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# Integrating individual trip planning in energy efficiency – Building decision tree models for Danish fisheries

Francois Bastardie*, J. Rasmus Nielsen, Bo Sølgaard Andersen, Ole Ritzau Eigaard

*Technical University of Denmark, Institute for Aquatic Resources, Section for Management Systems, Charlottenlund Castle, DK-2920 Charlottenlund, Denmark*

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ABSTRACT

Danish fishermen have provided information on dynamics in their fuel consumption, running costs, and fishing patterns through a web-based questionnaire. This detailed documentation of the fishing practices is used in spatial modelling tools to improve advice and research for fisheries. The tools integrate detailed information on vessel distribution, catch and fuel consumption for different fisheries with a detailed resource distribution of targeted stocks from research surveys to evaluate the optimum consumption and efficiency to reduce fuel costs and the costs of displacement of effort. The energy efficiency for the value of catch per unit of fuel consumed is analysed by merging the questionnaire, logbook and VMS (vessel monitoring system) information. Logic decision trees and conditional behaviour probabilities are established from the responses of fishermen regarding a range of sequential hypothetical conditions influencing their trip decisions, covering the duration of fishing time, choice of fishing ground(s), when to stop fishing and return to port, and the choice of the port for landing. Fleet-based energy and economy efficiency are linked to the decision (choice) dynamics. Larger fuel-intensive but efficient vessels conducting pelagic or industrial fishing are more inclined to base their decision on fish price only, while numerous smaller and less efficient vessels conducting demersal mixed or crustacean fishery usually consider other flexible factors, e.g., the potential for a large catch, weather, previous knowledge and experience, and the distance to/from port, which affect the number and duration of trips and the fuel consumption. Integration of the results into our recently developed spatially explicit individual-based fishing vessel model (IBM) incorporate the variability and predict the adaptations of individual fishermen to resource availability dynamics, increasing fuel prices, changes in regulations, and the consequences of socioeconomic external pressures on harvested stocks. A new methodology is described here to obtain quantitative information on the fishermen's micro-scale decisions initially required.



## 1. Introduction

Economic and energy efficiency has drawn increasing attention and causes concerns in the fishing capture sector because of rising fuel prices which cannot be expected to decrease over the coming decades (Tyedmers et al., 2005; Sumaila et al., 2008; Audsley et al., 2009; Driscoll and Tyedmers, 2010). The reduction of $CO_2$ and pollutant emissions is also a focus area for shipping and fisheries as it impacts the global climate debate and politics. To establish less fuel-intensive fishing practices for seafood production was already a key issue three decades ago (FAO, 1995) and extensive efforts have been expended to find technical solutions for this such as investments in new energy efficient propellers, gears and other equipment, engines, vessel hulls as well as a general modernisation and renewal of the fishing fleet (Suuronen et al., 2012).

Recent policy developments such as the EU Marine Strategy Framework Directive (MSFD) (EC, 2007) acknowledge that economic and energy efficiencies in fisheries are important components of ecosystem-based approaches to fishery management. A future policy outcome may be the definition of environmentally friendly fisheries that acquire a sustainability certificate for energy use (e.g., carbon labelling for attaining a low footprint aimed at changing consumer habits, Thrane et al., 2009) in the same way that a marine stewardship council (MSC) certification was set up for good fishing practices advised by the FAO Code of Conduct (FAO, 1995).

When including energy efficiency objectives of fisheries in maritime policies it is essential to acknowledge the large heterogeneity of individual vessel operations, both when setting policy targets and when defining the means (regulations) of achieving the targets. This goes for all policies pertaining to fishing activities such as, e.g., area-based management in the form of fine-scale real-time closures or marine protected areas (e.g., Eastwood et al., 2007; Holmes et al., 2011; Needle and Catarino, 2011). Because these measures

* Corresponding author. Tel.: +45 35883398; fax: +45 35883333.
*E-mail address:* fba@aqua.dtu.dk (F. Bastardie).

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affect energy and economic efficiency of individual vessels, side effects such as 'borderline' fishing have been identified, which can sometimes negate the expected policy outcome (Dinmore et al., 2003; Suuronen et al., 2010; Bastardie et al., 2010a; Mascia et al., 2010; Smith et al., 2010; Fox et al., 2012). For example, the economic return of closures is uncertain over the short term especially when fisheries are excluded from the high catch rate zones (Smith et al., 2010), which overall affects catch rates, prices and markets. The compliance and response of fishermen to management actions is a key factor to be accounted for in managing fisheries (Wilen et al., 2002; Nøstbakken, 2008; Fulton et al., 2011), and it is critical that potential unintended and undesirable outputs (the so-called 'implementation errors') resulting from hidden disincentives (e.g., extra costs, loss of catching power) can be identified at an early stage and, if possible, tested prior to the implementation of the regulations to avoid suggesting suboptimal and inefficient regulations. Consequently decision tools that take into account variability in energy efficiency, fishing tactics and choices among vessels are among the prerequisites for proper policy making.

Agent-based modelling (Dreyfus-Leon, 1999; Millischer and Gascuel, 2006; Beecham and Engelhard, 2007) offers a framework to incorporate individual decisions and their processes in fisheries. An important goal of this type of modelling is, among others, to circumvent the so-called 'ecological fallacy' problem (Robinson, 1950) that arises from the aggregation of heterogeneous factors, such as the aggregation of different fishing activities, which might neglect the internal variability among vessels. With off-set in agent based modelling, we have so far established a spatial bio-economic individual vessel-based model (IBM) where the efficiency in a fishery can be evaluated according to energy consumption and profit (Bastardie et al., 2010b). This model includes a decision tree enabling the IBM to mimic the individual sequential decisions of individual fishermen. A key step is to strengthen this aspect by empirically establishing realistic decision trees and their interlinkages, which would improve the precision in IBM modelling of individual vessel behaviour.

The present paper describes the methodology and quantification of energy efficiency in the catch sector segmented by the fishing (or métier) exemplified by Danish VMS-equipped vessels (i.e., >15 m in length, EC, 2003) through the coupling of their logbook and VMS data. Estimated fuel consumption is allocated to the particular species landed and specific fishing methods. Because fishing operations and procedures are likely to influence the energy efficiency, we introduce a web-based questionnaire designed to evaluate fisherman tactics and behaviour to ultimately inform the IBM with the collected answers. The responses of the fishermen are converted into quantitative information which can direct and strengthen the completion of any individual vessel-based model dedicated to the evaluation of energy and economic efficiency for supporting well-informed incentive-based conservation policies.

## 2. Materials and methods

### 2.1. Design of the questionnaire

The questionnaire concern vessel fuel consumption, costs per fishery, and the details of fishing patterns and effort. The questionnaire is Internet-based and written in the PHP web language (http://www.php.net) as well as connected to a MySQL database (Beighley and Morrison, 2009). The use of a web interface has the advantage of wider coverage for the survey than time-consuming face-to-face interviews. The questionnaire was answered by the individual with the best knowledge of the vessel fishery, fishing pattern and economy. The incentive provided for completing the questionnaire was a lottery for a money prise among the respondents and assurances that the results are only used for research purposes to transform the fishermen's detailed knowledge into models, evaluation tools and methods that can provide the fisheries with research and advice. The information obtained is treated confidentially and no individual information is published. The respondents are asked questions in three main areas (supplementary materials): (i) the individual vessel fuel consumption per hour (when either steaming or fishing) and costs over the last year for their main fishing activity; (ii) their attitude and reactions to hypothetical fishing situations to determine their trip decisions and tactics; (iii) their potential reactions to external impacts such as increasing fuel prices. Questions on information that could be retrieved from other sources (e.g., logbooks) are not asked.

### 2.2. Quantification of energy (VPUF) and economic efficiency (VPUE) per activity

The coupling of satellite-based VMS data with the logbook declaration of landings and sale slips is presented in Bastardie et al. (2010a). This coupling enables a proxy of economic efficiency to be computed in terms of the monetary value of the landings per unit effort (VPUE), where one fishery might be recognised as more efficient than others if they use less input effort for obtaining a comparable value in output. The energy efficiency is measured in terms of the monetary value of the landings obtained per unit of fuel (VPUF). From the questionnaire responses, a proxy for fuel consumption per hour ($C$) is estimated for each vessel. Different fuel consumption during the steaming and fishing activities for trawlers is assumed as well as when the vessel is inactive at sea (all positions with speed less than 1 knots):

$$C = (3.976 + 0.236 \times \text{kW}) \times A \tag{1}$$

given the power of the engine in kW (known from the national vessel register), with the multiplier A being 1, 0.8 and 0.1 for the fishing, steaming and inactive states, respectively (extracted from the answers). $C$ is then connected to the VMS data (to link to the hours at sea) and the official logbook declaration (to link to the declared landings). An energy audit including collection of the annual fuel consumption data for 46 Danish vessels was conducted in 2009 (Jakobsen, 2011), offering the possibility to regress upon and assess the quality of fuel consumption per hour proxy ($R^2 = 0.78$) based on the questionnaire.

Energy efficiency in terms of the diesel consumption during displacement can be expressed in litres of fuel consumed during the entire trip at sea (steaming plus fishing) related to either the monetary value or to the weight of the landings. Energy efficiency in kg refers to the uptake in terms of the protein energetic value (e.g., edible energy return on investment, EROI), while energy efficiency in value (value per unit fuel, VPUF) refers to uptake in terms of cash profit for the fisheries-segment or the society as a whole. These two measures have different implications as particular fisheries are likely to obtain a low volume of catch which is actually highly profitable. For others, a high volume of catches may have a low price depending on market price dynamics. Because the economy is more likely to drive the fishermen than catch volume per se, only VPUF are analysed here.

The segmentation of the fishing activity into a set of fisheries (also called 'métiers' in Europe) is performed according to the EU Data Collection Framework (DCF; EC, 2008) that groups fishing operations into several combinations: (i) a type of fishing gear (OTB: otter bottom trawl; OTM: otter mid-water trawl; PS: purse seine; PTB: pair bottom trawl; PTM: pair mid-water trawl; SDN: anchored seine; SSC: fly shooting seine; GNS: set gillnet; and DRB: dredge, see http://www.datacollection.jrc.ec.europa.eu/dcf-legislation); (ii) a target assemblage of species (DEF: demersal fish; SPF: small pelagic fish; CRU: crustaceans; and MOL: molluscs, see EC, 2008); and (iii) a mesh size range for the trawl or the net (in mm) with the purpose of identifying activities with similar exploitation patterns. The DCF segments are, thus, supranational entities to which EU regulations apply. The identification of the target assemblages usually performed from declaration of catches (logbook data) is subject to improvements discussed elsewhere (Deporte et al., 2012). Here we use the current DCF métiers keeping the 30 most fuel-intensive métiers within the Danish fleets in 2010; less frequent métiers are pooled into an 'other' category. VPUE and VPUF are also compared with an additional segmentation of grouping vessels by length categories (15–18 m, 18–24 m, 24–40 m, and >40 m) to identify the contribution of the vessel type in the estimates.

The fuel dependency of each fleet segment is the percentage of fuel cost in relation to (ratio of) the revenue from landings. The fuel cost for each vessel is deduced from the fuel consumption multiplied by the average fuel price per litre for each vessel size category. The fuel price is calculated as the total fuel cost divided by the total fuel consumption for each category of vessel size. The stability of the aggregated VPUF per fleet-segment over years is investigated by a linear model for the period 2005–2010:

$$\begin{aligned}\mathrm{VPUF}_{\mathrm{year,fleet}} = {} & \beta_1 + \beta_2 R_{\mathrm{FLEET_{year}}} + \beta_3 R_{\mathrm{PRICE_{year,vsize}}} \\ & + \beta_4 R_{\mathrm{VPUC_{year,fleet,stock}}} + \beta_5 R_{\mathrm{BIOM_{year,fleet.stock}}} \\ & + \beta_6 R_{\mathrm{TVOL_{year,stock}}} \end{aligned} \quad (2)$$

where the term $R_{\mathrm{FLEET}}$ denotes the categorical fleet segment variable, $R_{\mathrm{PRICE}}$ the relative fuel price per vessel size category *vsize* (scaled to maximum within the time period, i.e., 2008), $R_{\mathrm{BIOM}}$ the relative abundance of the species (provided by ICES stock assessment) specific to the fleet-segments, and $R_{\mathrm{VPUC}}$ the relative fish price of the main targeted species (which is also fishery specific). $R_{\mathrm{TVOL}}$ is the relative total landed volume for the main targeted stocks, where $\beta$ denotes the coefficient parameters of the multiple linear model. The main targeted stock for a given fisheries corresponds to the species with the highest VPUE for the given fishery.

### 2.3. Revealing the decision trees behind the fishing tactics

Heterogeneity in energy consumption and efficiency depends on vessel type, vessel operation and vessel speed. The fishing tactics are related to the choice of fishing grounds, targeting of stocks and ports, etc. Decision choices on the way fishing is operated are likely to result from a mixture of various triggering factors that make reactions to encountered situations (various feedbacks, thresholds, etc.) variable. Tree-based decision classification is well suited to investigate such non-linear and mechanistic relationships (Ripley, 1996). Answers from fishermen are yes/no-answers that enable them to be partitioned into binary graphic trees. These binary graphic trees are computed with the R add-on package 'rpart' (Therneau et al., 2009). Trees represent the splitting of the answers to each question according to a list of categorical variables, each having two or more levels, for all combinations of levels representing as many of the hypothetical encountered situations as possible (supplementary material A.1). The root of each resulting tree is the top node, and observations are passed down the tree with decisions being made at each node until a terminal node (or leaf) is reached (Ripley, 1996). The identification of the relevant variables was performed from previous studies (Nielsen and Mathiesen, 2003; Christensen and Raakjær, 2006; Andersen et al., 2012). To ensure that the right questions are asked, a qualitative in-depth interview was performed with three selected fishermen, where the relevance of the questions, design of the survey, and range of suggested response values are evaluated. Instead of asking for the full possible combinations of variables, each of the six questions (supplementary material A.1) asks the respondent to answer a sample of four situations only to reduce the individual load. Allowing the tree classification to be estimated from fewer responses, a D-optimal experimental design was implemented to help in identifying a reduced optimal set of combinations among all of the possible combinations (Cook and Nachtsheim, 1989; Wheeler, 2004). The questionnaire was answered by 34 respondents representing approximately 10% of the 275 targeted vessels covering 15, 13, 5 and 1 of the vessel size categories 15–18 m, 18–24 m, 24–40 m, >40 m, respectively. Six decision trees are built from the answers where each respondent reply on four potential situations, corresponding to a total of more than 100 answers per question.

### 2.4. Investigation of the reactions to increasing fuel prices

The everyday practices of fishermen can be affected by new events and external factors such as the implementation of new or modified regulations (e.g., multiannual management plans affecting effort levels; EC, 2007), increasing fuel prices and price dynamics. To evaluate the adaptability, trend or inability to comply with the changes and external factors, the fishermen are asked for their potential reactions on increasing fuel prices in particular cases by a yes/no multiple entry question (supplementary material A.2). The purpose of this is to design well-informed effort displacement and reallocation scenarios for which the consequences on sustainability of the fisheries can be tested by modelling. Answers cover 21 vessels only because the length of the questionnaire was reduced at the mid-period of the investigation to increase the response rate.

## 3. Results

### 3.1. Effort, landings and spatial application

Overall, the nominal fishing effort of the Danish fleet above 15 m decreases over the period 2005–2010. A similar decrease is observed in the fleet capacity as measured by the number of active vessels (469–275), whereas the value and weight of landings is almost identical between 2006 and 2010 (251 and 266 million euros and 672 and 619 thousand tons, respectively, Fig. 1). The total estimated fuel consumption decline from 181 to 118 million litres, leading to a change in energy efficiency from 3.70 to 5.25 kg caught per litre (~4.42 against 6.24 landed tons per ton of fuel). In the particular case of the central Baltic fishery (Fig. 1), the decline in total fuel consumption is accompanied by an increase in average fuel consumption per vessel, which indicates a change in the composition of the vessel size in this area towards larger vessels. The fuel dependency is expected to increase together with increasing fuel prices. However, the percentage of fuel costs compared to the revenue is variable between fleet-segments (Table 1) but remains stable within fleet-segments, even if a peak is observed for 2008, a general indication of the better use of fuel by the vessels remaining in the fishery in recent years.

The location of the landings of Danish vessels is clearly distinguished according to the type of fishery and the fishing management areas (North Sea, Skagerrak, Kattegat and Baltic Sea). The main fuel consumption in Danish fisheries comes from vessels landing in the North Sea and Skagerrak harbours where the larger ports have specific industries for processing the high amount of industrial and pelagic catches, as well as the landings of North Sea mixed demersal species. In Southern Denmark, the fuel consumption is dominated by vessels fishing brown shrimp. The Pandalus shrimp fishery explains the fuel consumed in the Skagerrak area while Nephrops is the main fishery in Kattegat. The fuel consumption of the Danish fishery in the Baltic Sea originates mainly from vessels landing cod or sprat. Some Danish vessels usually land in

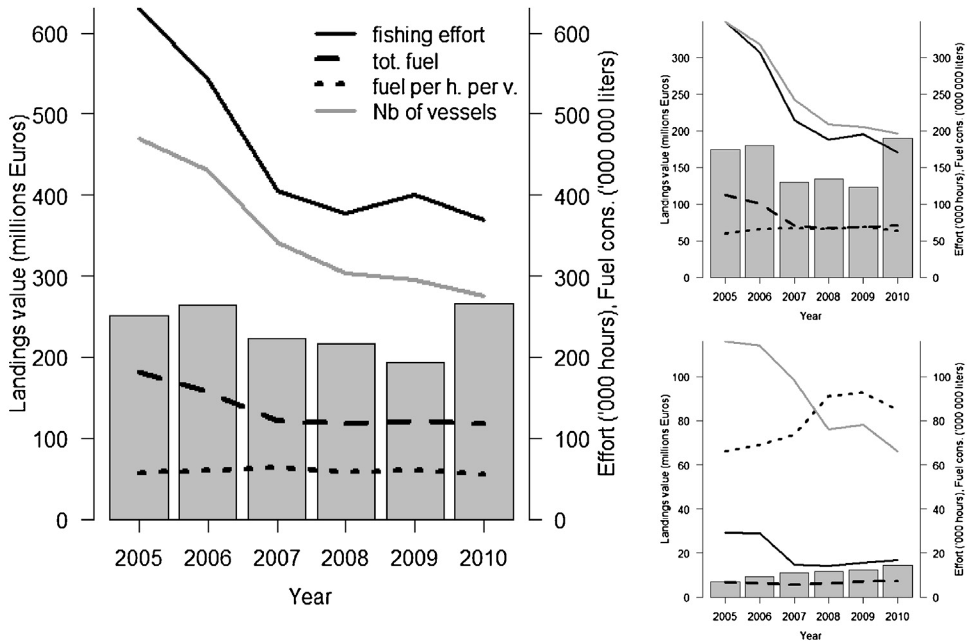


**Fig. 1.** Periodical (2005–2010) landing value (bars), fishing effort (solid line), total fuel consumption (vessel length > 15 m) (dashed line), fuel consumption per hour by vessel (dotted line) and number of vessels (solid grey line) in all fishing areas around Denmark (left figure), North Sea only (upper right figure) or Eastern Baltic Sea (ICES subdivisions 25–32) (lower right figure).

foreign ports, mainly within the pelagic fishery (Norway), the Pandalus fishery (Sweden), and the Baltic cod fishery (Sweden and Poland).

The spatial application of the Danish fishing effort covers from the North Sea to the central Baltic Sea (Fig. 2). Within this area, hot spots of high catch rates are identified because they are very distinct and consistent over the years (Dogger Bank, Shetland Islands, central Baltic Sea) (Fig. 2a). These hot spots probably match with zones of concentrations of the species with high commercial value, but the hot spots also reflect differences in the application of differential catching power by different vessels (larger vessels generally having higher catching power and mobility), and, to a minor extent, reflect regulated areas limiting the exploitation by Danish fisheries. The CPUF (integrating the fuel consumption of entire trips) is mostly higher closer to the Danish shore, indicating that areas with lower catch rates may actually be beneficial in terms of energy efficiency due to a shorter steaming time. High CPUF areas are, however, also still identifiable on remote fishing grounds where the highest catch rates usually are found (Fig. 2a).

**Table 1**
Percentage of the fuel cost related to the landing value during the period 2005–2010 for the ten most important fisheries (fleet-segments) relative to the 2010 landing value. The average fuel price per litre was calculated as the total fuel costs divided by the total fuel consumption for the aggregated figure of the Danish 18 to 24 m vessel size category (*source*: http://www.statistikbanken.dk), and gave results of 0.41, 0.45, 0.46, 0.58, 0.39, and 0.52 euros per litre per year from 2005 to 2010, respectively.

| Fleet-segments | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 |
|---|---|---|---|---|---|---|
| >40 m.OTB_DEF_<16 | 57 | 29 | 24 | 36 | 24 | 19 |
| >40 m.PS_SPF_32–69 | 11 | 14 | 13 | 13 | 13 | 7 |
| 24–40 m.OTB_DEF_>=120 | 41 | 37 | 29 | 34 | 24 | 26 |
| >40 m.OTM_SPF_32–69 | 16 | 18 | 24 | 29 | 18 | 20 |
| 15–18 m.OTB_CRU_90–119 | 36 | 30 | 25 | 37 | 34 | 38 |
| >40 m.PTM_SPF_16–31 | 33 | 37 | 36 | 39 | 25 | 23 |
| >40 m.OTM_SPF_16–31 | 80 | 39 | 33 | 60 | 22 | 25 |
| 24–40 m.OTB_DEF_<16 | 49 | 26 | 20 | 32 | 21 | 13 |
| 18–24 m.OTB_CRU_90–119 | 42 | 32 | 27 | 43 | 29 | 29 |
| 24–40 m.OTB_CRU_32–69 | 46 | 40 | 33 | 47 | 37 | 42 |

### 3.2. Energy and economic efficiency

The trends and differences in energy efficiency and the economic efficiency between fisheries are apparent when comparing fuel

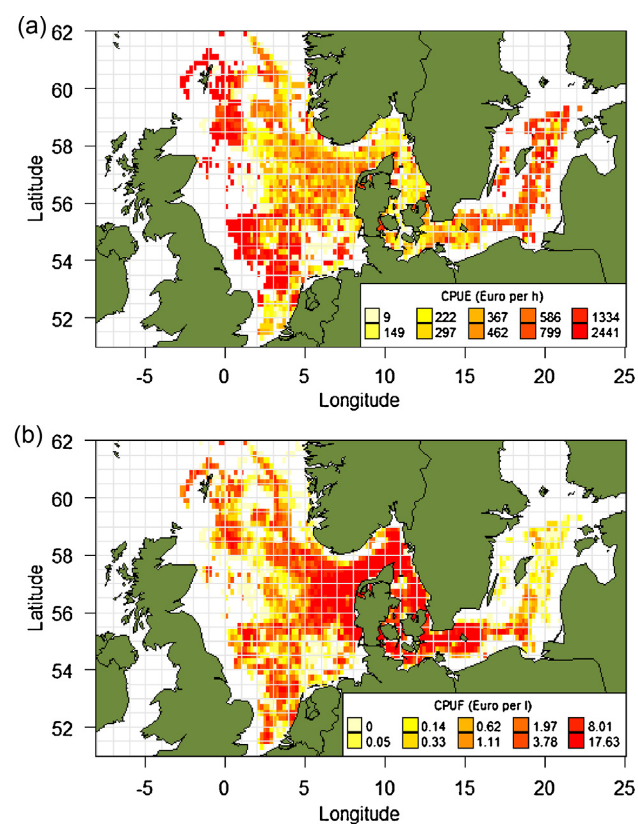


**Fig. 2.** Gridding (0.2 x 0.2 degree) of (a) CPUE (catch per unit of effort in euros per hour) and (b) CPUF (catch per unit of fuel in euros per litre of fuel) of all Danish fishing activities equipped with the VMS (i.e., vessels larger than 15 m in length) in the entire region around Denmark (see also Bastardie et al. (2010b) for details on methods). The breaks of the legends correspond to the 10 percentiles of the CPUF and CPUE distributions. The larger grid corresponds to the ICES rectangle delineations.

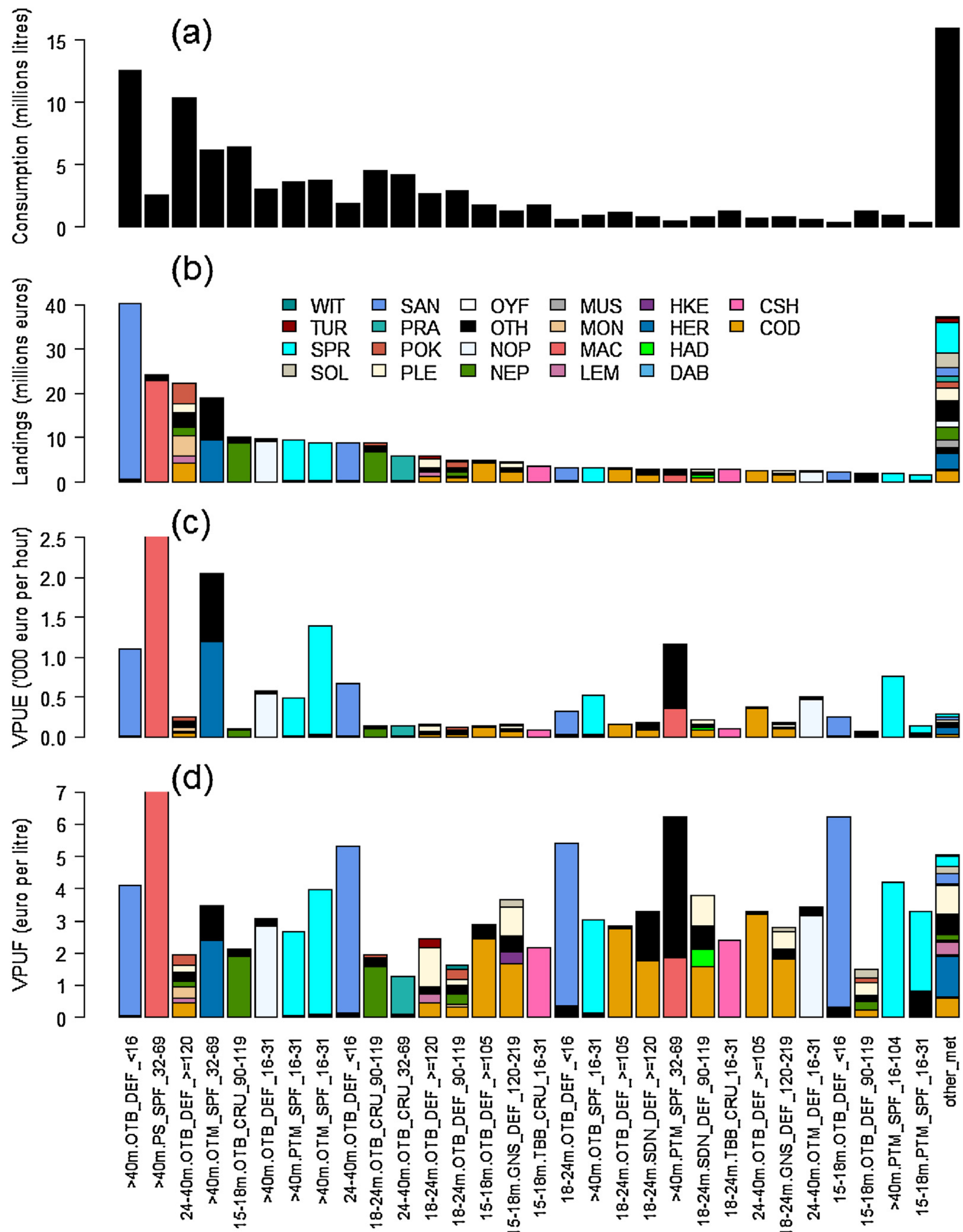


**Fig. 3.** Danish fisheries and fleet-segment aggregations described by vessel length category and metier, which is a combination of a gear and target assemblage of species and a mesh size range. Fuel consumption, landing weight, VPUE and VPUF are given by fishery for 2010. Data are ordered by decreasing 2010 landings values, keeping the first 30 segments only, other segments being aggregated into 'other_met': (a) the fuel consumed per vessel (millions of litres) belonging to the segments, (b) the landings values (millions of euros), (c) the economic efficiency (thousands of euros per hour at sea) and (d) the energy efficiency (euros per litre). The bars are further split by species (species FAO code).

consumption, total landings and fishing effort per segment (Fig. 3). Danish pelagic and industrial segments represent a large portion of the total fuel consumed while contributing a small fraction of the total effort. The Sandeel (SAN) fishery, the most important Danish fishery in volume and in value (ca. 45 million euros), also consumed the most fuel, amounting to ca. 15 million litres in 2010, followed by the pelagic herring (HER) and sprat fisheries (SPR) with a consumption of approximately 10 million litres each. The mackerel fishery (MAC) landed approximately for 20 million euros while consuming less than 5 million litres and is characterised by both higher VPUE and VPUF (Fig. 3). The commercially important North Sea mixed demersal fisheries (for cod (COD), pollock (POK), monkfish (MON) and plaice (PLE)), as well as the crustacean fisheries (for prawn (PRA), crangon (CSH) and nephrops (NEP)), have significant fuel consumptions associated with a large effort at sea but relatively low VPUE and VPUFs. Even if the total value is high (>20 million euros for mixed demersal fishery, >25 million euros for crustaceans), VPUFs are actually lowest for this group (Fig. 4). A third group constituting specialised target fisheries for mainly cod, mussels (mussel (MUS) dredgers) and plaice or turbot (gillnetters) is characterised by smaller catches both in terms of volume and value. The smaller catches are associated with a relatively small

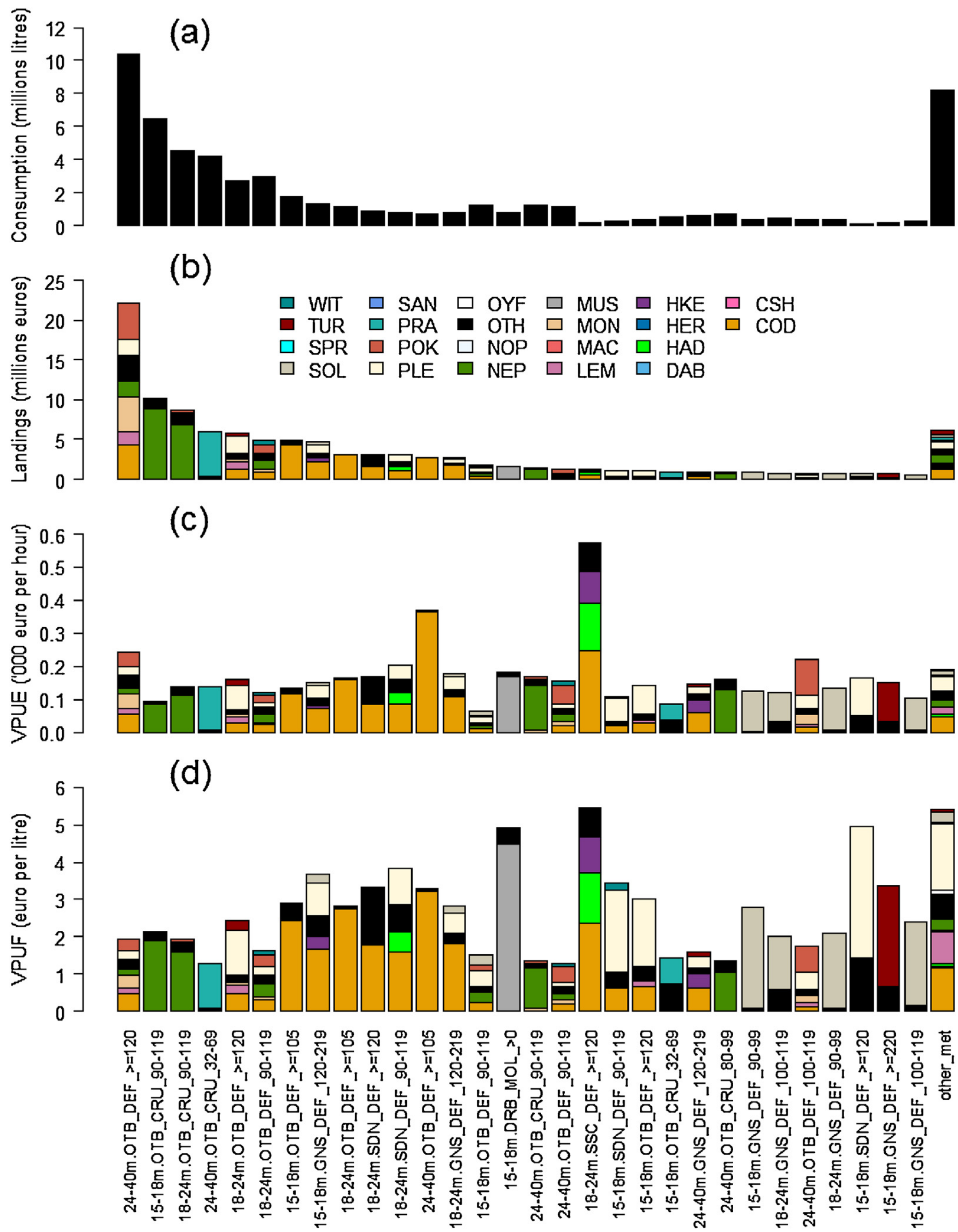


**Fig. 4.** Same as Fig. 3 but partially excluding the fleet-segments targeting pelagic species (SPF) and the demersal fleets using mesh sizes less than 16 mm.

total effort, resulting in relatively high VPUFs per segment. Among this last group, all Danish seiner segments (Fig. 4, COD, HAD or PLE fishery) are among the highest in VPUE and VPUF. Mussel fishery (MUS) is also found to be a highly energy-efficient fishery. The gillnet fisheries for vessels above 15 m have a moderate energy and economic efficiency. These differences appear consistent and stable over the period 2005–2010 for the pelagic and demersal fisheries, while slight increases in VPUF and VPUE are observed for all segments (discussed further below).

The variable performance between fisheries (Figs. 5 and 6) is explained partly by the characteristics of the vessels where pelagic fishery for MAC and HER is conducted by vessels >40 m using half a millions litres of fuel each per year (purse seiners), representing approximately 10% of their revenue. Other fisheries, such as those fishing for NOP, SPR or SAN, also utilise large trawling vessels but the fuel consumption is lower for these vessels (than for the vessels targeting MAC and HER), and they also each have a lower landing value, which is directly proportional to the gradient of fuel consumption. For the demersal fisheries (Fig. 6), the fuel consumption per vessel is partly linear with the effort spent at sea and partly dependent on the difference in horsepower between vessel size categories.

Performances are related to difference in activities, where the mixed demersal fisheries and the MAC fishery represent about the same value, the mackerel fishery is using less effort and much fuel per vessel, whereas the demersal fishery consumes much total fuel because the fishing is conducted by a larger number of vessels spending more time at sea. When comparing within the same activity (for example, among demersal activities) crustaceans and PRA fisheries are globally less efficient whatever the vessel size

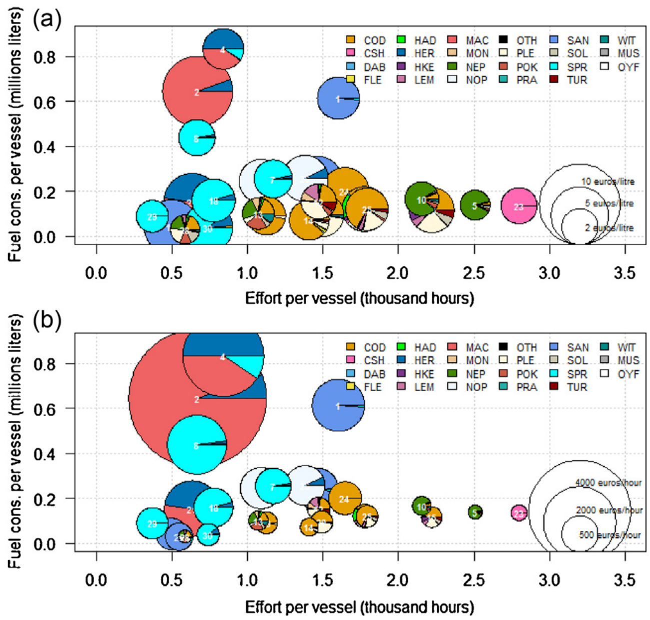


**Fig. 5.** Vessel specific energy efficiency (a) in euros per litre of consumed fuel, and economic efficiency (b) in euros per hour, as a function of fuel consumption (millions of litres) and effort (thousands of hours) for the Danish fisheries (keeping the first 30 fisheries (segments) only, as in Fig. 3, labelled from decreasing total landings value). The circle size is proportional to the average efficiency of vessels belonging to given fleet-segments, and the circle is further divided (sectored) by species.

category. Comparing the vessels targeting the same (assemblage of) species but using different fishing methods, seiners out-compete trawlers even though they consume more fuel and spend more effort in total. Among demersal segments, the large gillnetters use less fuel per individual vessel but they are globally less economically efficient by having lower landing value (e.g., SOL fishery).

Performances are related to difference in price and quality, especially among the demersal fisheries targeting exclusively cod

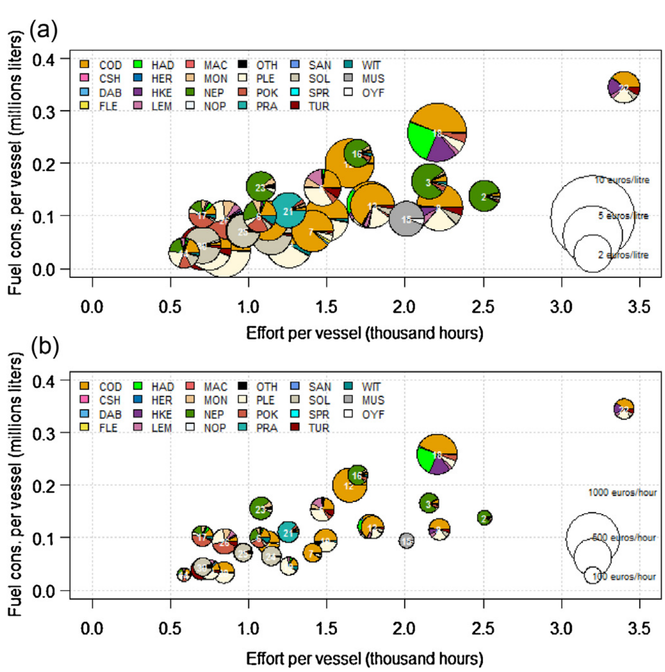


**Fig. 6.** Same as Fig. 5 but for the first 30 demersal Danish fleet-segments (labels correspond to Fig. 3 organised by decreasing total landings value). The circle size is proportional to the average vessel efficiency of vessels belonging to given fleet-segments, and the circle is further sectored by species.

(trawlers), COD and PLE (seiners), or exclusively sole (gillnetters), with sole (approximately 10 euros per kilo) being more valuable than fisheries for other species (e.g., COD and PLE with 2.5 and 1 euro per kilo in 2010, respectively). In 2010, the cod price per kilo is up to 35% and 41% higher for static and seine fisheries respectively than for trawlers.

The segmentation into fisheries is the main factor explaining the differences in VPUF and VPUE, but the relative fuel price is also a significant factor ($\alpha < 0.1$). The relative increase in the average fuel price between 2005 and 2008 and for 2010 lead to an increase in VPUF, while the decline in fuel price in 2009 lead to a lower VPUF. The relative stock abundance at sea is also a significant factor in relation to VPUF and VPUE ($\alpha < 0.05$). The relative fish price also slightly impacts the VPUE ($\alpha < 0.05$), indicating that fish prices might not be related to total volume landed.

### *3.3. Decision tree classification*

When all activities are viewed together, the fish price is the prime factor when deciding when to go fishing (Fig. 7, stage 1). A high fish price determines whether the fishermen go fishing, unless the remaining quota is low and the last trip catch was low or unless the weather is not acceptable and no other fishermen go. The time of the last trip and the expected cost for the next trip have no effect on this decision. Perception of the significant factors is, however, partly dependent on the type of the vessels (Fig. 8) more than the gear they use (Fig. 9). Smaller vessels put more emphasis on the weather factor, medium-sized vessels on whether other fishers choose to go, and larger vessels focus on the fish price when deciding to go or not. A high potential catch is the prime factor when choosing a fishing ground (Fig. 7, stage 2), unless the last trip was not satisfying and previous knowledge of the ground is low. Hence, the fishermen are usually not willing to search for other suitable or better fishing grounds for a long time. The potential for high by-catch on the ground is not an important decision factor at this earlier stage. The surveyed fishers usually choose to start fishing only if they arrive at the ground they previously chose, and no other factors are influencing their decision on starting fishing before they are on their way (Fig. 7, stage 3). Hence, most fishermen know before departure what to target and where to fish and opportunistic detection with an echo sounder or knowledge of other fishermen fishing in the area has only a minor impact on the decision. But some of fishermen can start fishing on the ground unless the risk for unwanted catches is considered high and the bottom type is not suitable for fishing. No contrasting factors are found to explain the decision to change the fishing ground within the same trip, as the respondents answer they will change in most of the submitted situations (>70% change, results not shown). Full storage definitely leads fishermen to go back to port (Fig. 7, stage 5), but whether full storage is a frequent event is variable from vessel to vessel. If the catch volume is “OK” or low, then most fishermen choose to continue to fish, unless the trip duration has already been more than 2 days and the fuel reserve is low. The percentage of events where the vessel return to port because of a shortage in fuel is, however, low (<5%). The weather encountered and the trip duration seems not to influence the decision at this stage. The fishermen tend to choose a port based on its proximity within a range of 12 nm (Fig. 7, stage 6). Remote ports are only chosen when the fish price is higher and/or if a specific delivery agreement exists with processing firms. The nationality of the port, the fuel price at the port, and whether the fish market will open soon in the port seem irrelevant when fishermen choose a port.

When asked about their medium-term effort displacement reactions to an increasing fuel price, fishermen show a strong will to improve their energy efficiency (Fig. 10) by choice of gear, increase

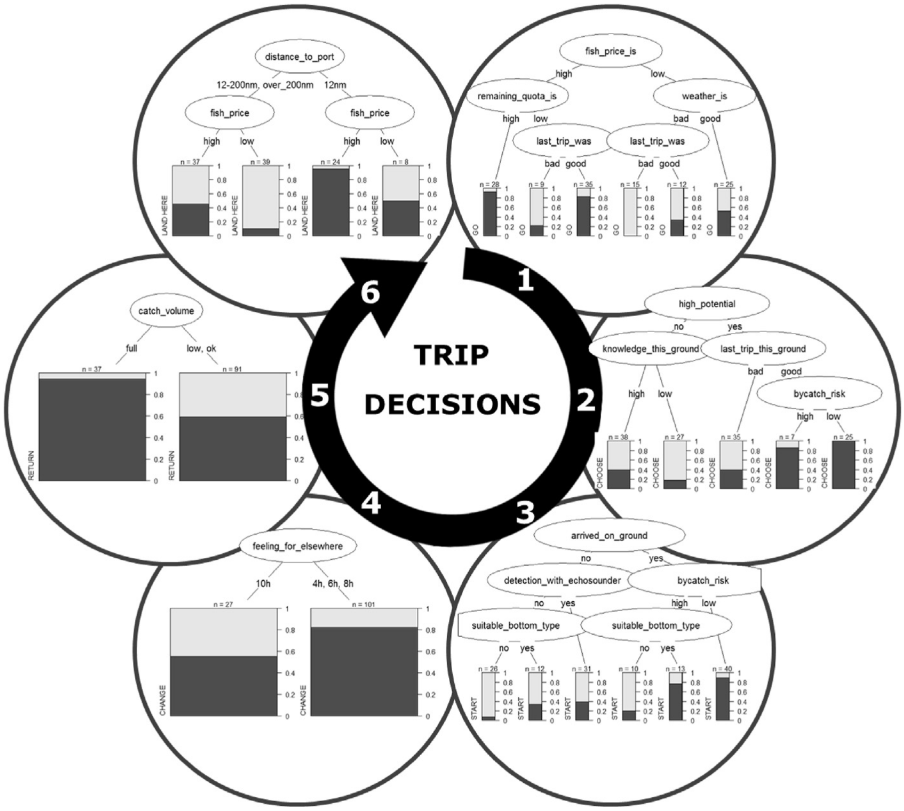


**Fig. 7.** Sequential decisions of skippers made before, during and at the end of a trip at sea shaped by different decision trees that were built from the answers of the aggregated skippers (see also supplementary materials). The proportion of decisions is given as a histogram for each terminal node. Each decision tree has been built assuming a threshold of 0.80 for significance. The number *n* denotes the numbers of observations reaching a certain terminal node. Stage 1, decision tree for the 'go fishing' choice; Stage 2, related to the fishing ground choice; Stage 3, related to the decision of starting a fishing sequence; Stage 4, related to the decision of changing of area for fishing within a given trip; Stage 5, related to the decision about when to stop fishing to return to the port; Stage 6, related to the decision about the choice of the port for landing.

of catch rates according to increase of their knowledge of usual fishing grounds, change of departure port according to a shorter distance to fishing grounds, reduce vessel speed, and obtain a better fuel price. However, in many cases they tend to be reluctant to change their fishing grounds according to distance to ports (which then would imply a change of fishery for them), reduce vessel crew, stop fishing temporarily, or leave the business totally. Almost all do not wish to shift to another fishery.

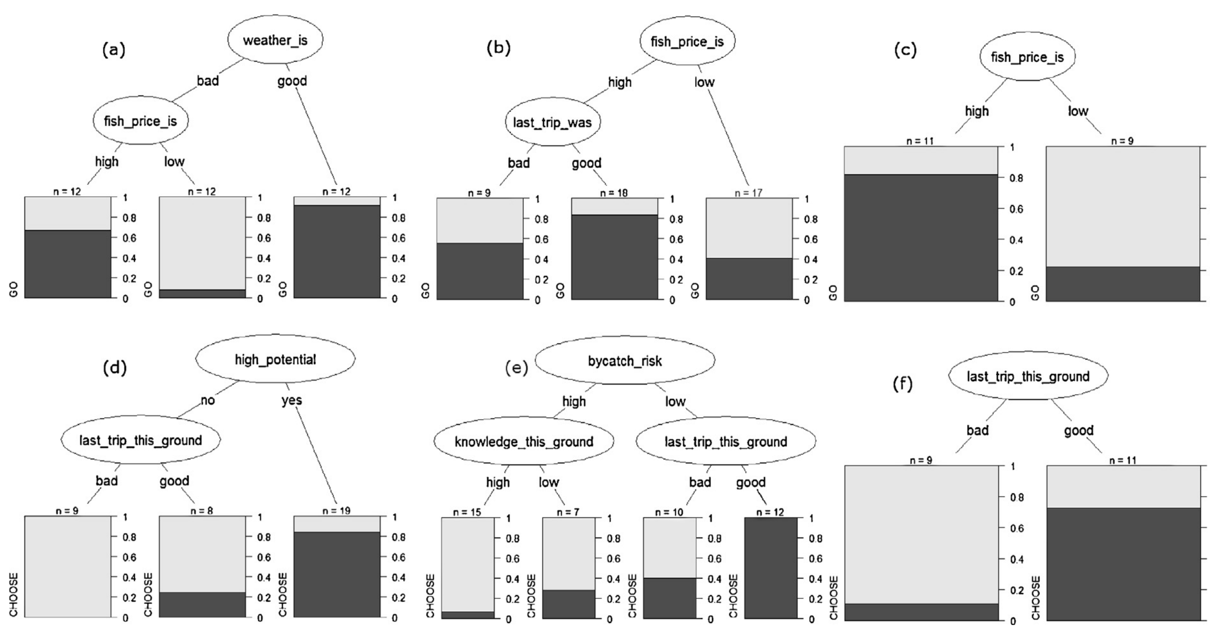


**Fig. 8.** Decision tree for the 'go fishing' choice per vessel size: (a) 15–18 m, (b) 18–24 m, (c) 24–40 m, and for the 'choose this ground' choice per vessel size: (d) 15–18 m, (e) 18–24 m, and (f) 24–40 m.

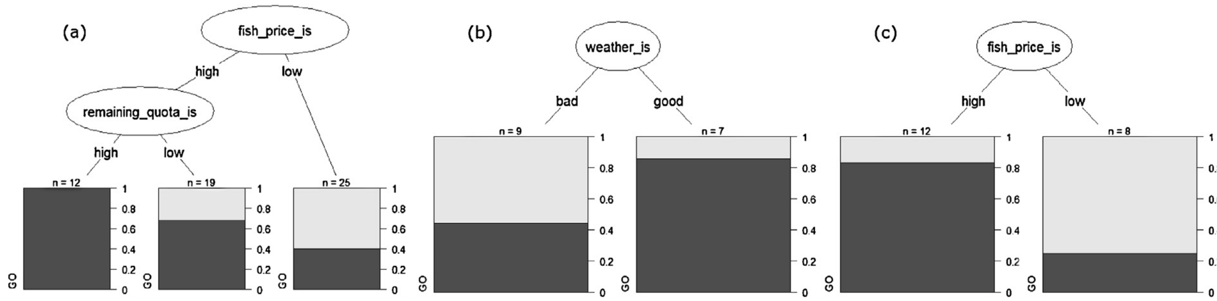


**Fig. 9.** Decision tree for the 'go fishing' choice per gear type: (a) OTB (otter board trawlers), (b) TBB (beam trawlers), and (c) GNS (gillnetters).

## 4. Discussion

When adapting their practices to save fuel, the fisherman responses suggests that a gain in energy efficiency can be realised by reducing the vessel speed when steaming and/or the trip length, visiting high fish density areas only (to increase the catch rate), and reducing visits to distant fishing grounds. When steaming, there is considerable efficiency gained by a small reduction in speed (Ronen, 2011; Beare and Machiels, 2012), so fishermen may adjust their fishery and trip duration accordingly. A counterpart, however, is that a longer stay at sea may actually lead to higher fuel consumption overall due to the additional extra time needed with the engine switch on. Present results on the relative efficiency between activities also indicate that a gain is expected (when no dynamic process on stock abundances is assumed) when changing fishing methods, either by a change to more energy efficient gear or by changing the catch composition for more valuable fish by changing the gear and method. One might also expect that some investments may benefit the fisheries as well, such as investing in storage or processing equipment (on-board processing, freezing and cooling facilities, an option not investigated here) to save time when staying at sea for a longer period and potentially increasing the quality of the products. For the Danish fisheries, reducing the duration at sea may actually give higher quality products, as almost all fish are landed as fresh product (EFF, 2007).

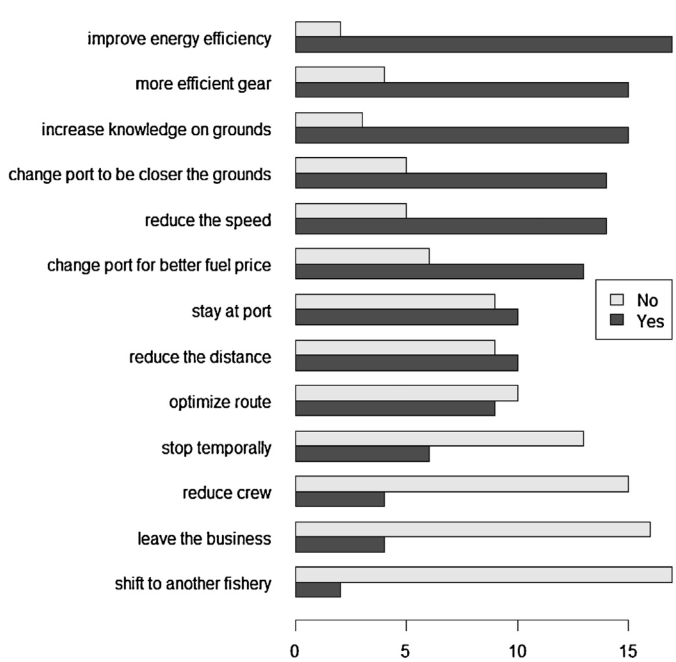


**Fig. 10.** Medium-term responses of surveyed fishermen to the questions on increasing fuel price (see supplementary materials for details).

Similar to Thrane (2006) and Schau et al. (2009), this study confirms that fuel consumption depends on the fishing methods and the targeted assemblage of species where some fisheries have proven more energy efficient than others. The composition and total landings are also important factors in cases where the ability to catch is dependent on several commercial species targeted in the same fishery (e.g., North Sea mixed fisheries). Increased efficiency among segments is interpreted by the following (not mutually exclusive) aspects: (i) catching relatively more valuable species and size groups; (ii) taking the same or higher amount of catch with less time spent and accordingly saving fuel; and/or (iii) using fishing methods that catch higher priced fish because of their better quality. We find that pelagic fisheries are the most efficient, represented by a few large fuel-intensive vessels that each use relatively low effort to obtain high landing values per unit of fuel and effort. For the demersal fleets, the efficiency is more heterogeneous, but a change of fishing methods towards static gears and Danish seines may benefit the energy efficiency if only this aspect is considered. Fish caught by static gears and seine fishing methods are also priced slightly higher. These results do not encompass smaller vessels than 15 m in length which were not investigated here. However, Carvalho et al. (2011) found that, while small-scale fisheries may utilise the same amount of capital in overall, small-scale fisheries tend to be more fuel efficient than large-scale fisheries. Small-scale fisheries appear then to be more resilient in case of higher fuel prices. The weather at sea is for example a major concern for smaller vessels, while larger vessels are less sensitive and fish regardless in order to meet their higher costs. Bad weather leads to an increased consumption of fuel as the vessel must waste energy breaking high waves. The total impact can be approximately 30% depending on the conditions and speed (Jakobsen, 2011).

The relative fuel price does not appear to be a determinant for the surveyed vessels with respect to decisions on going fishing and choosing port, most likely because fuel price has no obvious seasonal pattern and is likely to be rather equal between ports and countries, assuming tax exoneration. However, by assuming that the fisherman will go fishing in any cases the present questionnaire overlooked the fact that the absolute fuel price is likely to have a strong threshold effect (Abernethy et al., 2010) on the decision of 'going fishing' vs. 'staying on quayside', while some fisheries are likely not to be sustainable without subsidies on fuel price because the running costs will exceed the revenue (Sumaila et al., 2008). For the surveyed vessels, the choice of port relies more on limiting the distance to the grounds, in addition to the fact that area-based management requires the fish to be landed in the same area. Most fishers respond that they will likely try to improve their energy efficiency by lowering fuel use when fuel prices are continuing to increase. This study confirms that fuel prices cause some fishermen to be more careful about where and when to allocate their fishing effort. For other fishermen (for instance, netters), the fuel cost does not seem to be a major issue. Instead, they are trying to optimise their economic efficiency by targeting high-priced fish, which may lead to higher effort by searching for a bonus from landing a high quality of fish rather than quantity.

Additional investigations should establish a direct causal link between the fleet/métier efficiency and the decision choices by capturing the exact trajectory of individual vessels changing of activity during the year in response to a change in drivers. The number and duration of trips are affected by decisions on when to go, when to stop, which port to land in, etc. For larger vessels (pelagic fleets), the decision to go fishing is highly dictated by the fish prices, which create a variation in efficiency for catches arising from the same landing quota. The influence of prices can be more important for fishermen than searching for a large abundance. For example, the spatial and temporal heterogeneity in fish prices is likely to lead to heterogeneity in the application of the effort in space and time. Larger vessels are adequately mobile to adapt their activity to target different stocks depending on fluctuations in stock abundances and prices (Christensen and Raakjær, 2006). But large pelagic fleets are presumably not flexible with regard to choosing a location for landings, as pelagic vessels choose larger ports and may sometimes land directly at fish mills (with whom they have agreements; Thrane et al., 2009). In addition, some vessels can own a part of the harbour industries and accordingly land in a certain harbour most of the time. Other fishers are also sometimes very explicit on what they target and focus on the total trip duration (for example, a daily trip). In those cases, the vessel tonnage and storage capacity can be limited when predicting the return of vessels to port because the fishing operation depends more on time or the expected landing value than the particular catch amount. Smaller vessels (demersal fleets) are also more inclined to follow what other fishers do or base their decisions on the success of their previous trips. The decisions and results on previous trips have also been found to be an important explaining factor for trip-related behaviour in several other commercial fisheries (Andersen et al., 2012; Holland and Sutinen, 2000).

Patterns in fishing behaviour are typically stable choices, and fishermen answer that they are reluctant to shift fisheries under any circumstances, likely because of the costs perceived with such a change. The Danish fishery regulation system has, however, experienced a major change in 2007 with the implementation of the individual vessel transferable quota system (ITQ), which has led to a significant reduction in the number of active vessels (Hegland and Raakjær, 2008). The ITQ system has obviously caused a major increase in efficiency in the fishery by offering each vessel a chance to be more flexible in their decision and giving the less efficient vessels the economic opportunity to leave a fishery while not forcing them to go fishing even during bad weather or low fish price conditions (Hegland and Raakjær, 2008). The catch efficiency may also depend on the change in total and spatial variability in the abundance, distribution and relative density of the resources, as well as the variability in their age and size relative to the allocation of the fishery. Energy consumption also occurs in the processing of the catches depending on amount, type of fish and quality as well as on the processing, packaging and transportation of the seafood products towards few important port/selling locations. This consumption of energy needs to be accounted for in the total figure. However, this actually represents a minor fraction in the Danish fisheries of the total consumption compared to the catching processes (Thrane, 2006). Beside this, the impact of the fishery on trophic interactions within the ecosystem is sometimes more important for the biological sustainability than the amount of fish caught (Piet et al., 2007; Willison and Côté, 2009; Pikitch et al., 2012; Suuronen et al., 2012). In line with this, impacts of trawling activities are reported in the literature (e.g., the ecological impacts of relative differences in area/sea floor swept by demersal trawlers (Nilsson and Zielger, 2007) compared to pelagic trawlers or gillnetters or to the by-catch of mammals in gillnet fisheries (Larsen et al., 2007)). As a synergistic effect, recent projects are developing new gear designs with less resistance to reduce fuel consumption and simultaneously be more selective and reduce environmental impact on, e.g., the sea floor.

With the purpose of rationalising the fishing behaviour according to efficiency, impact evaluations for the optimal fisheries should be carried out together with existing or innovative regulations, or appropriate incentives. The dynamics of the underlying resource abundance patterns on a spatial and temporal disaggregated scale also need to be considered to advise and manage the fishing in certain areas. Presumably, the responses will also vary with individual situations of participating vessels due to the skipper effect that accounts for over 50% of the variance in fishing power (Mahévas et al., 2011). Other major components are the gear and vessel characteristics (Marchal et al., 2006; Eigaard, 2009; Mahévas et al., 2011), indicating that individual vessel-based models are better tools to use because scaling local conditions up to the global scale is otherwise biased in unknown ways when the conditions vary from fishery to fishery and from vessel to vessel (Bastardie et al., 2010c). We identify decision trees and IBM as a valuable approach to disentangle the determinants of the different behaviours of fishermen and to support a quantitative analysis for the generalisation of the impacts at the macro-scale. By contrast, random utility models (RUMs) which have so far been applied for this purpose for the commercial fishery (Holland and Sutinen, 2000; Van Putten et al., 2012; Andersen et al., 2012) perform at the aggregated fleet level. An important advantage of the decision tree and IBM approach upon the RUMs is the inherent flexibility when quantifying non-linear (nested) decisions, which could make predictions more valuable and provide robust predictions from a complex causal link between fuel consumption, energy and economic efficiency, fishing practices and the decisions of fishermen. The objective of the approach is not to propose a case-by-case advice and management system dealing with every single fisherman. We still aim at using the results in context of aggregation by fisheries (the fisheries and fleet-based framework; e.g., Nielsen and Limborg, 2009; Ulrich et al., 2012) defining useful and manageable aggregated entities by identifying patterns of activity (and groupings) to which the vessels belong. The goal is rather to incorporate the effect and variability of every single fisherman decision that would have an impact on the macro-scale, especially for explaining the determinants of different energy efficiencies among fishing activities.

## 5. Conclusions

The methodology developed here aim to guide and improve the assessment of potential effects of fisherman choices when they respond to fluctuations in targeted stock abundances, fuel prices or regulations. By building decision trees from the knowledge of fishermen, the present work provides important information on the mechanisms behind their decisions on a daily basis. This can directly guide the existing advisory tools in the form of the developed agent-based models or IBMs by improving the predictive capacity facing the actual dynamics and conditions (e.g., shifts in spatial resource distribution, rising fuel prices, more area closures, etc.) when, e.g., testing potential gains in energy and economic efficiency for fishers. A second aspect of the questionnaire is to ask fishermen for their potential choices in effort allocation to different fishing situations so that 'what if' management evaluation and impact scenarios can be based on sound knowledge of the actors participating in the fishery.

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## Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.fishres.2013.01.018.

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