased by specific management interventions with decarbonization benefits realised on potentially much shorter required timeframes, depending on the starting point status of stocks and extent of fleet over-capacity. In the short run, this could imply a decrease in total catches from a fishery, but in persevering through such a transition to a point where long-term sustainable yields are maximised, FUI and resulting GHG emissions will be reduced while supporting the longer term project of fully decarbonizing fisheries. Maintaining high stock status and reducing fleet size is only one tool available to reduce the total carbon footprint of fisheries.

Costello et al. (2016) estimated that rebuilding overfished stocks could result in roughly 15% increase in global fish landings. Thus, our results suggest a potential win-win in that rebuilding overfished stocks could increase both fisheries yield and reduce carbon emissions per tonne of fish produced.

The most obvious next step would be to conduct a similar analysis to some other types of fisheries if robust data may be found, particularly fisheries at low stock abundance. This would be particularly valuable for bottom trawl fisheries for crustaceans which overall have particularly high FUI but vary both in FUI and in terms of abundance. It would also be useful to find bottom trawl fisheries with higher-than-average FUI to contrast with case studies examined here. It would also be of interest to examine correlates for other gear type categories, such as large pelagic longline fisheries which have a FUI between 1500 and 2000 L/t (Parker and Tyedmers 2015).

Our analysis highlights the importance of good monitoring of the fuel efficiency of fisheries over time. Better incentives for collection and publication of quality-checked, standardised data of fuel use in fisheries are needed to improve our understanding of key driving factors, provide opportunities for future analysis, and to evaluate the effects of management interventions.

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## Conflicts of Interest

R.H. has received research funds from a range of sources, including governments, foundations, non-governmental organisations, and industries that have interests in conservation, sustainable use, and effective fisheries management. F.Z. and S.H. are employed by an institute that does research and contract work in their areas of expertise (e.g., carbon footprint of fisheries) commissioned by governmental and non-governmental organisations or by seafood companies. P.T. has received research funding, and provided advice under contract, to a range of governmental, nongovernmental, and industry organisations with an interest in improving the environmental performance of seafood production systems. These sources of funding may be perceived as a conflicts of interest. All other authors declare no conflicts of interest.

## Data Availability Statement

The data that supports the findings of this study are available in the Supporting Information of this article.

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## Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Table S1:** Sources of data for case studies. **Table S2:** Aggregated data used in statistical analysis and graphs.