The Drivers and Dynamics of Fisher Behaviour In Irish Fisheries

Sarah Louise Davie

PhD

Galway Mayo Institute of Technology

Supervised by Dr Colm Lordan & Dr Rick Officer

Submitted to the Higher Education and Training Awards Council, July 2013

Abstract

It is widely acknowledged within the scientific community that a single species approach to European mixed fisheries can result in species-specific advice inconsistent with multi-species management objectives. Within the reformed Common Fisheries Policy a move toward mixed fisheries and ecosystem based management is encouraged.

The overall objective of this research was to improve understanding of the complex targeting behaviour undertaken by commercial fishers. Whereby, improved understanding will enhance the ability to predict the responses to future mixed fisheries management measures and changing economic conditions within the Irish fishing industry.

Irish métiers (groups of homogeneous fishing trips) highlight the complexity of fishing activities within the Irish fleet, having identified 33 otter trawl métiers and 19 in the remainder of the fleet. Métier dynamics identified over compensation to introduced management, resulting in effort displacement and increased temporal specific fishing pressure. Therefore were deemed as appropriate base units for all subsequent analyses. Two economic variables, operational fishing cost and trip landings value, considered to represent important drivers were developed. This lead to application of a general additive model to estimate and predict fuel consumption estimates according to fleet segment definitions.

A linear mixed effects model with random vessel effect was developed as a method of standardising value generating an index of value per unit effort. This identified kilowatt fishing days as the most appropriate effort measure. The final investigation stage successfully amalgamated the knowledge gained into the formulation of novel Markov transition probability for a multinomial model to predict fisher métier strategy choice. This is to be incorporated into management strategy evaluation, aiding the assessment and possible impacts of future management proposals on the Irish fleet and commercial stocks around Ireland.

Developments presented will benefit the progression toward optimising sustainability within a mixed fisheries approach to management through incorporation of economic considerations.

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Glossary

BIM: An Bord Iascaigh Mhara, The Irish Sea Fisheries Board, charged with responsibility for development of the fishing and aquaculture industries in Ireland. (See http://www.bim.ie)

CFP: Common Fisheries Policy – The instrument of fisheries management within the European community (see http://ec.europa.eu/fisheries/ reform/index_en.htm)

CLTP: Cod long term management plan – A management plan developed to reduce the fishing mortality on a number of European cod stocks through effort restrictions (see EC, 2009a). Definition of regulated gears under the plan:

TR1 – Bottom trawls, Danish seines, and similar towed gear (excluding beam trawls) of codend mesh size ≥100mm

TR2 – Bottom trawls, Danish seines, and similar towed gear (excluding beam trawls) of codend mesh size ≥70mm and <100mm

TR3 – Bottom trawls, Danish seines, and similar towed gear (excluding beam trawls) of codend mesh size ≥16mm and <32mm

BT1 – Beam trawls of mesh size ≥120mm

BT2 – Beam trawls of mesh size ≥80mm and >120mm

GN1 – Gillnets and entangling nets (excluding trammel nets)

GT1 – Trammel nets

LL1 – Longlines

DCF: Data Collection Framework – EU Commission Regulation 665/2008 establishes the Data Collection Framework (DCF), a Community framework for the collection, management and use of data in the fisheries sector and support for scientific advice regarding the Common Fisheries Policy (CFP). Under this regulation the European Commission requires Member States to collect data on Biological and Economic aspects of many European fisheries and related fisheries sectors. (See: https://datacollection.jrc.ec.europa.eu/)

Derogation: A form of special dispensation permitting the holder to an exemption from or relaxation of a rule or law. For example vessels permitted additional fishing effort allocation when applying gear adaptations which avoid the capture of cod.

EA or EAFM: Ecosystem approach or Ecosystem approach to fisheries management – Management that takes into account the effects of fisheries on the ecosystem and the effects of the ecosystem on the fish stocks.

FAO**:** Fisheries and Agriculture Organization – Based in Rome, this organization is part of the United Nations (see http://www.fao.org/fi/default.asp).

Fishery: A group of vessel voyages targeting the same (assemblage of) species and/or stocks, using similar gear, during the same period of the year and within the same area (e.g. the Irish flatfish-directed beam trawl fishery in the Irish Sea).

Fleet: A physical group of vessels sharing similar characteristics in terms of technical features and/or major activity (e.g. the Irish beam trawler fleet < 300 hp, regardless of which species or species groups they are targeting).

Gear code definitions:

DRB	Dredges
FPO	Pots
GNS	Set gillnets
GTR	Trammel Nets
LLS	Set longlines
OTB	Bottom otter trawl
OTM	Mid-water otter trawl
PTB	Bottom pair trawl
PTM	Mid-water pair trawl
SSC	Scottish Seines
TBB	Beam Trawls

GEPETO: (for Gestion de las PEsquerias and Transnational Objetivos (fisheries management and transnational objectives) A European INTEREG1V project to draw up long-term fisheries management proposals more appropriate to the socioeconomic aspects of fishing, and to the necessity to preserve resources. (See: http://gepetoproject.eu/)

***Grouped métier*:** The codes as used in Chapters VI and VII

Neph	Nephrops directed fishing trips based on Nephrops targeted otter trawl métiers
Dem	Demersal directed fishing trips based on otter trawl métiers targeting demersal taxonomic groups (cod, haddock, whiting, pollack, saithe, flatfish, and rays)
Deep	Deep water species directed fishing trips based on the deep water otter trawl métier
DRB	Fishing trips utilising dredging gear
Pa	Fishing trips utilising passing type fishing gears, including pots, longlines, and gillnets.
Pel	Fishing trips targeting pelagic or tuna species based on herring, mackerel, horse mackerel, sprat, blue whiting and tuna targeted otter trawl métiers
Ot	Otter trawl fishing trips which do not occur within the four previous groups, which includes those with mixed compositions
Slope	Fishing trips targeting species occurring on the continental shelf edge based on megrim, monkfish, hake, ling, and witch targeted otter trawl métiers
SSC	Fishing trips utilising Scottish seine gear
TBB	Fishing trips utilising beam trawl gear

ICES: International Council for the Exploration of the Seas – Ireland shares the Total Allowable Catches TACs for many stocks we exploit with our European Union partners. Because of this international dimension many stocks need to be assessed in an international forum such as ICES. (See: http://www.ices.dk/)

MSY: Maximum Sustainable Yield – The largest average catch or yield that can continuously be taken from a stock under existing environmental conditions. (For species with fluctuating recruitment, the maximum might be obtained by taking fewer fish in some years than in others.) Also called maximum equilibrium catch, maximum sustained yield, or sustainable catch.

MEFEPO: Making European Fisheries Ecosystem Plans Operational European funded scientific project.

Métier: Homogeneous subdivision of a fishery by vessel type (e.g. the Irish flatfish-directed beam trawl fishery by vessels <300 hp in the Irish Sea).

NWWRAC: North Western Waters Regional Advisory Council

Recovery Plan: This is a multi-annual plan to recover seriously depleted stock. The plans general involve agreed Harvest control Rules, Technical Measures, effort controls and various control and enforcement measures.

R: R is a free software environment of facilities for data manipulation, calculation and graphical display through a simple and effective programming language (available from www.r-project.org).

Acknowledgments

A large number of people have helped me to achieve the work within this thesis, it wasn’t always easy and I would not have been able to do it without you, so a massive thanks to you all.

I’d specifically like to acknowledge my two supervisors, Dr Colm Lordan and Dr Rick Officer combined for all their time, dedication, advice, support and encouragement. To Colm, immeasurable thanks for giving me the opportunity to make this thesis happen by supporting my wish to carry out a PhD and providing valuable suggestions back in those carefree days before I started my project. Also for sheltering me from extra ‘day job’ tasks giving me time to carry out this interesting research within my employment, and for providing the occasionally shoulder. To Rick, I must thank his support from the academic side, his unending enthusiasm and pep talks which got me over the line. Thanks must also go to the amazing Dr Cóilín Minto of GMIT who’s statistical and R based knowledge, unending patience and willingness to help were truly invaluable to me and this project.

With immense thanks and bear hugs to my parents and friends, both here and abroad, for their unconditional love, support, encouragement, patience and advice throughout the whole process, and for getting me away from the books when I couldn't see I needed it. I'm so lucky to have you all in my life. The "you can do it"s, cakes, muffins, chocolate, and wine were always appreciated. Additional thank you to my parents for flying over to do the "chores" for a week toward the end of my write up, leaving me with a freezer full of food, and for being at the other end of the email in my final week, you are amazing people.

I am truly grateful to the Marine Institute for sponsoring this research. The Marine Institute paid the majority of my college fees and allowed time to undertake this research, for which I am eternally grateful. I would like to thank the Irish Department of Agriculture, Food and the Marine for providing Logbook information and Bord Iascaigh Mhara for providing additional data. Specific acknowledgements go to Emmet Jackson of BIM for his help in generating data and Catherine Cronin from DAFM for providing information on quota allocations.

Finally, my thanks to the unknown, and unsung, peer-reviewers of professional journals for their constructive comments and suggestions to improve the published papers.

Chapter I: General Introduction

Introduction

The status of the World's fisheries has been a topic of increasing concern over recent times. Global overexploitation, pollution and habitat loss are threatening the health of marine biodiversity (Hilborn, 2007; Fulton *et al.*, 2011). Between the early 1990's and 2007 the Food and Agriculture Organization of the United Nations estimated that over a quarter of global stocks were overexploited, depleted or recovering from depletion where assessments were available (FAO, 2007). This included a number of stocks considered to have been exploited unsustainably within the European Community. Fernandes & Cook (2013) highlighted that the status of many European stocks has improved. In 2011 the majority of European assessed stocks were considered to be fished sustainably (where reference points were available; Fernandes & Cook (2013)).

Whilst the general situation for European stocks has improved this has taken quite a long time (over a decade) and several key stocks remain severely depleted. This points to the fact that more efficient management tools are required to ensure long-term sustainability, particularly within mixed fisheries.

Management

Within Europe, traditionally, stocks have been assessed and managed under a single-species framework within the Common Fisheries Policy (CFP). The CFP's main management tools have involved limiting single species removals through total allowable catches (TAC) and minimum landings sizes (output controls), combined with input restrictions, including technical measures (gear and/or mesh size restrictions), seasonal closed areas and fleet capacity limits. In the early 2000's the poor biological status of North Sea cod played a key role in the development and implementation of European stock specific recovery management plans. Such management plans are now in place for several European cod stocks, including the North Sea, Irish Sea, and West of Scotland (Davie & Lordan, 2011a; EC, 2002; EC, 2003; EC, 2004; EC, 2008a). These plans often incorporate fishing effort limitations as the primary method to reduce fishing mortality. The main difference between effort management and TACs is that effort is an input control, although both aim to limit fishing mortality (Tidd, 2013).

Concurrent concerns over the deteriorating health of stocks encouraged actions to prevent further declines and stimulate recovery, especially of North Sea cod. However, the efficacy of the existent controls to restore stocks and ensure long term sustainability remained a concern. Particularly for stocks within complex multi-species fisheries systems. Such concerns were a fundamental driver in the shift of European management approaches from single species management. Integrated mixed fisheries and ecosystem approaches came to the fore from a policy perspective, having being discussed, debated, and investigated within the background by the scientific community for several decades.

Mixed fisheries here are described as systems in which the same resources are caught together in a variety of fisheries (multi-species) by various fishing multi-fleet activities. These systems can exhibit variation in spatial and seasonal distribution in both the resource and the fishing activity where fishers are able to simultaneously and/or sequentially target different species (Mahévas & Pelletier, 2004). The ecosystem approach, or ecosystem approach to fisheries management (EAFM), develops the mixed fisheries approach to a much broader, holistic level, encompassing not only interactions of entire species communities, but also the inclusion of environmental factors influencing a system. This policy shift has been underpinned within Europe by the Integrated Maritime Policy (IMP) through the Marine Strategy Framework Directive MSFD (EC, 2008b) aimed at achieving, and maintaining, healthy resources and environments. This has been integrated into the reformed CFP, recently passed through the parliament of the European Commission (EC, 2013), placing greater focus on sustainability, long-term goals, and an EAFM.

As part of the drive toward ensuring future sustainable exploitation, Europe has committed to bring exploited stocks to maximum sustainable yield (MSY) targets by 2015 (UN, 2002) and maintains an MSY objective in the 2013 CFP reform (EC, 2013). However, there is concern that the current single species approach to Europe's MSY commitment may not be attainable within the context of European mixed fisheries (Mace, 2001; Mackinson *et al.*, 2009; Nolan *et al.*, 2011; Guillen *et al.*, 2013). It has become increasingly clear that these commitments will not be achieved by the 2015 target, and even highlighted within the CFP reform where the target date has been pushed back to "2020 where possible" (EC, 2013).

The reformed CFP intends to move away from the current top-down, centralised micro-management, towards simpler, decentralised, results-based regional management through multi-annual plans encompassing multiple stocks. Fulton *et al.* (2011) consider that an integrated management system, incorporating a range of policy tools is the most robust to behavioural and implementation uncertainty, blending complementary management initiatives to achieve convergence of multiple incentives and objectives. Greater responsibility will be held by both Member States and stakeholders to promote stakeholder buy-in, particularly from the fishing industry. However, there are increasing and competing demands on marine resources and as such legitimate stakeholders are diversifying significantly beyond the traditional sphere of fisheries managers and fishers (Hilborn, 2007). It is often the case that stakeholder groups have conflicting and sometimes competing objectives. Consideration of this complex, multi-dimensional issue is unavoidable in the decision-making processes associated with the selection of fisheries regulations (Gourguet *et al.*, 2013). Trade-offs must now be balanced between the ecological, economic, and social objectives of the various managers and stakeholders. Through transference of greater responsibility and development of co-management between stakeholders, it may be possible to achieve a mixed fisheries equivalent of MSY to satisfy European sustainability commitments, exemplified by the multi-species, multi-fleet MSY estimation explored in Guillen *et al.* (2013) for the Bay of Biscay.

Advice

Mixed fisheries and ecosystem based management advice must be founded on advice generated at the fleet or fishery level. Vinther *et al.* (2004) correctly stated that development of such a process takes time, and is still a developing field of research. As an interim Vinther *et al.* (2004) proposed a method of estimating multispecies TACs through utilisation of stock-based advice optimised with fleet information (MTAC). However as an advice tool it was not considered appropriate (ICES, 2006a). This led to the development of Fcube (Fishery and Fleet Forecasts) (ICES, 2006a; 2007a). Fcube is a mixed fisheries model for use in addressing mixed fisheries issues in a "simple, flexible and operational manner" which is able to provide short-term mixed fisheries advice (Ulrich *et al.*, 2011). Following development and subsequent trial, this is the current model favoured by the International Council for the Exploration of the Sea (ICES) to provide mixed fisheries advice in the North Sea (ICES, 2012b) and was trialled within the west of Scotland in 2012 (ICES, 2012c). This model estimates the potential future effort levels by fleets corresponding to fishing opportunities available to that fleet, based on how fleets distribute effort across métiers, and the catchability of each métier (ICES, 2006a). Potential effort is then used to estimate landings and catches by fleet and stock. Hoff *et al*. (2010) developed this further to include economic considerations (FcubEcon). Insertion of fleet and fisheries based advice into one of Europe's primary advisory mechanisms is a tremendous improvement on the traditional single species advisory system providing a bridge towards the advisory system required for mixed fisheries and ecosystem approaches to fisheries management.

Behaviour

Some failures of fisheries management may have resulted from poor understanding of fisher behaviour rather than from limited knowledge of the status of fishery resources (Hilborn, 1985 in Vermard *et al.*, 2008). Recent investigations have shown that diverse fleets react differently to the same underlying constraints as group incentives and alternative opportunities differ, highlighting that stocks cannot be managed in isolation and that fleet/fishery management must be incorporated (e.g. Reeves *et al.*, 2008; Andersen *et al.*, 2010; Ulrich *et al.*, 2011). Thus rather than addressing the symptoms of fishing management should consider the drivers of fishing pressure (Sethi *et al.*, 2010).

Current management measures are focused primarily on the resource (biological) aspect of fisheries management, disregarding economic (and social) imperatives and drivers. However, fisheries management is not solely a biological issue (Tidd *et al.*, 2012) but rather an interdisciplinary field encompassing all three aspects in which fisheries managers must focus on managing people to maintain the resource. As such, understanding fishers and their behaviour is as vital in fisheries science as the ecology and resource dynamics (Wilen *et al.*, 2002; Branch *et al.*, 2006; Hilborn, 2007).

Fishing is a business operation, influenced by changing economic pressures. Like any other business, fishing aims to generate profits through achieving greater revenues than costs. Fishers can be assumed to act in a profit maximising, rational manner using the information available to them to choose the most profitable fishing options (Wilen *et al.*, 2002; van Putten *et al.*, 2012). In the dynamic environment of fisheries, fishers constantly develop tactics and strategies adapting to the likes of fluctuating stock levels, regulations, and market conditions (Tidd *et al.*, 2012). Variation in landings prices at first sale, for example, have been shown to alter fisher behaviour (Marchal *et al.*, 2007; Sumaila *et al.*, 2007), as has the cost of fuel (e.g. Abernethy *et al.*, 2010; Bastardie *et al.*, 2013; Cheilari *et al.*, 2013).

Consequently, aspects driving fisher behaviour should be accounted for within management to attempt to achieve alignment between fisher and management objectives. It is widely acknowledged within the scientific community that the single species TAC management approach to European mixed fisheries can result in species-specific advice inconsistent with multi-species management objectives and reduce effectiveness of fisheries management (for example Hoff *et al.*, 2010; Kraak *et al.*, 2012). Gourguet *et al.* (2013) reiterate the conclusion that ignoring multi-species and multi-fleet interactions reduces effectiveness of management, where such interactions are an important driver of fishing mortality and economic profitability. Such inconsistencies can lead to overfishing, increased discarding and, in some cases, loss of possible profit due to quota underutilisation.

One of the greatest perverse consequences resulting from the mismatch between fisher and management objectives is discarding, a topic which recently has attracted much public attention (e.g. www.fishfight.net). This includes discarding of over quota catches while fulfilling quota for other species, economically or quota incentivised discarding of fish above minimum landing size (high-grading), and can cause indirect implications to foodweb interactions (Ulrich *et al.*, 2011; Tidd, 2013). Essentially fleets continue to target fisheries and areas where multiple species are available even after the TAC of one species present has been exhausted, discarding this species until other remaining TACs are reached (Vinther *et al.*, 2004).

Increasing understanding of fisher behaviour can be used to reduce the level of uncertainty within the whole management system (Fulton *et al.*, 2011; Tidd *et al.*, 2012). Fulton *et al.* (2011) acknowledge that it is difficult to account for all uncertainties (such as estimation of resource dynamics which includes recruitment strength and survival) within the management process. However, they consider it likely that recent instances of unexpected or limited management outcomes result from not fully understanding the influence of fisher behaviour within the system. Therefore improved understanding of the processes driving human behaviour can be used to reduce the uncertainty and error within the implementation aspect of management. This can reduce potential unintended and undesirable outcomes, which may result from hidden disincentives (Bastardie *et al.*, 2013), and which then adversely affect fisher compliance and response to management. Implementation uncertainties encompass management decisions (e.g. political pressure), application of the management (e.g. insufficient control and enforcement), and fishing activity (e.g. unanticipated and adverse responses). In the current TAC system implementation error regularly occurs, in addition to incentivising discarding, when set TACs do not strictly follow scientific advice (Andersen *et al.*, 2010). Such differences were estimated to have been up to a 21% between 2002 and 2008 (Villasante *et al.*, 2011).

Insight into the factors influencing the decision process is necessary to help understand observed individual and group behaviour. This is becoming an accepted view. Investigation of fleet, fisheries, and fisher behaviour has become more common within fisheries science in recent years (example studies include Tidd *et al.*, 2012; Andersen *et al.*, 2012; Edwards *et al.*, 2011; Bastardie *et al.*, 2013). From a management perspective, understanding of fisher behaviour is important so as to manage the system better in adapting environments (Fulton *et al.*, 2011). A detailed knowledge of the multi-fleet nature of fisheries and of the multi-species interactions taking place is a critical first step in developing sound mixed fisheries advice on which management can be developed. Thorough understanding of the complexity, dynamics and adaptive capability within operating fisheries is therefore necessary (Holley and Marchal, 2004). Thus, in the first instance an appropriate mixed fisheries level management unit must be identified, as highlighted by the Study Group on the Development of Fishery-based Forecasts (ICES, 2003).

An Irish perspective

Ireland, as an island nation, has a virulent and long standing fishing industry which exploits the diversity of species inhabiting the surrounding waters (ICES area VI and VII; Figure 1.1) as well as further afield (including pelagic fisheries off the east coast of the African continent). Over the last three years (2010-2012) these exploitations have annually resulted in landings of around 190-310 thousand tons[*], equating to monetary values of approximately 200-240 million Euro[*] at first sale. Table 1.1 details the top 20 species by value in 2012. Under the Common Fisheries Policy, Ireland is rarely the sole nation exploiting stocks and fisheries are often targeted by several nations. In a number of such international fisheries the activity of Irish fishers is relatively low compared to other nations (Anon, 2009). The level of involvement within fisheries is something which should be considered when assessing impact of Irish fishing.

The Irish commercial fleet typically consists of around 400 vessels annually, ranging in length from 10m to 71m, with two previously Irish vessels measuring over 100m (no longer registered in Ireland). There are roughly an additional 650 smaller vessels (<10m) which fish inshore waters. The majority of ≥10m vessels hold "polyvalent" fishing licences issued by the Irish government which allows them the freedom to vary gear types (or more loosely fleet segments) during the year to target multiple species (assemblages) giving these Irish fishers a high level of flexibility in how to go about their business of utilising the variety of fishing opportunities in nearby waters. Within the multitude of gear configurations the most widely applied gears include: mid-water pair trawls used to target pelagic species (e.g. mackerel, herring, and horse mackerel), bottom otter trawls and beam trawls both of which target bottom dwelling assemblages, as well as passive gears such as pots and gillnets. The pelagic fisheries generate the greatest landings, while demersal fishing has the highest vessel involvement and can achieve higher values. Of particular importance, in value, are the high volumes of *Nephrops* landed (Table 1.1).

Ireland has a large number of ports (several highlighted in Figure 1.2), many of which are surrounded by small communities for which fishing has traditionally been the

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[*] Landings and values relate to vessels ≥10m in length

greatest employer, such as Castletownbere. That said, over time several ports have developed into larger landing ports favoured by particular fleet segments. Killybegs has developed with the pelagic fleet to deal with large vessels with high volume catches from pelagic fisheries North of Ireland. In contrast the majority of landings into Greencastle are demersal. As with the variable fidelity to fleet segments, vessels do not necessarily operate out of their registered port favouring instead a diversity of ports where particular catches can be processed, obtain a better price at auction, or are closer to buyers/transport connections.

From an Irish perspective migrating from the traditional single species to mixed fisheries management and the EAFM is likely to result in a greater need for scientific input by both government and industry. Advice on the best ways to achieve sustainability, develop effective mixed species management strategies, and develop ways of predicting the outcome of such strategies will help to identify possible adverse consequences in advance. There is already progress in this direction. The North Western Waters Regional Advisory Council (NWWRAC) has developed a long term management plan for mixed demersal fisheries in the Celtic Sea, supported through scientific research projects.

Fishery or fleet-based management strategy evaluations (MSEs) are an emerging evaluation method utilised to analyse such integrated management initiatives (e.g. Kraak *et al.*, 2008; Andersen *et al.*, 2010). Within MSEs the fleet or fishery dynamics (fleet module), resource dynamics (operating module), and regulation implementation (management module) may be run in concurrent simulations to determine the possible outcomes of changing drivers and management pressures. For this, models capable of adequately reproducing fisher behaviour (choice) through incorporation of explanatory drivers are necessary to improve the underlying reality, predictive capabilities, and accuracy of MSE fleet modules. One such specific area of fisher behaviour currently expanding is the incorporation of economic drivers (examples listed previously); a critical consideration given that commercial fishing is a profit driven occupation.

In the first instance, given the complexity and heterogeneity of fisheries exploited by Ireland, there is a need to identify and segment into smaller grouped units or "métiers" ("a homogeneous subdivision of a fishery by vessel type" incorporating both spatial and temporal components of variability (ICES, 2003)). Formulation of métiers allows landings and effort to be allocated into units that most appropriately reflect the fishing activities within them (ICES, 2003) and can provide more “accurate” catch per species and effort calculations for assessment, and effective partitioning of fishing mortality (Pelletier & Ferraris, 2000). Well-defined métiers can therefore, represent building blocks aiding the assessment of fleet and fishery dynamics (e.g. Ulrich & Andersen, 2004).

A spectrum of information is required to support the progression toward developing and supporting mixed fishers management, including:

- Thorough grasp of species compositions, spatial occurrence, and fishing activity characteristics to assess the needs for protection and preservation.
- Detailed knowledge of the multi-species interactions and the multi-fleet nature of fisheries.
- Comprehension of the drivers affecting fisher decisions
- An understanding of the complexity, dynamics, and adaptability of operational fisheries (Holley & Marchal, 2004) and an ability to predict the impacts of changing management strategies on the behaviour of fishers (Soulié & Thébaud, 2006).

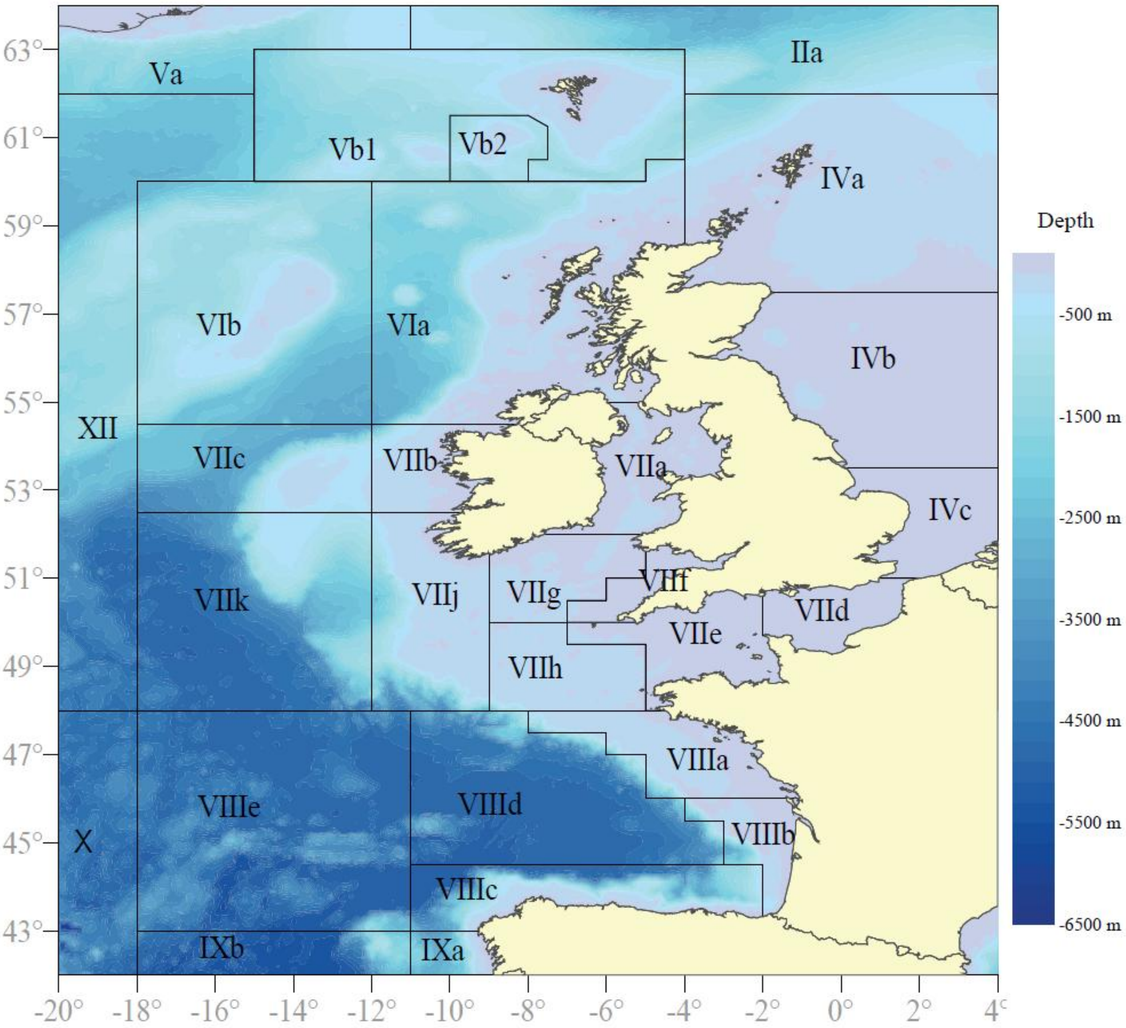

Figure 1.1. Map of the ICES Divisions around the Irish and UK Coast, detailing water depth ranges.

Figure 1.2. Map of Ireland highlighting a number of fishing ports and species groups landed.

Table 1.1. Top 20 most economically valuable species landed by Irish ≥10m vessels in 2012. Information obtained from Irish logbook data and rationalised first sale prices.

Species	Live weight Tonnes	Landed weight Tonnes	Value (million Euro)
Mackerel	63,119	63,031	54.32
Nephrops	10,142	6,375	44.51
Horse Mackerel	45,297	45,297	24.62
Herring	28,250	28,104	15.70
Monkfish	3,747	3,023	13.14
Megrim	3,424	3,231	10.59
Tuna	3,672	3,667	8.79
Boarfish	55,949	55,949	8.00
Crab	4,752	4,742	7.32
Haddock	5,563	5,073	7.18
Whiting	5,987	5,598	6.83
Scallop	2,532	2,532	5.01
Cod	1,963	1,602	3.99
Hake	1,849	1,663	3.41
Whelk	2,498	2,498	2.46
Sole Black	209	201	2.04
Ray	1,142	1,011	1.90
Lobster	87	87	1.79
Pollack	989	852	1.76
Turbot	193	177	1.54

Objectives

The overall objective of this research was to improve understanding of the complex targeting behaviour undertaken by commercial fishers. Greater understanding will enhance our ability to predict fisher responses to future management measures and changing economic conditions within the Irish fishing industry. The research facilitated this through the formulation of a bio-economic model of métier dynamics, modelling the dynamics and behaviour of fishers.

The previous responses within the Irish fleet and métiers to management initiatives, changes in fishing opportunities, and the driving influences behind behaviour were of particular interest. The model developed is intended for future incorporation within existing simulation frameworks, enhancing representation of fleet dynamics. This is particularly important when evaluating mixed demersal fisheries management scenarios where examination of key questions, such as the effectiveness of proposed policies and the predictability of future fisher responses to new initiatives, is critical. This work informs the debate on current and future fisheries management and policy options accounting for fisher adaptability at appropriate spatial and temporal scales where the simulation outcomes can be translated into impacts on the Irish fleet and commercial stocks around Ireland.

Thesis Structure

This thesis is divided into six main chapters representing discrete, but inherently connected studies. Each relates to an aspect of the identification, exploration and examination of fishing dynamics and drivers of behaviour. The first five elements build knowledge for the final study which models Irish fishing behaviour utilising aspects of the preceding chapters. The introduction and final discussion outline how findings advance this topical research area. A number of the chapters are published or under review in peer reviewed fisheries journals with the chapters here representing the associated paper. Consequently, the individual chapters follow the normal structure of scientific papers, with an abstract, key words, introduction, methodology, results, discussion and conclusion. The outline, objectives and publication details of each chapter are summarised below.

Chapter II:

An analysis carried out to separate the diverse and complex heterogeneous fishing practices within the Irish otter trawl fleet into similar homogenous groupings of fishing trips, or métiers, fundamental to all subsequent analyses. The objectives were to:

Identify métiers using ‘best practice’ multivariate techniques;

Describe and characterise these métiers;

Assess métier stability and persistence;

Discuss the utility and application of métiers.

Published as:

> Davie, S., and Lordan, C. (2011). Definition, dynamics and stability of métiers in the Irish otter trawl fleet. Fisheries Research, 111: 145–158.

Chapter III:

A follow on analysis carried out to separate the diversity of fishing practises related to the non-otter trawl fleet, i.e. those not utilising otter trawl gear, into homogeneous métiers, completing the fundamental base analysis. The objectives were to:

Identify métiers using the multivariate techniques of Chapter 2;

Describe and characterise non-otter trawl métiers;

Assess métier stability and persistence.

Chapter IV:

To investigate métier dynamics on using a case study analysing the impact of the cod long-term management plan (CLTP), introduced in 2009, on the Irish fleet, fisheries, and métiers. The objectives were to:

Describe and discuss vessel movements within and between métiers;

Identify responses to implementation within the CLTP remit;

Identify changes beyond the CLTP remit occurring as a consequence of implementation.

Published as:

> Davie, S., and Lordan, C. (2011). Examining changes in Irish fishing practices in response to the Cod Long-Term Plan. ICES Journal of Marine Science, 68: 1638–1646.

Presented to the following conference:

> Davie, S., and Lordan, C. (2010). Examining changes in Irish fishing practices in response to the Cod Long-Term Plan. ICES Symposium on Fishery-Dependent Information, Galway 23-26 August 2010.

Chapter V:

Fuel usage and cost were identified as drivers of fisher behaviour. These drivers must be translated into variables to improve accuracy and enhance predictive capabilities of fishery simulations. Thus this investigation utilised annual Irish fuel cost data to produce per day fuel consumption estimates. The objectives were to:

Estimate models to describe per day fuel consumption based on fleet segments (gears), vessel length, and engine power;

Predict per day fuel consumption;

Test predicted fuel consumption against un-modelled consumption values.

Submitted as:

> Davie, S., Minto, C., Officer, R., Lordan, C., and Jackson, E. *In review*. Modelling fuel consumption of fishing vessels for predictive use. ICES Journal of Marine Science.

Chapter VI:

The first sale value obtained for catches was also identified as a driver of fishing behaviour. It is therefore important to translate this into a variable which can be used in bio-economic models. As such, this investigation aimed to develop a unit which could be used to represent the turnover of fishing activity by:

Calculating Irish price at first sale (€ per kg) values to examine spatial and temporal trends for several gear and species target groups for:

Species landed into Ireland, and

Total first sale values achieved per trip (VPT; € per kg);

Exploring several factors known to influence catch rates and value per trip;

Standardising per trip value to account for these factors.

Submitted as:

> Davie, S., Minto, C., Officer, R., and Lordan, C. *In review*. Defining value per unit effort in mixed métier fisheries. ICES Journal of Marine Science.

Chapter VII:

The intention of this final investigation was to model and predict likelihoods of transition between métiers for a given set of conditions mimicking fisher choice behaviour. The objectives were to:

Test a variety of explanatory variables and identify those best able to describe switching behaviours between métiers,

Formulate a Markov chain multinomial model with main effects and interactions between main effects and the previous métier.

Test the model's capacity to predict responses to a series of changing pressures.

Chapter VIII:

An overall discussion of the work and main findings is presented in the context of mixed fisheries management. The relevance of these results to future management initiatives and decision making within mixed fisheries are discussed with reference to the further extension of this research.

Chapter II: Definition, dynamics and stability of métiers in the Irish otter trawl fleet

Published:

Davie, S., and Lordan, C. (2011). Definition, dynamics and stability of métiers in the Irish otter trawl fleet. Fisheries Research, 111: 145–158.

Abstract

The Irish otter trawl fleet operates in a complex multi-species, multi-gear, fishery, spanning a wide geographic area, and involving around 275 trawlers. Factorial and clustering methods were applied to 2003 fishing trip data to define thirty-three métiers. Definitions were based on six trip characteristics taken from logbooks, namely: fishing gear, mesh size, vessel length, species composition, area, and month. Métiers exploiting demersal species or species groups are characterised by single vessel bottom otter trawls, typically with mesh sizes of 70mm or more, operating year round. This includes nine *Nephrops* dominated métiers highlighting the importance of this species to the fleet. Many demersal métiers are characterised by groups of species, such as mixed whitefish or slope species. Métiers exploiting pelagic species are often focussed on single species, and are typically seasonal, mid-water trawling (often paired) with mesh sizes less than 70 mm. Pelagic métiers account for the majority of landings by over an order of magnitude in several cases. Demersal métiers account for the majority of fishing trips and effort, (primarily *Nephrops* métiers), and vessels (primarily mixed species métiers). The new métier definitions were found to be appropriate and remained relevant despite declining fleet landings and effort between 2003 and 2006. Species compositions within these métiers have generally remained similar to the proportions defined in 2003. These robust métier definitions present opportunities to improve fisheries sampling, assessment and management. Although métiers pose a complexity challenge for such applications, they can be used as the building blocks for appropriate management units.

Key words

Irish otter trawl fleet; Métiers; Multivariate analysis; Fleet dynamics; Mixed fisheries

Introduction

The poor performance of traditional single species stock management systems has lead to a change in management perspectives. Moves towards mixed or multi-species fisheries management are consistent with the nature of operation of most trawl fisheries. However, sound mixed-species fisheries management requires detailed knowledge of the multi-fleet nature of fisheries, and of the multi-species interactions that are taking place. In addition, an understanding of the complexity, dynamics and adaptability within operating fisheries (Holley and Marchal, 2004) is very important, particularly in response to evolving management strategies.

Due to the heterogeneity of the fisheries exploited by Irish otter trawl fleet, it is generally inappropriate to attempt to manage such fleets as a single unit. Thus, there is a need to identify and segment fisheries and fleets into similar groupings, or métiers. A métier being "a homogeneous subdivision of a fishery by vessel type" incorporating a spatial and temporal component (ICES, 2003), also called ‘fishing tactic’ (Pelletier and Ferraris, 2000), ‘fishing strategy’ (Holley and Marchal, 2004), or ‘fleet component’ (Silva *et al.*, 2002; Campos *et al.*, 2007) in the literature. Defining métiers allows landings (and effort) to be allocated into "sensible" sized units reflecting the fishing activities within them (ICES, 2003). The complexity of the Irish otter trawl fisheries and fleet require that the métiers are based on a variety of factors including species assemblage, vessel characteristics, fishing grounds and season.

The homogeneity within métiers can provide for more "accurate" catch per species and effort calculations in assessment, and for more effective partitioning of fishing mortality" (Pelletier and Ferraris, 2000). Well-defined métiers can create building blocks, for use at a national level to stratify sampling and discard programs which can be incorporated into European sampling initiatives (namely the Data Collection Framework), aid in assessing fleet/fishery dynamics (e.g. Ulrich and Andersen, 2004), and are becoming increasingly important in management strategy evaluations and simulations (e.g. ISIS-Fish (Drouineau *et al.*, 2006) and Vermard *et al.*, 2008). Ultimately, well defined métiers provide the building blocks of more effective management.

The main technique previously used to identify and define métiers has been quantitative multivariate analysis, primarily forms of cluster analyses. This is either in conjunction with factorial/ ordination analyses (for example Pelletier and Ferraris, 2000; Holley and Marchal, 2004; Ulrich and Andersen, 2004; Campos *et al.*, 2007) or through clustering methods alone (Duarte *et al.*, 2009; Castro *et al.*, 2010, 2011). These multivariate methods have also been recommended by the ICES Study Group on the Development of Fishery based Forecasts (SGDFF; ICES, 2003). The SGDFF group proposed a three step open framework approach, combining quantitative analysis with ad hoc qualitative classification to define métiers. First species groupings are identified using catch/landing profiles. Relationships between landing profiles and trip/vessel characteristics are then assessed, followed by hierarchical classification obtaining groupings which are subsequently defined into métiers with expert knowledge of the fisheries and fleets. This framework has been followed in several investigations including Ulrich and Andersen (2004), and Holley and Marchal (2004). The main advantage of this technique is that it reduces subjectivity and dependence on a priori knowledge.

The objectives of this study were to (i) identify métiers using 'best practice' multivariate techniques, (ii) describe and characterise these métiers, (iii) assess métier stability and persistence. The analysis was undertaken using data for the Irish trawl fleet. The utility and application of métiers to the Irish national sampling program and wider management are discussed.

Materials and Method

Data

Irish otter trawl logbook data were used for analysis, from the Integrated Fisheries Information System (IFIS) database, provided by the Department of Agriculture, Fisheries and Food. The Irish trawl fleet consists of between 250 and 300 vessels. This fleet utilizes a variety of different gear configurations and lands over 100 species from various species assemblages annually. Total landings in 2006 were around 210,000 tonnes in live weight, worth approximately 250 million euro at first sale. This equates for around 75% of annual Irish landings in value.

Within this analysis the data for "trawl gears" is restricted to Irish ≥10m vessels utilising bottom and mid-water otter trawls and paired bottom and mid-water trawls (OTB, OTM, PTB, and PTM). All vessels 10m and over, fishing in European waters which are at sea on fishing voyages longer than 24h are required to complete a daily logbook during each fishing trip (EC, 1993). For each fishing trip the following data were recorded for the analysis: overall vessel length, gear type, mesh size (including non-recorded as zero), ICES area, landing date, and estimated live weight (using conversion factors) of all species landed from the "landing declarations". Fishing trips were considered independently from the vessel, once overall vessel length was established. Fishing trips from 2003 to 2006 were available for analysis, 33,717 trips by 396 vessels. Due to the size of the data set, 2003 was used as a reference year to identify and define métiers for application to 2003–2006 data. This restricted the number of fishing trips to 9030 carried out by 282 vessels. All analyses were performed within the R language and environment for statistical computing (R Development Core Team, 2007).

Prior to analysis data were subjected to initial screening, to remove unusable records. Landed weights recorded as "mixed boxes" were excluded from weight calculations, as the species are unknown (~0.2% of total annual Irish landed weight). Four fishing trips were excluded from the analysis, two trips landing solely mixed boxes and two recording use of multiple gears within the trip. Species contributing less than 0.1% of total landings were grouped together into an "other" category thus reducing the influence of ‘less abundant’ species. Cumulatively this "other" category accounts for, on average, less than 1% of total Irish landings annually. To reduce the impact of uncertain identification and variation in logbook coding practices some individual species were grouped to a higher taxonomic level e.g. *Rajiformes*. This resulted in the use of thirty-eight taxonomic categories within analyses.

Typology of Métiers

The methodology in this investigation is based on that used by Pelletier and Ferraris (2000), and Ulrich and Andersen (2004), following the three step framework recommended for métier definition by SGDFF (ICES, 2003). This combines the use of quantitative multivariate analysis of landings and effort data with qualitative expert knowledge, avoiding prior assumptions on homogeneous groupings.

In the first step, groups homogeneous in relation to species composition (i.e. landing profiles) are identified. There has been debate on the species metrics appropriate for defining métiers. Most previous investigations used either landed weight or first sale value. In this investigation, and an earlier Irish Sea study (Davie and Lordan, 2009), landing profiles are used based on the relative species proportions in trip landings. Weight was primarily chosen as accurate first sale value data were not available at the time of analysis. It is possible that species with low landed weights but high relative values could have resulted in these species having a greater influence in defining métiers, had values been used. Management is primarily focussed on maintaining biological and ecological imperatives where catch weight is a more relevant metric than value.

Landing profiles were identified using non-normalised Principal Component Analysis (PCA) allowing for species dominance. PCA reduces the dimensionality of the dataset and identifies the main reoccurring species combinations that explain the greatest variation. Components are presented in order of importance, with the greatest variation described by the first component (Fowler *et al.*, 2004). Subsequent application of Hierarchical Agglomerative Cluster analysis (HAC, utilising Euclidean distance and Ward's algorithm (Ward, 1963)) created successive clusters based on previously identified clusters, and built a hierarchy from individuals to a single group. Determination of the appropriate number of clusters to employ was considered to be the level at which the increase in the proportion of variance explained levelled off (via sums of squares and r^2 values), similar to that in Ulrich and Andersen (2004). The relevance and size of clusters was considered in the formulation of landing profiles, considered as categorical variables for input to Multiple Correspondence Analysis (MCA).

Multiple Correspondence Analysis is analogous to PCA but is applied to categorical variables. MCA was used to investigate relationships between the landing profiles and the five descriptive variables, as recommended by SGDFF (ICES, 2003). These variables were: (1) ICES divisions, (2) gear type, (3) mesh size range[1], (4) overall vessel

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[1] Mesh size range was based on groupings in Council Regulation (EC) No 850/98: EC, 1998.

length[2], and (5) month (a proxy for season). The MCA output was also entered into an HAC (based on Euclidean distance and Ward's algorithm (Ward, 1963)) to cluster trips into homogeneous groups based on the relationships between variables. The appropriate number of clusters was again estimated using the proportion of variance explained, each of which was fully described using the categorical variables. Some clusters were pooled to avoid over complexity and excessive disaggregation. This pooling was necessary in a small number of cases to retain important information on the structure of the dataset whilst preserving integrity for future analysis (Anon, 2005a).

Results

Landings Profiles

The Principal Component Analysis to identify landing profiles indicates high variability in trip species composition, and thus a great complexity of species combinations. This accounts for the low percentage variation explained by individual components. The first four components, which were considered as relevant to depict the relationships between species, explained 22% of the variability associated with trip landings. Figure 2.1 is a bi-plot showing the first and second PCA components to illustrate the species differentiations between landings profiles. In this plot trips dominated by "deepwater species", "slope species" (inc. ling (*Molva* spp.), hake *(Merluccius merluccius*), forkbeard (*Phycis* spp.)), "*Nephrops*" (*Nephrops norvegicus*), megrim (*Lepidorhombus* spp.) & monkfish (*Lophius* spp.), haddock (*Melanogrammus aeglefinus*), and mackerel (*Scomber* spp.) & herring (*Clupea harengus*) clearly formed separate groupings. Trip distribution was more dispersed across the third and fourth components (not shown) showing groups of megrim & monkfish, rays & plaice (*Pleuronectes platessa*), black sole (*Solea solea*), and haddock.

All principal components were included in the Hierarchical Agglomerative Cluster analysis (HAC) due to the apparent complexity of interactions and to maintain sufficient variation. Choice of the appropriate number of clusters was made based on the level of

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[2] Vessel length overall was based on the category outlined by the RCM NEA October 2005 report (Anon, 2005a).

variance within the dataset explained by clusters (from sums of squares and r^2 values). Little increase in the explained variance occurred with groupings of greater than 40 clusters. Therefore 40 clusters were considered an appropriate level of resolution, explaining 73% of the variation. The number of trips within clusters varied considerably (from 1 to 1887) where the majority of clusters each contained less than 5% of all trips. Of those clusters representing a small proportion of fishing trips (<5%), only those clusters considered to represent realistic target species or assemblages were retained as valid landing profiles. The remainder were either recombined with the next nearest linked cluster when species compositions were similar, or assigned as non-allocated ("A"). The latter occurred when the species composition was very rare (e.g. mussels) or where the species composition was considered unlikely (e.g. pelagic and shellfish species caught together). This resulted in sixteen landing profiles (Table 2.1) varying in the number of characteristic species, named as the dominant species by proportion and occurrence within clusters. The number of characteristic species within a profile varies from one (mainly pelagic species) to five (mainly demersal species). The largest landing profile, (21% of all fishing trips) is characterised by high proportions of *Nephrops*, generally over 50% of the landings.

Métier Identification and description

To obtain groupings of similar trips with respect to key trip factors Multiple Correspondence Analysis was performed followed by HAC clustering. Six key trip factors (descriptive variables) were used; landing profile, ICES division, vessel length range, gear type, mesh size range, and month (season proxy). MCA produced 134 factorial axes, each explaining a small portion of variance. The first three axes are considered as relevant to depict the dominant relationships between trip details, combined explaining 6% of the variability within the dataset. The percentage of variation explained on the first axes was almost twice that of the second axes, suggesting a particularly different group of trip characteristics from the remainder.

On the first and second axes (Figure 2.2) a well separated group of multi-ICES division trips linked to area VIII and vessels greater than 80m in overall length occurs, with no clear landing profile association. There is also a second, more centralised, trip grouping associated with the mixed pelagic landing profile (L13) and ICES areas VIII, XII, and division IIa. The main grouping is also seen on the second and third axes (not shown). Trips associated with deepwater species (L16) and tuna (*Thunnus* spp.) (L14), linked to larger mesh sizes (≥100mm) and multi-ICES areas to the north and west of Ireland (i.e. VIa, VIIb, VIIc and VIIk) are also separated. All MCA axes were included in the HAC analysis due to the complexity of interactions (i.e. low level of variance explained by individual axis) to maintain sufficient variation. The appropriate number of clusters was estimated as the point at which the level of variance within the dataset explained by clusters levelled off with increasing numbers of clusters. This resulted in 103 clusters explaining 80% of total variation. Figure 2.3 depicts the resultant HAC dendrogram with 103 clusters. The number of trips within these clusters varied greatly, from 1 to 4668 trips. Many clusters contained a consistent variable factor, for example: a single gear type, landing profile, mesh size range or ICES area. The majority of clusters contained a variety of vessel length ranges and months, indicating that these are not key factors. Clusters with low fishing trip numbers, less than 1% (equating to 90 trips) were recombined with closely related clusters, unless considered to represent a true métier.

Once clusters were fully described, trip characteristics (i.e. vessel length, gear type, mesh size, area and time) and parameters for minimum and maximum species compositions were used to define the 33 métiers within the Irish trawl fleet (Table 2.2). In addition a number of ‘non-métier’ groups were established to cover trips with incomplete or misspecified logbook information and trips with landings profiles or other characteristics outside the métier definitions outlined in Table 2.2.

Métiers can be divided into two main groups. Ten utilise <70mm mesh mid-water and/or pair trawls with high proportions of pelagic species landings. While the majority of trips and vessels employ 70mm or greater mesh bottom otter trawls, dominated by demersal species with a greater diversity, often with mixed targets. Pelagic métiers are mainly populated by larger vessels (≥24m), whereas the majority of demersal métiers are mainly populated by smaller vessels (<24m). The demersal métiers include nine with high *Nephrops* proportions, divided by ICES divisions and proportion of *Nephrops* landed. There is also a deepwater métier reporting landings cardinal fish (*Apogonidae* spp.), grenadier (*Macrourus* spp. and *Coryphaenoides rupestris*), deepwater shark and fish species operating to the west of Ireland (VIa, VIIb, VIIc, VIIj and VIIk).

In several cases, a landing profile occurred within several métiers exhibiting different vessel and trip factors (e.g. 70–89mm or 100–119mm mesh). The reverse was also observed, where métiers are formed with similar factors yet differing landing profiles. This highlights the importance of utilising both trip and vessel characteristics and species compositions to define métiers.

Examining the importance and dynamics of métiers

Métier definitions were applied to fishing trips from 2003 to 2006, to observe temporal dynamics in relation to number of trips, vessels, landings, and effort. Identified métiers persisted throughout the period, with exception of pilchard and mackerel targeted mid-water otter trawling. This would indicate that the analysis and subsequent métier definitions successfully identified recurring patterns of fishing activity within the Irish trawl fleet.

Fishing trips and vessels

Métier allocated fishing trips accounted for between 70 and 76% of all trips annually, with 94–98% of all vessels operating in at least one métier (Table 2.3). These levels remained relatively stable. It must be noted that vessels may practice several métiers annually (Figure 2.4), targeting different species compositions or utilising varying gear configurations on different fishing trips.

Vessels targeting pelagic species rarely occur in a single métier, likely related to quota and seasonal restrictions on pelagic fisheries. Some vessels operating within pelagic métiers also fish demersal métiers, and vice versa. Not all vessels operate across all the areas in which the Irish trawl fleet occurs. *Nephrops* is a good example, vessels belonging to a VIIa métier are also likely to operate in VIIg, but less likely to operate in VIIj, VIIc or VIIk. This may relate to vessel limitations or fidelity of vessels to fishing ports. Around half of vessels operate within two to four defined métiers (Figure 2.4). However, vessels have operated within up to eleven defined métiers in a year, with few specialising in a single métier. Thus, the majority of vessels are polyvalent in relation to métiers, targeting different species, areas, or varying gear and mesh size. For some vessels this may not be intentional, where trips do not obtain the minimum species thresholds to qualify, e.g. occurring in both mixed and clean VIIa *Nephrops* métiers. Although not included in this analysis, the authors also note, vessels occasionally employ different gear types during a trip, for example a trawl net and pots.

Over time, the greatest increases in vessel numbers occurred in the same métiers as those with the greatest trip increases. Trip and vessel numbers more than doubled within the *Nephrops* OTB VIIc and VIIk métier. This increase was not universal among all *Nephrops* métiers, indicating an expansion of the deeper water *Nephrops* fishery on the Porcupine Bank (FU16). Mid-water blue whiting (*Micromesistius poutassou*) trawling in VIb, VIIc, VIIk and XII showed a substantial increase, doubling in both trip and vessel numbers. Two métiers have contracted by around 75% in trip and vessel numbers. These are the deepwater métier and ≥100mm mesh OTB for pollack (*Pollachius pollachius*), saithe (*Pollachius virens*), cod (*Gadus morhua*), whiting (*Merlangius merlangus*) and dogfish (*Squalidae* and *Scyliorhinidae*).

Within a métier trip increases do not necessarily result in increased vessel numbers and vice-versa. OTB trips targeting megrim and monkfish show an increased number of trips per vessel. Trip numbers in both the 70–99mm and ≥100mm mesh métiers increased by ~60%, although vessel numbers remained relatively stable. Conversely, the mackerel targeted métier across VIa, VIIb and VIIj shows greater vessel participation but with fewer trips per vessel. Vessel numbers showed an increase of 26% whilst trip numbers declined by 50%. This change can be related to management restrictions limiting individual vessel quotas.

Clean *Nephrops* in VIIa and the 70–99mm mesh plaice and ray OTB métiers remained relatively stable across trip and vessel numbers. The stability suggests consistent fisher participation within these métiers. Mixed *Nephrops* in VIIa and VIIg show stability in vessel numbers, whilst clean *Nephrops* métiers in VIIg and VIIb and *Nephrops* in VIIj show relatively stable trip numbers.

Landings

There is a wide variation in the total weight landed by each métier (Table 2.4). Pelagic métiers land the greatest volumes, the largest of which, characterised by blue whiting mid-water trawling, landed ~33kt in 2006. By contrast, the largest demersal landings originated from the 70–99mm mesh whiting métier of ~2.5kt. At the other end of the spectrum, *Nephrops* in VIa contributed just 35t. Overall demersal métier landings account for less than 13% of total weight landed by the fleet.

Mid-water trawling for blue whiting exhibits a marked increase in landings over the period (+102%). Significant increases in landings have occurred within three demersal métiers. Primarily, *Nephrops* in VIIc and VIIk (+276%), 70–99mm mesh whiting has shown an increase of nearly 200% and ≥100mm mesh megrim and monkfish increased by 73%. However, the majority of métiers showed declining landings over the period. The most substantial decline observed relates to the deepwater métier, declining from ~2kt to ~0.2kt, reflecting a major contraction in Irish deepwater fishing. Two mixed Irish Sea based demersal métiers have also shown marked declines, the 70–99mm mesh whiting, cod, haddock and dogfish, and ≥100mm mesh plaice and ray métiers. This results, in part, to restrictive effort and catch management as part of cod recovery measures. Mackerel in IVa was the most significant pelagic métier to decline, showing continuous reductions in landings in response to quota restrictions and changing fishing pattern. Landings in several métiers remained relatively stable. These included the pelagic métiers, Non-VIa herring pair trawling, and horse mackerel (*Trachurus* spp.) mid-water trawling, clean *Nephrops* in VIIb and VIIg, and ≥100mm mesh pollack, saithe, cod, whiting and dogfish.

Species compositions show the majority of demersal métiers land a wide variety of species (Figure 2.5), many as chance-catch, i.e. species not directly targeted but landed in low levels (<10%). Several species occur in the majority of demersal métiers as chance-catch. For example, both cod and hake occur to some extent in most demersal métiers. Highlighting the many mixed fishery interactions within waters fished by the Irish otter trawl fleet. The range of species is less extensive in pelagic métiers (Figure 2.5), which tend to be more mono-specific, indicating fewer mixed species inter-actions. The major pelagic species combination observed within Irish landings is European pilchard (*Sardina pilchardus*) and herring. Chance-catch species within pelagic métiers primarily include boarfish (*Caproidae*), horse mackerel and mackerel. In general, pelagic species can be targeted effectively by a métier due to mid-water shoaling behaviour which reduces the number of species interactions.

Effort

Below, effort changes are examined in days-at-sea, being every 24h period or part thereof from the time a vessel leaves port to the time it returns, as this measure of effort is often defined within European fisheries regulations. Fishing days and fishing hours were also available, although not detailed here. It should be noted that the relationship between days-at-sea, fishing days, and fishing hours can vary between métiers due, for example, to travel distances or target species behaviour.

Many demersal métiers average 4–5 days per trip. Longer trips, those averaging over 7, often include ICES areas further from Irish shores, including VIb and VIIc, likely resulting from longer travel times and/or longer trawl times within deeper waters. ≥100mm mesh megrim and monkfish trawling trips in VIIj also average over 7 days. Trips within this métier are likely to occur towards the south-western corner of the division on the continental shelf slope, often crossing several ICES Divisions tracing the shelf edge.

Over the period examined total otter trawl fleet effort has declined, whilst the proportion assigned to métiers has fluctuated between 66% and 72%. This indicates métier definitions have remained relevant over time, encompassing the dominant fishing strategies of the Irish otter trawl fleet.

Several individual métiers have shown substantial effort increases (Table 2.3). In particular, VIIc and VIIk *Nephrops* and blue whiting mid-water trawling in which effort has doubled or more since 2003, indicating increased targeting by Irish fishers. Effort increases were also observed in the 70–99mm mesh whiting although, in this case little increase in trip numbers occurred and vessel numbers declined by 50% indicating a change in métier fishing practice. For example, vessels increasing trip length and amount of fishing activity per trip.

Effort declined by 75% or more over the period in five métiers. Three demersal métiers: ≥100mm mesh deepwater trawling, ≥100mm mesh ling, witch (*Glyptocephalus cynoglossus*), forkbeard and hake, and ≥100mm mesh plaice and ray. The latter of which is unlikely to continue in future years, given the observed declines. Two pelagic; mackerel mid-water trawling in Iva, and sprat in VIa and VIIa. Several of these métiers have also shown large reductions in landings, trips, and vessel numbers, indicating contracting métiers. Few métiers have shown little change. Only clean *Nephrops* in VIIg and mixed *Nephrops* in VIIa remained relatively stable.

Discussion

Understanding fishermen's behaviour through the aggregated behaviour of fishing fleets is a key ingredient to successful fisheries management (Hilborn, 2007). The Irish fleet is diverse and complex with ~1900 vessels registered[3], ranging in length from only few meters to one of the largest fishing vessels in the world at 134m[4]. Trawling is the most common fishing method used by Irish fishing vessels ≥10m and is multi-species in nature, occurring across a wide spatial distribution. This investigation has succeeded in separating the large heterogeneous fleet into more homogeneous métiers, the definitions of which persist throughout the period examined. Case studies discussed below, highlight particular changes in behaviour, mixed species considerations, and impacts of external drivers. Possible contributions to sampling program design and national management advice are also considered.

This analysis framework applied similar statistical methodologies of ordination followed by clustering to several pervious métier studies (Pelletier and Ferraris, 2000; Holley and Marchal, 2004; Campos *et al.*, 2007). Alternative approaches such as Partitioning Around Medoids (PAM) algorithm (Duarte *et al.*, 2009) and an extension of this for large datasets, CLARA (Clustering LARge Applications) (e.g. Punzón *et al.*, 2010; Castro *et al.*, 2010, 2011) have been used in recent studies. However, as cautioned by Castro *et al.* (2010), the CLARA algorithm samples subsets of the overall data matrix. As a result, clusters of information may be missed and/or oversimplified in complex datasets, such as the Irish trawl fleet. This is the first time métiers have been defined on a broad scale for Irish trawl fisheries, although investigation into métier definition was carried out in the Irish Sea (Davie and Lordan, 2009). The data available were in general of high resolution (i.e. detailed logbook), however it is prudent to point out that this analysis is only as reliable as the input data. Misspecified and misreported

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[3] Base on fleet register October 2007.

[4] Note that the Atlantic Dawn one of the largest fishing vessels in the world was deregistered in Ireland in 2006.

landings, changing discard practices and other data anomalies will have impacted the results obtained. This is exemplified by the large proportion of trips and effort allocated to "non-métiers". Future studies should minimise these through data screening and algorithms to correct anomalous logbook data. Discards have not been included in this analysis as recent sampling levels (<1% of trips) would not be sufficient to allow for a catch based analysis. Nevertheless, the purpose of the investigation was to identify métiers based on reported logbook information, which are conditioned on current management constraints, reporting, and discarding practices.

The métier definitions here are based on a "snapshot" in time, i.e. the reference year, 2003. Landing profiles, and subsequent métiers definitions, are impacted by species availability during this period. There is a certain circularity in the way métiers are identified, necessitating periodic review of métier definitions. This is in line with the conclusions of previous métier studies (e.g. ICES, 2003; Ulrich and Andersen, 2004). A review periodicity of 5–10 years would seem appropriate for the trawl fisheries examined here. Other studies utilised a range of years to identify métiers, inferring change through the persistence or occurrence of observations from different years within clusters (e.g. Campos *et al.*, 2007; Castro *et al.*, 2011) or carried out separate analyses on annual data (e.g. Holley and Marchal, 2004). These approaches may limit the ability to compare variation over time, and give little continuity between years.

The analysis showed gear, mesh size and landing profile as dominant factors in defining the thirty-three métiers identified. Gear type and mesh size configuration can strongly influence species selectivity. What is evident from the analysis is that the fleet are able to utilise various gear configurations to target a specific species or assemblages (subject to management constraints e.g. catch composition rules; EC, 1998), as well as a specific gear configurations to target multiple assemblages. Similar studies such as Pelletier and Ferraris (2000), Ulrich and Andersen (2004), and Campos *et al.* (2007) have had similar results between assemblages or gears. This underlines the need to consider targeting behaviour in management as well as technical constraints.

This analysis here allowed for varying spatial distribution and several métiers span multiple ICES Divisions. Within the demersal métiers, those operating along the continental slope, for example, span six divisions, whilst others occur within a discreet area in a single division, such as the Irish Sea *Nephrops* métier. The spatial extent of pelagic métiers also varies. The west of Scotland (VIa) herring métier for example is spatially discreet, whereas the blue whiting and tuna métiers cover a much broader area spanning around six ICES Divisions. This type of result is informative from a sampling, assessment, and management perspective since often there is a tendency to stratify fisheries and data based on ICES Divisions.

The majority of métiers show year round activity with the primary exception of pelagic métiers, therefore season appears of relatively minor importance in the definition of Irish métiers. This is a similar finding to Ulrich and Andersen (2004) for Danish fisheries. It is important to note that this does not mean that seasonal variations, in LPUE for example, do not occur within métiers. Rather that, subtle, seasonal variations in fishing activities or species assemblages were not identified due to the quantity and resolution of data analysed. Lewy and Vinther (1994) classified directed fisheries into two groups, those in which a wide variety of vessel size groups participated, "common fisheries", whilst those with specific size groups were described as "special" fisheries. Vessel length showed little overall importance in métier definitions here. This was unexpected but may be explained by the greater importance of other factors in identifying métiers, and the high variation in vessel length categories within many métiers. So whilst "special fisheries" exist, the majority of Irish activity occurs in "common fisheries", reflecting the polyvalent nature of the fleet.

The diversity of species targeted by the Irish other trawl fleet was highlighted by the identification of 16 landing profiles in the first stage of analysis, with up to five target species characterising landing profiles. Demersal métiers tend to be more complex (high diversity of species in the landing) with more mixed fisheries inter-actions than pelagic métiers. The occurrence of by-catch species within métiers is an important consideration when formulating species specific management measures. For example, cod is present to some extent in all demersal shelf and slope métiers. Therefore management measures to rebuild cod stocks need to take account of both targeting and non-targeting métiers. The cod long-term plan introduced in 2009 (EC, 2008a) seeks to encourage cod avoidance in all fisheries by using derogations.

Of the demersal métiers, nine are defined by high landing proportions of *Nephrops* accounting for a third of otter trawl fishing trips reflecting the importance of this species to the Irish fleet. The largest *Nephrops* métiers operate within VIIa and VIIg and have remained relatively stable indicating these are well established, stable fishing practices. Most *Nephrops* métiers appear to be reliable and low risk, where fishers are likely to obtain consistent catches to achieve adequate economic returns. In contrast, there was a substantial expansion of the *Nephrops* métier on the Porcupine Bank (VIIck) between 2003 and 2006. This "riskier" métier is carried out by larger vessels in deeper water, mainly in the second and third quarters when weather conditions and *Nephrops* emergence patters are more favourable. The métier expand rapidly between 2003 and 2006 due to a combination factors: good prices for large *Nephrops*, increased at sea freezing of catches, stable LPUE of larger *Nephrops* (ICES, 2009a) and lack of other economically viable fishing opportunities for these larger vessels. This expansion of the fishery has subsequently been shown to be unsustainable since ICES have recommended a closure of the fishery in 2009 (ICES, 2009a).

This métier analysis exposes interesting changes in fishing practice due to economic, stock abundance, and management changes. The megrim and monkfish targeting ≥100mm mesh bottom otter trawl métier in VIIj increased effort during trips suggesting a shift to closer fishing grounds than in 2003, most likely due to increasing fuel cost. Landings and effort per trip and vessel in the whiting, plaice and ray 70–99mm mesh métiers reflect behavioural changes in response to increased availability of those target species. The ≥100mm mesh bottom otter trawl mixed plaice and ray métier in area VIIa has contracted over time due to restrictive days-at-sea management linked to a cod recovery plan. The contraction of this métier is unlikely to have resulted from reduced species availability since landings and effort within the 70–99mm mesh plaice and ray métier in the same area have increased. Vessels operating in this métier have increased their tendency to move between métiers, changing gear, mesh size or fishing ground.

The pelagic industrial métier targeting blue whiting showed expansion between 2003 and 2006 with increases in effort, landings, trips, and vessels. Simultaneously there were increased landings of blue whiting in areas not originally specified in the métier definition. In this case, the métier definition should be expanded to incorporate blue whiting trips outside of the original métier. Development of this métier was due to good recruitment from the mid 1990s to mid 2000s, particularly 2001 with spawning stock biomass at its highest in 2003 (WGWIDE; ICES, 2009b). The blue whiting stock is migratory and widely distributed, involving a number of countries. This led to difficulties in agreeing and inter-national TAC and national quotas prior to 2006 (WGNPBW; ICES, 2006b) resulting in uncontrolled growth in catches. The expansion however was short lived as the recent trends show declining spawning stock biomass and low recruitment (WGWIDE; ICES, 2009b). This métier is a good example of an opportunistic fishery, where fishing practices rapidly expand when stock size is high and quota was available or unlimited. At present an Irish and Danish industrial fishery for boarfish appears to be showing a similar pattern to that of blue whiting. Exploratory trips targeting boarfish were observed within this analysis. A dedicated fishery developed in 2006 and has subsequently expanded rapidly. This fishery was unrestricted and unregulated up to 2011 when a TAC was introduced (EC, 2011). Precautionary management is required given that the stock size and dynamics are unknown, to prevent declines similar to the blue whiting fishery.

The Irish deepwater fishery developed in the mid to late 1990s, expanding into the early 2000s, peaking in 2002. Landings had already fallen by over 75% in 2003 the first year of this analysis (Anon, 2009). The deepwater métier consisted of large vessels (18–80m) using single trawls ≥100mm and reporting landings of cardinal fish, grenadier species and deepwater sharks. Between 2003 and 2006 this métier exhibited further large declines in effort, landings, trips, and vessels. The declines can be partially attributed to the collapse of several deepwater stocks (ICES, 2009c), as well as the introduction of a number of management measures to reduce fishing pressure on these vulnerable species. These measures included permits (2002), TACs and quotas (initially set in 2003 and 2005) and effort limitation (2005). Since 2006 the Irish deep water métier has largely become insignificant.

The emerging data demands for fleet based and mixed fisheries management differing from that of stock based advice. This analysis used landings post-stratification to determine Irish otter trawl métiers and their importance. This information has subsequently been used to inform sampling programs and ensure adequate coverage. The main drawback of such an approach is that it may not be directly compatible to other international sampling frameworks such as the Data Collection Framework (DCF) introduced in 2009 (Council Regulation (EC) No 199/2008 (EC, 2008c) and EC Decision 2008/949/EC (EC, 2008d)). The DCF specifies stratification similar to the "Nantes matrix" (Anon, 2005b), to a level analogous to that of métier segmentation, incorporating mesh size and/or gear selectivity measures. The métier species assemblages identified within this analysis are more specific than those detailed by the broad DCF categories following the Nantes matrix. Therefore, métiers had to be merged to match the given species assemblages (e.g. demersal fish and small pelagic fish. Merging was mainly carried out on the basis of practical considerations, rather than though statistical means recommended by WKMERGE (ICES, 2010a). Ultimately decisions to expand or merge métiers for sampling should be based on catches (both landings and discards) and species size- and/or age-structure to ensure adequate coverage of stock and fisheries.

Although some of the pelagic métiers are already managed close to the métier level, though single species quotas and licences by area, it would not be possible to manage demersal fisheries on the basis of each métier identified here. A compromise is required between accounting for the complexity of métiers and the practical need to manage métiers in combination. This type of analysis helps to transparently highlight which métiers are the most important to consider in management. At present within Ireland, demersal quotas are allocated monthly or bi-monthly to vessels regardless of target assemblage. An alternative system, informed by this métier analysis, could be developed where vessel allocations by species are made according to métiers. Quota could then be distributed to métier groups providing higher allocations for target species and smaller allocations for non-target, and chance-catch quota species. Vessels could sign up for a métier group for a set period, for example 2 months, with maximum vessel participation to prevent excessive quota uptake. This could maximise quota uptake, and possibly reduce quota related discarding.

The Irish fishing industry is dynamic in nature, continuously changing, adapting and evolving to changing biological, economic, and management conditions. Fleet segmentation through métier definition is an important first step in the understanding of fine scale fleet dynamics. A critical understanding for formulation of effective mixed fisheries and fleet based management. A future step would be the investigation of métier dynamics at finer spatial and temporal resolution through the integration of logbook data and vessel monitoring systems (as in Gerritsen and Lordan, 2011). Ultimately understating the métier composition and dynamics in mixed fisheries will be critical in the development of effective integrated mixed fisheries management plans.

Acknowledgements

This work is based on the logbook data which is imputed, managed and provided by the Department of the Agriculture, Fisheries and Food and we thank all those involved. The authors wish to thank Niamh Slattery and Chris Allsop for their assistance with the logbook database, Rick Officer and two anonymous reviewers for their helpful and insightful comments on manuscript drafts. This work was funded by the EC Advisory funding mechanism FISH/2004/03, and we would like to acknowledge this support.

Figures

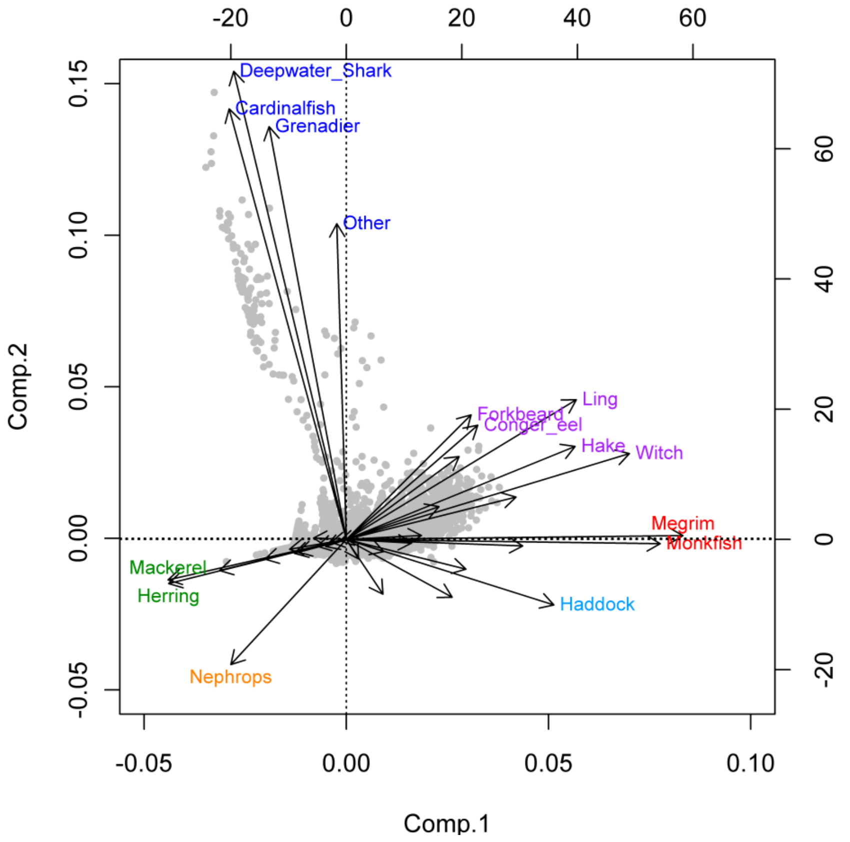

Figure 2.1. Principal Component Analysis scores of the first two axes from fishing trip species proportions within the Irish trawl fleet, 2003. Only those species considered to influence the axes are labelled. A number of species are differentiated on these axes: deepwater species (blue), slope species (purple), megrim and monkfish (red), pelagic species (green), haddock (light blue), and *Nephrops* (orange).

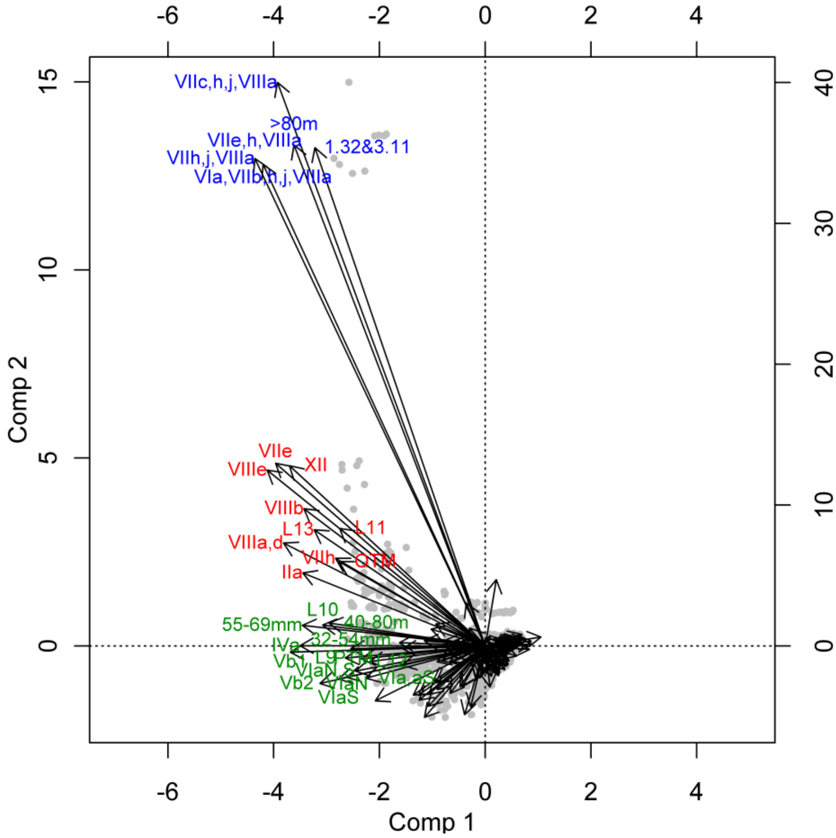

Figure 2.2. MCA scores of the first two axes from fishing trip descriptive characteristics within the Irish trawl fleet, 2003. Only those factors considered to influence the axes are labelled. Descriptive characteristics: mesh size range (mm); vessel length range (m); month and gear (3 letter code); area (ICES Division); landing profile (see Table 2.1). A number of characteristics are differentiated on these axes: VIIIa related multi-divisions and vessels >80m (blue); pelagic profiles L11 and L13, OTM gear, areas VIII, VIIe, VIIh, XII, and IIa (red); pelagic profiles L9 and L10, 40–80m vessels, PTM gear, 32–54mm and 55–69mm meshes, and areas V and VI (green).

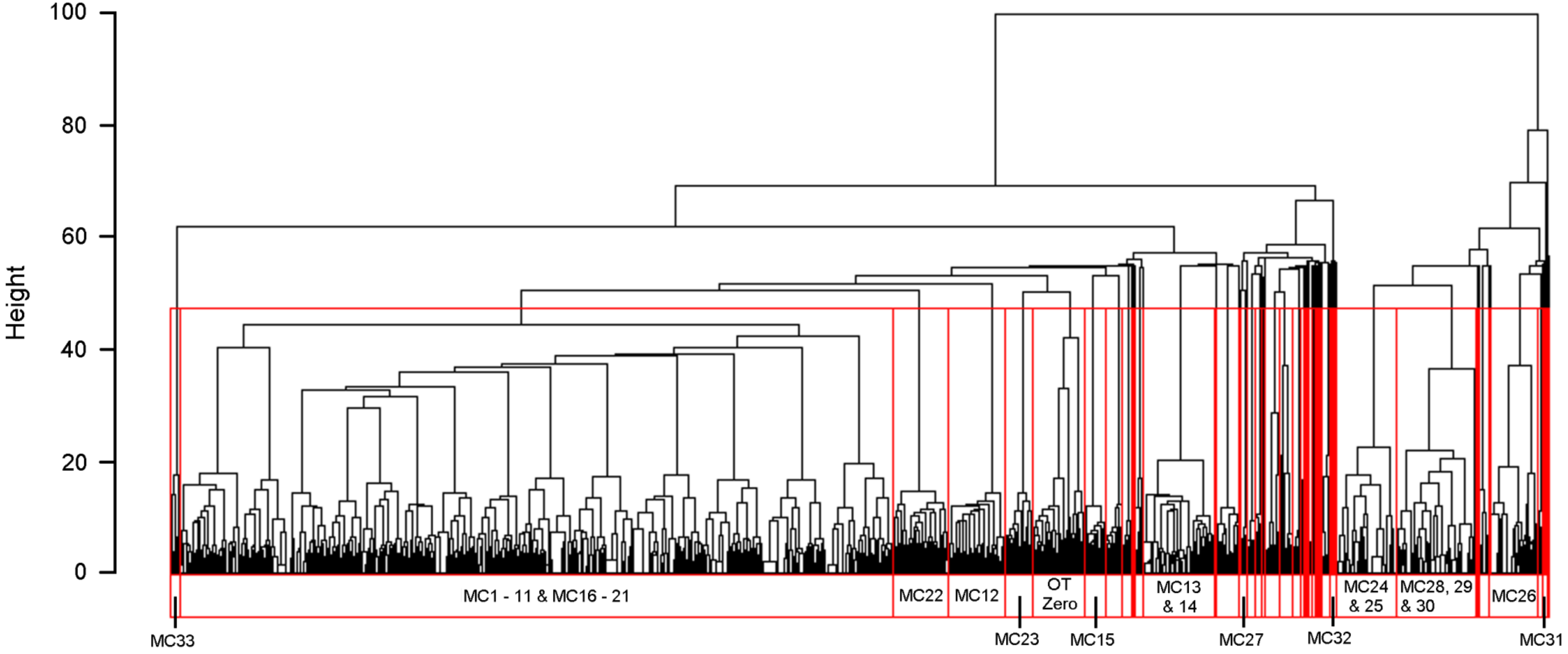

Figure 2.3. Results from HAC of fishing trip descriptive characteristics within the Irish trawl fleet, 2003. Boxes identify the 103 clusters identified by r^2 values, explaining 80% of the total variation. Labels below clusters correspond to métiers detailed in Table 2.2.

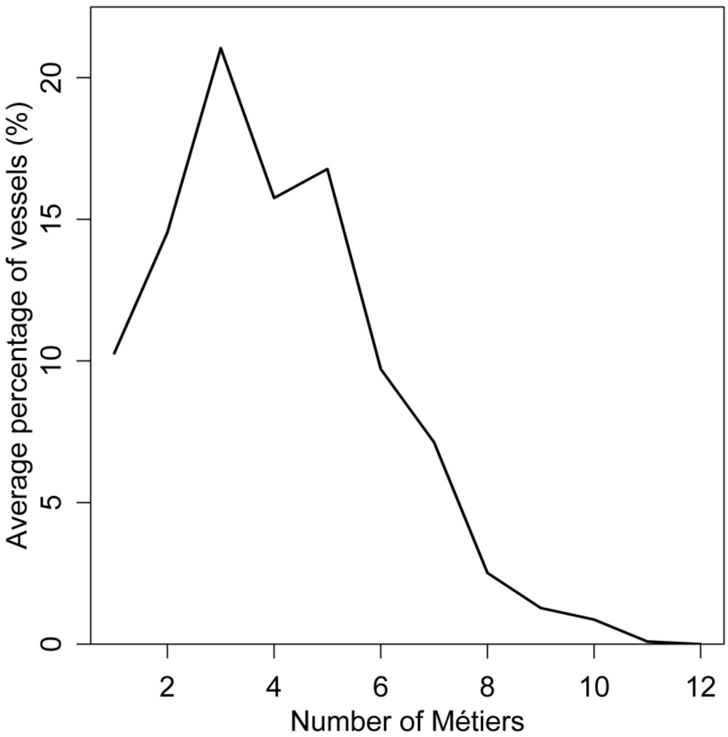

Figure 2.4. The percentage of the Irish otter trawl fleet in relation to the number of métiers individual vessels operate in based on an average of 2003–2006 data.

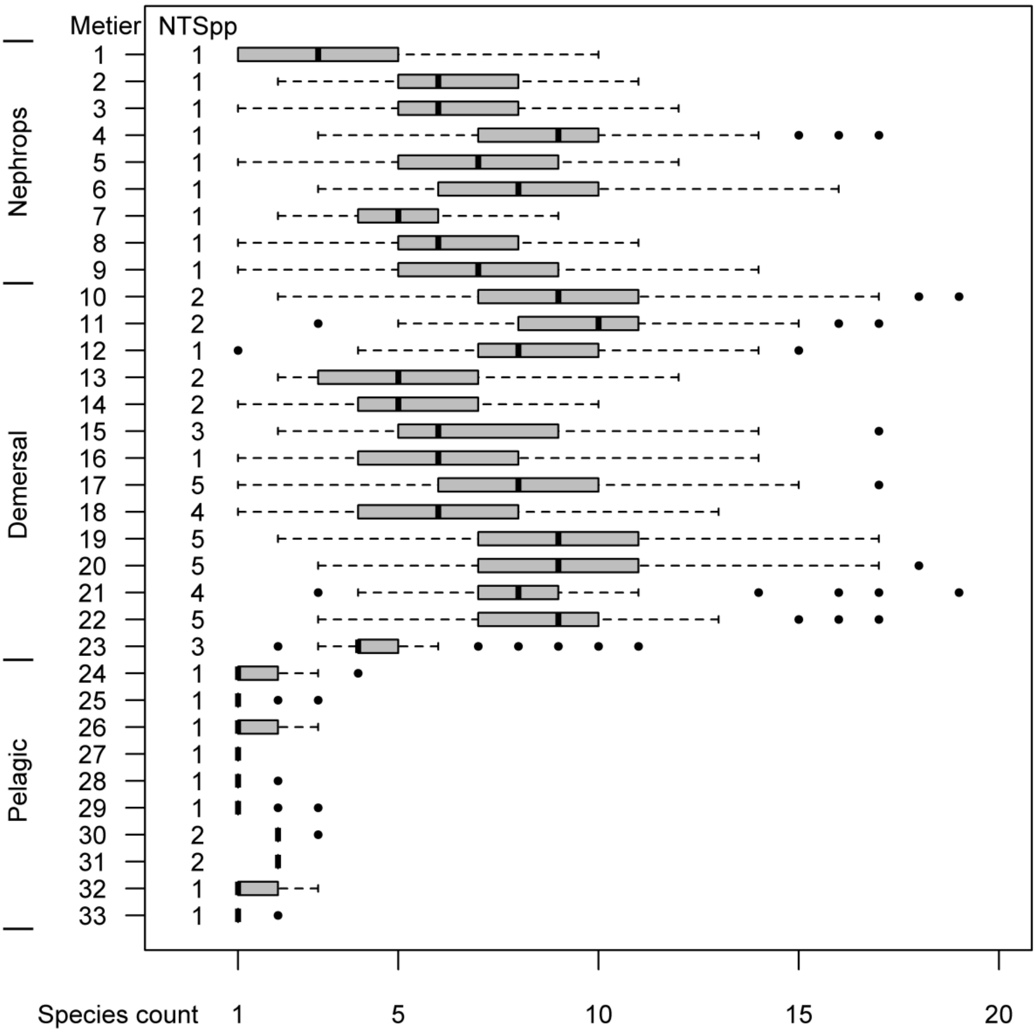

Figure 2.5. Métier species diversity boxplot of species present within fishing trip landings (2003). Annotation (left to right): target species category, métier code and number of identified target species (NTSpp).

Tables

Table 2.1. Landing profiles main target species identified by PCA and HAC of fishing trip species proportions within the Irish trawl fleet, 2003, detailed with the number of associated trips. A landing profile could not be identified for 60 trips.

Profile	**Target Species**	**Fishing trips**
L1	*Nephrops* Mixed	738
L2	*Nephrops* Clean	1 887
L3	Megrim, monkfish	742
L4	Haddock	449
L5	Black sole, plaice, ray species	145
L6	Pollack, saithe, cod, whiting, dogfish	1 268
L7	Ling, witch, lemon sole, forkbeard hake	1 381
L8	Ray species, plaice	544
L9	Mackerel, boarfish	538
L10	Horse mackerel	304
L11	Blue whiting	16
L12	Herring	588
L13	European pilchard, herring, mackerel	33
L14	Tuna	76
L15	Sprat	151
L16	Cardinalfish, grenadier, deepwater shark	112

Table 2.2. Irish trawl fleet métier definitions, detailing the métier ID, name and the conditions of each métier in relation to species composition and fishing trip descriptive characteristics.

Métier	Name	Gear type	Mesh size	Vessel length	ICES area	Period	Target	Species composition Lower species threshold	Special conditions
1	Clean *Nephrops* OTB VIIa	OTB	70-89	12-40m	VIIa	All	*Nephrops*	≥80% Nephrops	
2	Mixed *Nephrops* OTB VIIa	OTB	70-89	12-40m	VIIa	All	*Nephrops*	≥45% Nephrops	<80% Nephrops
3	Clean *Nephrops* OTB VIIb	OTB	70-119	15-40m	VIIb	All	*Nephrops*	≥80% Nephrops	
4	Mixed *Nephrops* OTB VIIb	OTB	70-119	15-40m	VIIb	All	*Nephrops*	≥45% Nephrops	& <80% Nephrops <30% Monkfish <30% Megrim
5	Clean *Nephrops* OTB VIIg	OTB	70-119	10-40m	VIIg	All	*Nephrops*	≥65% Nephrops	
6	Mixed *Nephrops* OTB VIIg	OTB	70-119	10-40m	VIIg	All	*Nephrops*	≥40% Nephrops	& <65% Nephrops <30% Monkfish <30% Megrim < mesh related cod (25% 70-99mm, 30% 100-119mm)
7	*Nephrops* OTB VIIc & VIIk	OTB	70-119	18-40m	VIIc VIIk	Q2-4	*Nephrops*	≥50% Nephrops	
8	*Nephrops* OTB VIa	OTB	70-119	12-40m	VIa	All	*Nephrops*	≥40% Nephrops	<30% Monkfish <30% Megrim
9	*Nephrops* OTB VIIj	OTB	70-119	10-40m	VIIj	All	*Nephrops*	≥35% Nephrops	& <30% Monkfish <30% Megrim
10	Megrim & Monkfish Small OTB VIa, VIIb,g,j	OTB	70-99	10-80m	VIa VIIb VIIg VIIj	All	Megrim & Monkfish	≥30% Megrim Or, ≥30% Monkfish	<80% VIIb related Nephrops <65% VIIg related Nephrops <50% VIIc or VIIk related Nephrops
11	Megrim & Monkfish Large OTB VIIj	OTB	≥100	15-80m	VIIj	All	Megrim & Monkfish	≥30% Megrim Or, ≥30% Monkfish	& <20% Forkbeard <25% Hake
12	Haddock OTB VIIg & VIIj	OTB	ALL	10-40m	VIIg VIIj VIIg.j	All	Haddock	≥30% Haddock	& < area related Nephrops % <30% Monkfish <30% Megrim <30% Whiting
13	Plaice & Ray Small OTB VIa, VIIa,b,g,j	OTB	70-99	10-40m	VIa VIIa VIIb VIIg VIIj	All	Plaice & Ray species	≥40% Plaice Or, ≥40% Ray species	& < area related Nephrops % <30% Megrim <30% Monkfish <30% Haddock VIIg, VIIj & VIIg.j <30% Pollack <25% Cod
14	Plaice & Ray Large OTB VIIa	OTB	100-119	15-40m	VIIa	All	Plaice & Ray species	≥40% Plaice Or, ≥40% Ray species	& <45% Nephrops <30% Pollack <30% Cod

Table 2.2. Continued.

Métier	Name	Gear type	Mesh size	Vessel length	ICES area	Period	Target	Species composition	
								Lower species threshold	Special conditions
15	BSPR OTB VIa, VIIa,b,g,j	OTB	ALL	10-40m	VIa VIIa VIIb VIIg VIIj	All	BSPR	≥30% Ray species Or, ≥25% Plaice ≥20% Black Sole	& < area related Nephrops % <40% Plaice <40% Ray species <30% Whiting when ≥ Plaice or Ray < mesh related cod (25% 70-99mm, 30% 100-119mm) < mesh related witch (25% 70-99mm, 20% 100-119mm) < area related and mesh specific megrim and monkfish < mesh related saithe (25% 70-99mm, 30% 100-119mm) <30% Haddock VIIa related, VIIg, VIIj & VIIg.j <25% Hake <30% Pollack <25% Lemon sole <25% Liing
16	Whiting Small OTB VIa, VIIa,b,g,j	OTB	70-99	10-40m	VIa VIIa VIIb VIIg VIIj	All	Whiting	≥60% Whiting	& < area related Nephrops % <40% Plaice <40% Ray species <30% Megrim <30% Monkfish
17	PSCWD Small OTB VIa, VIIb,g,j	OTB	70-99	10-40m	VIa VIIb VIIg VIIj	All	PSCWD	≥30% Pollack Or, ≥25% Saithe ≥25% Cod ≥30% Whiting ≥35% Dogfish	& < area related Nephrops % If ≥25% Cod, <65% Nephrops in VIIg <60% Whiting <40% Plaice (when ≥35% Dogfish plaice <25%) <40% Ray species (when ≥35% Dogfish Ray <30%) <30% Megrim <30% Monkfish <30% Haddock in VIIg, VIIj, VIIg.j (unless ≥30% Whiting) <25% Hake <20% Black Sole If ≥35% Dogfish, <20% Witch & <25% Ling
18	WCHD Small OTB VIIa & VIIa.g	OTB	70-99	12-40m	VIIa VIIa.g	All	WCHD	≥30% Whiting Or, ≥25% Cod ≥30% Haddock ≥35% Dogfish	& <45% Nephrops <40% Plaice (when ≥35% Dogfish plaice <25%) <40% Ray species (when ≥35% Dogfish Ray <30%) <20% Black Sole <25% Hake <60% Whiting <30% area related megrim and monkfish

Table 2.2. Continued

Métier	Name	Gear type	Mesh size	Vessel length	ICES area	Period	Target	Species composition	
								Lower species threshold	Special conditions
19	PSCWD Large OTB VIIa,g & VIIa.g	OTB	≥100	15-40m	VIIa VIIg VIIa.g	All	PSCWD	≥30% Pollack Or, ≥30% Saithe ≥30% Cod ≥30% Whiting ≥35% Dogfish	& < area related Nephrops % If ≥25% Cod, <65% Nephrops in VIIg <30% area related megrim and monkfish <40% Plaice <25% Ling (unless saithe ≥30%) <25% Hake If ≥35% Dogfish, <30% Ray & <25% Plaice
20	PSCWD Large OTB VIa,b, VIIb,j	OTB	≥100	12-40m	VI VIIb VIIj	All	PSCWD	≥30% Pollack Or, ≥30% Saithe ≥30% Cod ≥30% Whiting ≥35% Dogfish	& < area related Nephrops % <30% area related megrim and monkfish <20% Forkbeard <25% Hake <40% Plaice <25% Ling (unless saithe ≥30%) If ≥35% Dogfish, <30% Ray & <25% Plaice
21	LWFH Large OTB VIa,b, VIIb,c,j,k	OTB	≥100	18-80m	VI VIIb-c VIIj-k	All	LWFH	≥25% Ling Or, ≥25% Witch ≥20% Forkbeard ≥25% Hake	& < area related Nephrops % <30% Saithe when Ling ≥25% <30% Pollack when Ling ≥25% <30% Cod <30% Haddock in VIIg, VIIj, VIIg.j If ≥25% Hake or ≥25% Forkbeard: <30% area related megrim and monkfish
22	LWLFH Small OTB VIa,b, VIIa,b,g,j	OTB	70-99	10-40m	VI VIIa VIIb VIIg VIIj	All	LWLFH	≥25% Ling Or, ≥20% Witch ≥25% Lemon Sole ≥20% Forkbeard ≥25% Hake	& < area related Nephrops % <25% Saithe when Ling ≥25% <30% Pollack when Ling ≥25% <40% Plaice <25% Cod <30% Whiting <40% Ray species <30% Haddock in VIIg, VIIj, VIIg.j , VIIa If ≥25% Hake or ≥25% Forkbeard: <30% area and mesh related megrim and monkfish
23	Deepwater Large Single Trawl VIa, VIIb,c,j,k	Single Trawl	≥100	18-80m	VIa VIIb-c VIIj-k	All	Deepwater species	≥25% Cardinalfish Or, ≥35% Deepwater shark ≥25% Grenadier	<20% Forkbeard
24	Mackerel Mid-Water VIa, VIIb,j	Mid-Water	<70	18-80m	VIa VIIb VIIj	Oct-May	Mackerel	≥70% Mackerel	

Table 2.2. Continued

Métier	Name	Gear type	Mesh size	Vessel length	ICES area	Period	Target	Species composition	
								Lower species threshold	Special conditions
25	Mackerel Mid-Water IVa	Mid-Water	<55	24-80m	IVa	Oct-Jan	Mackerel	≥75% Mackerel	
26	Horse Mackerel Mid-Water VIa & VIIb	Mid-Water	32-69	24-80m	VIa VIIb VIa.VIIb	Sep-Mar	Horse Mackerel	≥80% Horse Mackerel	
27	Blue Whiting Mid-Water VIb, VIIc,k, XII	Mid-Water	32-54	24-80m	VIb VIIc VIIk XII	Feb-Mar	Blue Whiting	≥90% Blue Whiting	
28	Herring PTM VIa	PTM	<55	15-80m	VIa	Oct-Mar	Herring	≥80% Herring	
29	Herring Pair Trawl Non-VIa	Pair Trawl	32-54	15-80m	Non VIa	Jul-Feb	Herring	≥80% Herring	
30	Pilchard & Herring PTM VIIa,g,j	PTM	32-54	18-40m	VIIa VIIg VIIj	Oct-Jan	Pilchard & Herring	≥20% European Pilchard & >5% Herring	& <80% Herring <1% all other species
31	Pilchard & Mackerel OTM VIIe,h, VIIIb,e	OTM	32-54	40-80m	VIIe VIIh VIIIb VIIIe	Oct-Dec	Pilchard & Mackerel	≥20% European Pilchard & ≥5% Mackerel	& <1% all other species
32	Tuna PTM VIIj,k,VIIIa-d	Trawl	ALL	15-40m	VIIj-k VIIIa-d	Jul-Oct	Tuna	≥80% Tuna	
33	Sprat Otter Trawl VIa, VIIa	Otter Trawl	16-54	10-40m	VIa VIIa VIa.VIIa	Oct-Feb	Sprat	≥95% Sprat	

Table 2.3. Annual fishing trips, vessel participation and days-at-sea effort within métiers, 2003–2006 with relative change over the period within brackets.

		2003			2004			2005			2006		
Métier name	ID	Trips	Vessels	Effort	Trips	Vessels	Effort	Trips	Vessels	Effort	Trips	Vessels	Effort
Clean Nephrops OTB VIIa	1	755	52	2 157	895	39	2 549	822	41	2 427	837 (0.11)	49 (-0.06)	2 414 (0.12)
Mixed Nephrops OTB VIIa	2	379	51	1 449	323	44	1 234	393	52	1 468	318 (-0.16)	50 (-0.02)	1 290 (-0.11)
Clean Nephrops OTB VIIb	3	110	21	475	57	18	265	148	22	551	106 (-0.04)	31 (0.48)	440 (-0.07)
Mixed Nephrops OTB VIIb	4	215	30	972	167	23	785	164	28	703	141 (-0.34)	32 (0.07)	618 (-0.36)
Clean Nephrops OTB VIIg	5	396	61	1 868	284	55	1 423	511	82	2 551	446 (0.13)	72 (0.18)	1 986 (0.06)
Mixed Nephrops OTB VIIg	6	427	59	1 696	445	66	2 023	545	80	2 383	584 (0.37)	73 (0.24)	2 566 (0.51)
Nephrops OTB VIIc & VIIk	7	43	11	464	72	15	679	160	24	1 494	156 (2.63)	32 (1.91)	1 458 (2.14)
Nephrops OTB VIa	8	29	9	92	23	8	96	30	10	141	19 (-0.34)	6 (-0.33)	73 (-0.21)
Nephrops OTB VIIj	9	227	30	654	172	43	652	201	38	606	223 (-0.02)	40 (0.33)	533 (-0.19)
Megrim & Monkfish Small OTB VIa, VIIb,g,j	10	342	77	1 602	297	76	1 406	442	94	1 843	552 (0.61)	87 (0.13)	2 071 (0.29)
Megrim & Monkfish Large OTB VIIj	11	103	27	837	55	21	453	129	25	915	165 (0.6)	24 (-0.11)	1 237 (0.48)
Haddock OTB VIIg & VIIj	12	216	48	600	235	65	742	240	57	766	278 (0.29)	63 (0.31)	818 (0.36)
Plaice & Ray Small OTB VIa, VIIa,b,g,j	13	259	56	683	298	58	910	357	64	1 023	283 (0.09)	54 (-0.04)	831 (0.22)
Plaice & Ray Large OTB VIIa	14	252	14	674	100	10	259	64	6	197	32 (-0.87)	5 (-0.64)	112 (-0.83)
BSPR OTB VIa, VIIa,b,g,j	15	200	69	619	179	73	709	116	56	381	98 (-0.51)	51 (-0.26)	408 (-0.34)
Whiting Small OTB VIa,VIIa,b,g,j	16	161	39	501	108	24	422	276	36	1 459	187 (0.16)	21 (-0.46)	1 043 (1.08)
PSCWD Small OTB VIa,VIIb,g,j	17	433	91	1 681	340	82	1 359	377	91	1 544	243 (-0.44)	74 (-0.19)	1 119 (-0.33)
WCHD Small OTB VIIa & VIIa.g	18	106	23	242	67	25	230	65	28	217	26 (-0.75)	16 (-0.3)	81 (-0.67)
PSCWD Large OTB VIIa,g,a.g	19	148	30	606	73	17	340	39	14	211	38 (-0.74)	6 (-0.8)	235 (-0.61)
PSCWD Large OTB VIa,b,VIIb,j	20	112	32	733	52	15	377	49	17	339	53 (-0.53)	16 (-0.5)	317 (-0.57)
LWFH Large OTB VIa,b,VIIb,c,j,k	21	157	25	1 618	94	22	993	64	16	497	36 (-0.77)	10 (-0.6)	305 (-0.81)
LWLFH Small OTB VIa,b,VIIa,b,g,j	22	66	28	349	56	27	365	38	26	170	30 (-0.55)	19 (-0.32)	153 (-0.56)
Deepwater Large Single Trawl VIa, VIIb,c,j,k	23	97	9	957	76	6	784	46	5	441	14 (-0.86)	2 (-0.78)	108 (-0.89)
Mackerel Mid-Water VIa, VIIb,j	24	422	34	1 376	338	42	1 442	171	42	574	212 (-0.5)	43 (0.26)	740 (-0.46)
Mackerel Mid-Water IVa	25	71	16	351	74	24	368	48	18	199	14 (-0.8)	12 (-0.25)	65 (-0.81)
Horse Mackerel Mid-Water VIa & VIIb	26	245	25	673	200	33	535	155	27	505	141 (-0.42)	29 (0.16)	463 (-0.31)
Blue Whiting Mid-Water VIb, VIIc,k, XII	27	14	7	74	5	5	25	24	13	90	39 (1.79)	18 (1.57)	188 (1.54)
Herring PTM VIa	28	248	28	526	167	34	353	77	23	180	153 (-0.38)	39 (0.39)	348 (-0.34)
Herring Pair Trawl Non-VIa	29	269	30	625	317	27	611	254	35	508	158 (-0.41)	40 (0.33)	391 (-0.37)
Pilchard & Herring PTM VIIa,g,j	30	13	4	25	17	4	30	1	1	2	4 (-0.69)	3 (-0.25)	11 (-0.56)
Pilchard & Mackerel OTM VIIe,h,VIIIb,e	31	19	1	63	8	1	39	0	0	0	0 (-1)	0 (-1)	0 (-1)
Tuna PTM VIIj,k,VIIIa-d	32	76	22	782	37	14	368	30	10	254	28 (-0.63)	8 (-0.64)	232 (-0.7)
Sprat Otter Trawl VIa, VIIa	33	103	18	148	14	6	16	64	19	73	32 (-0.69)	7 (-0.61)	33 (-0.78)
Annual Total		6 713	264	26 172	5 645	273	22 842	6 100	260	24 712	5 646 (-0.16)	242 (-0.08)	22 687 (-0.13)

Table 2.4. Average métier landings species composition (%) with average total landed (t), 2003–2006.

	Métier name	Clean Nephrops OTB VIIa	Mixed Nephrops OTB VIIa	Clean Nephrops OTB VIIb	Mixed Nephrops OTB VIIb	Clean Nephrops OTB VIIg	Mixed Nephrops OTB VIIg	Nephrops OTB VIIc & VIIk	Nephrops OTB VIa	Nephrops OTB VIIj	Megrim & Monkfish Small OTB VIa, VIIb,g,j	Megrim & Monkfish Large OTB VIIj	Haddock OTB VIIg & VIIj	Plaice & Ray Small OTB VIa, VIIa,b,g,j	Plaice & Ray Large OTB VIIa	BSPR OTB VIa, VIIa,b,g,j	Whiting Small OTB VIa,VIIa,b,g,j	PSCWD Small OTB VIa,VIIb,g,j	WCHD Small OTB VIIa & VIIa.g	PSCWD Large OTB VIIa,g,a.g	PSCWD Large OTB VIa,b,VIIb,j	LWFH Large OTB VIa,b,VIIb,c,j,k	LWLFH Small OTB VIa,b,VIIa,b,g,j	Deepwater Large Single Trawl VIa, VIIb,c,j,k	Mackerel Mid-Water VIa, VIIb,j	Mackerel Mid-Water IVa	Horse Mackerel Mid-Water VIa & VIIb	Blue Whiting Mid-Water VIb, VIIc,k, XII	Herring PTM VIa	Herring Pair Trawl Non-VIa	Pilchard & Herring PTM VIIa,g,j	Pilchard & Mackerel OTM VIIe,h,VIIIb,e	Tuna PTM VIIj,k,VIIIa-d	Sprat Otter Trawl VIa, VIIa
	ID	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33
	Average weight landed (t)	1 873	973	341	512	1 495	1 302	500	52	268	976	586	454	526	259	316	1 914	1 412	147	505	480	704	175	1 225	31 530	13 028	20 509	16 682	11 596	11 851	419	1 701	427	709
Average Percentage (%)	Blue Whiting											0.2													0.3			100.0						
	Boarfish																								0.6		0.2							
	Cardinalfish																					2.5		47.3										
	Cod	2.4	7.2	0.3	0.6	4.0	5.4	0.1	1.2	2.2	1.1	1.3	3.2	2.2	4.8	2.2	1.7	3.7	10.6	6.8	2.4	0.5	1.3											
	Conger eel		0.1	0.1	0.9	0.2	0.4	0.5	0.2	0.2	0.4	1.3	0.5	0.5	1.1	1.3	0.1	0.4	0.4	0.3	0.6	2.9	0.5	0.6										
	Crab				0.4					0.1	0.3	0.1	0.1			0.2		0.1	0.2		0.1													
	Deepwater Shark																				0.3	0.2	0.2	19.9										
	Dogfish		0.5	0.2	2.6	0.1	0.6	0.1	4.6	1.2	2.0	1.8	1.5	3.5	2.2	10.6	0.8	15.5	14.0	4.5	10.2	0.6	4.6	0.1									0.1	
	Pilchard																									0.2				0.4	43.0	64.9		
	Forkbeard							1.3		0.1	0.6	0.3						0.1			0.1	13.6	4.5	0.7										
	Grenadier											0.2									0.1	0.5	0.3	13.8										
	Haddock	0.9	4.4	0.9	2.2	1.6	5.1	0.1	5.2	7.4	6.8	4.6	43.6	3.6	2.0	6.4	4.3	10.0	15.0	6.6	11.6	1.4	3.8	0.1										
	Hake	0.2	0.7	0.5	1.3	0.5	1.6	4.7	4.8	1.4	3.1	4.9	1.4	0.3		1.0	0.4	1.6	0.9	0.9	1.8	19.1	6.1	0.2										
	Herring								0.2	0.5			0.1						0.3	0.1	0.3				0.5	1.8	0.1		99.7	99.4	56.9			0.1
	Horse Mackerel								0.1														0.1		1.5	0.2	98.2		0.1					
	John dory		0.2		0.2	0.6	1.0		0.4	0.7	0.9	2.3	0.9	0.8		2.1	0.6	0.9	0.6	0.7	1.1	0.5	1.4											
	Lemon Sole	0.1	0.4	0.2	0.5	1.1	1.5		0.4	0.7	1.0	0.6	1.6	1.3	0.8	2.0	0.9	1.3	1.3	1.8	1.4	0.4	3.0											
	Ling	0.2	1.4	0.1	0.5	2.0	2.8	1.8	0.5	1.2	1.7	2.4	1.5	0.3	0.1	1.4	0.9	2.0	1.8	2.6	3.4	10.4	12.7	0.7										
	Mackerel				0.2			0.1	0.3	0.4	0.1		0.1			0.1	0.3	0.2	0.7	0.3	0.3	0.1	0.1		96.7	97.8	1.5		0.1			35.1		0.1
	Megrim		0.2	3.7	9.0	1.9	6.5	1.9	6.6	8.9	25.3	21.3	8.8	1.3	0.1	5.4	0.4	5.2	0.6	1.2	7.9	6.8	9.5	0.2										
	Monkfish	1.7	4.2	3.1	7.6	4.4	8.0	15.0	8.8	8.7	30.1	36.7	8.1	3.5	1.8	5.1	0.8	3.8	3.9	1.6	3.5	11.1	8.0	0.2										
	Nephrops	91.7	68.4	88.3	64.5	77.8	53.2	71.9	55.8	53.2	6.6	2.3	3.7	2.2	0.3	5.2	0.9	5.5	7.6	0.6	0.6	7.7	4.5	0.3										
	Other	0.3	1.5	0.3	1.0	0.1	0.3	0.3	0.8	0.6	1.7	3.4	1.1	3.7	2.3	4.9	0.3	1.8	1.4	0.5	1.8	3.1	4.3	15.6	0.3								1.0	
	Plaice	1.1	2.9	0.1	0.6	0.1	0.2		0.7	0.8	1.8	0.5	3.0	11.9	19.2	9.6	0.2	1.5	3.2	1.2	0.4		0.4											
	Pollack	0.1	0.7			0.8	1.5		0.2	0.7	0.4	0.7	1.7	0.7	1.1	0.9	1.1	3.6	3.5	4.0	8.7	0.7	1.8											
	Ray	0.3	3.7	0.7	3.6	0.5	1.5	0.1	2.8	3.3	5.6	5.5	3.8	59.9	62.6	29.8	1.2	5.4	4.6	3.9	4.0	1.7	8.0											
	Saithe		0.2		0.1	0.1	0.2		0.2	0.7	0.3	0.6	0.2	0.1	0.1	0.3	0.5	2.7	1.1	1.4	13.4	1.9	2.6							0.1				
	Scallop													0.1	0.3	0.7		0.3	0.2		0.2													
	Sole Black	0.1	0.4	0.5	1.2	0.3	0.3		1.0	0.9	1.8	0.6	2.1	1.9	0.5	3.3		0.7	0.3	0.1	0.3		0.4											
	Sprat						0.1																						0.1	0.1	0.1			99.7
	Squid		0.1	0.1	0.2		0.1	0.3	0.1	0.3	0.5	1.3	0.6	0.4	0.2	1.5	0.4	0.8	0.8	1.2	1.4	3.0	2.0	0.1										
	Tuna																																98.8	
	Whelk						0.1						0.1						0.2															
	Whiting	0.1	1.1	0.4	1.6	3.0	7.6	0.1	2.3	4.1	4.7	3.3	11.5	1.5	0.3	4.2	83.6	31.6	26.2	59.3	21.8	1.0	4.0							0.1				
	Witch	0.5	1.5	0.3	1.3	1.0	2.1	1.5	2.8	1.9	3.2	3.9	0.9	0.3	0.1	1.8	0.2	1.2	0.6	0.4	2.5	10.0	15.7	0.1										

Chapter III: Definition, dynamics and stability of métiers within the Irish non-otter trawl fleet

Abstract

The Irish fleet comprises of two main sections, those using otter trawls, and those that do not. This investigation identified métiers within the latter. The non-otter trawl fleet shows great diversity, being both multi-species and multi-gear in nature. The ~150 vessels in this segment account for around one quarter of Irish landings in weight annually. The combination of multivariate statistical techniques applied to species landings compositions and trip characteristics, developed in Chapter II, were again capable of separating out homogeneous groups. A total of nineteen métiers were identified within fishing trips from 2003.

It was found that the same gear types typically occurred within several métiers defined by varying species assemblages, while the occurrence of similar species assemblages between gear types was limited. This was as expected given the diversity of gear types included in the analysis, and the influence of gear configuration on species selectivity.

Vessel length ranges varied between métiers, differing particularly in minimum length. Vessels active in pot and gillnet metiers encompassed the smallest of vessel length categories (10-12m). Conversely, beam trawl, dredge, and longline métiers typically consisted of larger vessels (18m+).

Métier definitions continued to identify the recurring species and trip characteristic patterns between 2003 and 2006. However, observed métier dynamics in the form of fluctuating landings, effort, and contribution of métiers suggest a lack of stability in métier structure. This indicates the fleet is in a phase of change, adapting its fishing practices in response to external pressures, be they biological in relation to species availability, economic viability such as rising fuel prices, or management limitations.

Key words

Irish non-otter trawl fleet; Métiers; Multivariate analysis; Fleet dynamics; Mixed fisheries

Introduction

The spatial co-existence of many (particularly demersal) species results in mixed fisheries, for which single species management measures may be insufficient, ignoring interactions between species (Lewy & Vinther, 1994).With growing realisation of the ineffectiveness of management systems based on single species, the emphasis has moved towards mixed fisheries and ecosystem based approaches. Such approaches require a detailed knowledge of the multi-species interactions and the multi-fleet nature of fisheries. An understanding of the complexity, dynamics, and adaptability within operational fisheries is also required (Holley & Marchal, 2004), particularly in relation to predicting the impacts of changing management strategies (Soulié & Thébaud, 2006). The Irish fleet comprises two main sections, those using otter trawls, and those that do not. The later fleet shows great diversity being both multi-species and multi-gear in nature. Annually the non-otter trawl segment (hereafter: non-otter fleet) lands around 90 species. These species are caught utilising a wide range of diverse fishing gears and configurations, including beam trawls, Scottish seines, gillnets, dredges, pots, and longlines.

The heterogeneity of the fisheries exploited by the non-otter fleet is the result of a diversity and complexity that a single unit approach to management would be unable to address. A more appropriate solution would be to segment this fleet into groupings of similar activity, namely métiers. A métier being a "homogeneous subdivision of a fishery by vessel type" (ICES, 2003). This definition has also been called a ‘fishing tactic’ (Pelletier & Ferraris, 2000), ‘fishing strategy’ (Holley & Marchal, 2004), 'fishing trip type' (Jiménez *et al.*, 2004), and 'fleet component' (Silva *et al.*, 2002; Campos *et al.*, 2007) within the literature. Aggregation by métiers allows for trip based variables, such as effort and landings, to be grouped into more meaningful harmonized units better able to reflect the fishing activities (ICES, 2003) for use in stock assessments, accounting for variation in catchability from species targeting (Quirijns *et al.*, 2008; Tidd, 2013). The complexity of fishing activities requires métiers to be based on a variety of factors, including target species assemblage, vessel characteristics, fishing grounds and season (Davie & Lordan, 2011a).

Exploring the métier structure for groups of fishing trips has numerous benefits. It aids understanding of fisher behaviour and fleet/fisheries dynamics (e.g. Ulrich & Anderson, 2004). Métiers represent building blocks, which can be used at a national level to stratify sampling and discard programs (Silva *et al.*, 2002; Campos *et al.*, 2007). Métiers can be used to effectively partition fishing mortality (Lewy & Vinther, 1994; Pelletier & Ferraris, 2000) for inclusion in management strategy evaluation models (e.g. ISIS-Fish: Drouineau *et al.*, 2006 and FLR: Kell *et al.*, 2007). Understanding métier level structure can ultimately lead to more appropriate and effective management regimes.

This investigation extends the analysis and definition of métiers within the Irish fleet from the otter trawling segment (Chapter II published as Davie & Lordan, 2011a) to all other gears employed by the Irish fleet. Consistent with the aims of Chapter II, the objectives were to (i) identify métiers using 'best practice' multivariate techniques, (ii) describe and characterise these métiers, and (iii) assess métier stability and persistence. Some note has also been made to the utility and application of the identified métiers.

Materials and Methods

Data

Analysis was based on Irish logbook data collected from vessels ≥10m total length between 2003 and 2006 provided by the Department of Agriculture, Food and the Marine. This investigation includes all Irish fishing trips conducted by non-otter trawl gears (i.e. excluding bottom and mid-water otter and pair trawls; gear codes: OTB, OTM, PTB, and PTM). The following trip details were used for analysis: overall vessel length (m), gear type, mesh size (mm), ICES area, landing date, and estimated live weight (using conversion factors) of all species recorded within the "landing declarations". Fishing trips were considered independently from the vessel once overall vessel length was established. Fishing trips from 2003 to 2006 were available for analysis, totalling 17,078 trips by a total of 268 individual vessels. Métiers were identified and defined using 2003 as a reference year due to data volume. This restricted the number of fishing trips to 4,233 undertaken by 147 vessels. Analyses were performed within the R language and environment for statistical computing (R Development Core Team, 2008).

Prior to analysis the data were subjected to initial screening to remove unusable records. This included removal of weights associated with "mixed boxes" from total trip weights due to unknown species compositions. Mixed boxes accounted for an average of 0.2% of total annual Irish landed weight, thus their removal will have had little impact. Three fishing trips were excluded from the analysis: one declaring only mixed boxes, and two reporting use of multiple gears within a single trip.

Typology of métiers

The methodology in this investigation is the same as that applied to the analysis of the Irish trawl fleet (Chapter II: Davie & Lordan, 2011a). This followed the three-step framework recommended for métier definition by SGDFF (ICES, 2003), and was based on the multivariate methodology used by Pelletier and Ferraris (2000), and Ulrich and Anderson (2004). This method combines the use of quantitative multivariate analysis of landings and effort data with qualitative expert knowledge, avoiding prior assumptions on homogeneous groupings. The methodology applied here has recently been confirmed as appropriate following an investigation by Deporte *et al.* (2012) into some of the most commonly applied methods.

In the first step, homogeneous groups in relation to species composition were identified as landing profiles. There has been debate on the appropriate species metrics for defining métiers. The majority of previous investigations used either landed weight or first sale value. In this investigation, as within previous studies of the Irish fleet (Davie & Lordan, 2009; Chapter II: Davie & Lordan, 2011a), landing profiles were based on the relative proportions of estimated live weight species landings per trip. Weight was chosen primarily because accurate first sale values were not available at the time of analysis (later calculated as part of Chapter VI).

Had value been applied, low volume high value species may have had a greater influence in identified landing profiles. However, in this case it is believed definitions for the majority of métiers would be broadly equivalent. Species constituting greater than 0.1% of total Irish landings (three year average) were retained for analysis removing the effect of ‘less abundant’ species. Some individual species were grouped into "species categories" to reduce the impact of uncertain species level identification and variations in logbook coding practices. Species contributing less than 0.1% to total landings were grouped together into an ‘Other’ category. The Other category contributes a minor percentage (0.7%) to average total Irish landings.

Non-normalised Principal Component Analysis (PCA) was used to identify landing profiles, allowing for species dominance. PCA reduces dataset dimensionality and identifies the main re-occurring species combinations that explain the variation within the dataset, with the greatest variation described on the first component (Fowler *et al.*, 2004). Hierarchical Agglomerative Cluster analysis (HAC) based on Euclidean distance and Ward’s algorithm (1963) was then applied. This method creates successive clusters based on previously identified clusters, building a hierarchy from individuals to a single group. Similar to the method used by Ulrich and Andersen (2004), the appropriate number of clusters to retain was determined when proportional increase with subsequent clusters levelled off (via sums of squares and r^2 values). The relevance and size of clusters were considered in formulating landing profiles, later applied as categorical variables in the following steps. In line with SGDFF recommendations (ICES, 2003), a factorial Multiple Correspondence Analysis (MCA) was used to investigate relationships between landing profiles and trip variables. MCA is analogous to PCA but for use with categorical variables. The categorical variables were: (1) ICES division, (2) gear type, (3) mesh size range[5], (4) overall vessel length[6], and (5) month (a proxy for season). The output was entered into an HAC which clustered trips into homogeneous groups based on relationships between variables. The appropriate number of clusters was estimated in the same way as above, using the proportion of variance explained, Each cluster was then fully described using the categorical variables. Some clusters were pooled according to expert knowledge to avoid over complexity and excessive disaggregation, whilst retaining important information on the structure of the dataset. Pooling also maintained sufficient trip numbers within métiers to preserve integrity for future statistical analysis (Anon, 2005b).

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[5] Mesh size range was based on groupings in Council Regulation (EC) No 850/98: EC, 1998.

[6] Vessel length overall was based on the category outlined by the RCM NEA October 2005 report (Anon., 2005a).

Results

The non-otter trawl segment consists of less than 40% of the Irish ≥10m fishing fleet, equating to around 150 active vessels per year. The segment accounts for around a quarter of annual Irish landings in weight.

Landing profiles

The individual components of the PCA accounted for a low percentage of explained variation. This would indicate a high level of variability in species composition and complex interactions between species. The first four components, considered as relevant to depict the dominant composition relationships, explained only 26% of the variability associated with trip landings. The first two components (Figure 3.1) identify a particular association between fishing trips with proportions of plaice (*Pleuronectes platessa*), black sole (*Solea solea*), and ray species, also distinguished on the third and fourth components (not shown). Other species associations noted on the first components included crab species, scallop (*Pecten spp.*), and whelk (*Buccinum undatum*) in close proximity. This combination is likely to result from a grouping of trips with similarly very high species proportions, rather than interactions between them. Megrim (*Lepidorhombus spp.*), witch (*Glyptocephalus cynoglossus*), and lemon sole (*Microstomus kitt*) are grouped, association can likely be extended to monkfish (*Lophius spp.*) and conger eel (*Conger conger*). Pollack (*Pollachius pollachius*) and saithe (*Pollachius virens*) show association, and likely linked to landings of ling (*Molva molva*) and dogfish (*Scyliorhinus spp.*). These latter groupings are not represented well on the third and fourth components. The third and fourth components suggest an additional association between haddock (*Melanogrammus aeglefinus*) and whiting (*Merlangius merlangus*).

All principal components were included in HAC analysis due to the complex species interactions indicated by the low percentage variation of individual components. Including all components also maintains sufficient variation within the dataset. Little increase in the explained variance (in terms of sums of squares and r^2) occurred beyond 36 clusters. This was thus considered the appropriate number of clusters and explained 78% of the dataset variation. Cluster size varied, from a single trip to 705. The majority of clusters contained less than 5% of total trips. This analysis contains a variety of gear types, each with differing species selectivity patterns, which goes some way to explaining the low trip numbers within clusters. Only clusters considered to symbolise true target species were retained as landing profiles. The remainder were pooled with the next nearest linked cluster. This resulted in fifteen landing profiles (Table 3.1). A landing profile could not be identified for 8 trips (>0.2% of trips); these were subsequently ignored. The number of target species (groups) within profiles varied. Several consisted of a single dominant target, for example scallops. Three landing profiles dominated: crab; combined whiting and haddock; and mixed megrim, monkfish, witch, and lemon sole, each accounting for between 17% and 19% of trips.

Métier Identification and description

MCA of the six trip characteristics resulted in 101 factorial axes, each explaining a very small portion of variance within the dataset. The relationships depicted on the first three axes are considered here, explaining 9% of the variability within the dataset. This emphasizes the heterogeneity of fishing trips within this dataset. Fishing trips are widely distributed on a representation of the first and second MCA axes (Figure 3.2), likely to result from the diversity of trip characteristics, particularly gear types and mesh sizes, included in the analysis. That said, a number of broad groupings were indicated. An association is observed between gillnet trips (GNS) and the mesh size ranges relating to this gear (<110mm, 110-219mm, ≥220mm). Two landing profiles are depicted with this gear, mixed saithe, ling, pollack and dogfish (L8), and hake (*Merluccius merluccius*) and forkbeard (*Phycis spp.*) combination (L9). There are additional possible associations with profiles ‘Other’ (L6) and cod (*Gadus morhua*) (L11). These associations are also present on the second and third axes representation (not shown). It appears these gillnet trips are related to vessels 15-18m in length fishing mostly in areas to the west of Ireland (VIIb, VIIc, VIIk). Beam trawling (TBB) trips occurred grouped with mesh ranges 80-89mm and 90-99mm as well as the larger vessel sizes (24-80m). Two landing profiles were associated with this group: ray, plaice, and black sole (L13), and megrim, monkfish, witch, and lemon sole (L14) with fishing occurring primarily to the south of Ireland (VIIg, VIIj). Dredging (DRB) and scallops are associated with a wide ranging of areas to the south and east of Ireland. Pots and traps (FPO) are shown to be linked to both whelk (L1) and crab (L5) targeting and a variety of areas including

VIa, VIb and VIIc. Scottish seines, although not as well represented on the first two axes, appearing associated with mesh range 70-89mm and haddock and whiting (L12). The association is better depicted on the second and third axes, with the addition of larger mesh sizes (100-119mm).

All MCA axes were included in HAC analysis, as with landing profiles, due to the complexity of the relationships between trip details, with each factorial axis accounting for a small percentage of the dataset variance. Again, retaining all axes also helps to maintain sufficient variation within the dataset. The appropriate number of clusters was estimated as 73 (Figure 3.3**)**, explaining 77% of total variation. The number of trips within clusters varied greatly, from 1 to 616 trips. Few clusters contained more than 1% of trips. Operations across multiple ICES divisions occurred within many clusters. Consistent with the identified landing profiles, the spread of trips across clusters highlights the micro-scale complexity within the dataset. A number of clusters contained a single dominant trip characteristic, for example a single gear type with a mixture of areas, or a single landing profile and a variety of mesh ranges. Two clusters were dominated by a month factor, mixed with several gear types and landing profiles. However, the majority of clusters contained either a wide range, or succession of months. This suggests that season is of low importance, with many clusters occurring throughout the year. The similar wide spread of vessel length categories throughout clusters indicates that vessel length is also of minor importance in cluster definition. Several of the mesh size ranges included within the analysis were gear type specific; for example, 80-89mm was specific to beam trawling. Even in these cases, multiple ranges often occurred within a single cluster. Clusters containing low trip percentages were pooled with closely related clusters, unless considered to represent a true métier (e.g. fourth quarter 70-89mm Scottish seining for sprat (*Sprattus sprattus*) in VIa and VIIa).

Nineteen métiers resulted from analysis of the non-otter fleet (Table 3.2). Seven "non-métier" groups were established based on gear type to account for trips with incomplete or misspecified logbook information and trips with landings profiles or other characteristics outside the range of identified métiers (Table 3.2). These groups also include exploration trips, rarely used gear types, and unusual species compositions. Within mixed/multiple species métiers, not all defining species were required to obtain threshold levels for the trip to be assigned to the métier. Although the species co-exist and are landed as part of a mixed fishery, natural variability in spatial and temporal distribution and density results in variable landing proportions.

In the majority of cases, species assemblage appears to be gear specific. Only one mixed species group occurred across gear types; the targeting of rays in combination with other species. In other cases the same trip characteristics such as gear type, mesh range and vessel length categories occurred across multiple métiers with different target species. Therefore highlighting the importance of using both trip characteristics and species composition to define métiers.

The gillnetting gear type gave rise to the greatest number of métiers, each differentiated primarily by a combination of species composition and mesh range. Beam trawl métiers are also defined by different species and mesh combinations. Vessel lengths, although similar between beam trawl métiers are higher than those within gillnet métiers (18-80m vs. 10-40m). Two Scottish seine métiers were identified targeting whiting and haddock year round divided by mesh size range. This was the only gear to target pelagic species (namely sprat) which showed seasonal operation in VIa and VIIa. Longlining métiers, which employ larger vessels (18-40m), were also identified as seasonal, targeting different species in different areas. Two year round pot and trap métiers were identified, targeting different species. Whelk were identified in only VIa and VIIa, whereas crabs and ‘other’ (primarily lobsters) occurred all round Ireland. A single dredge métier was identified, targeting scallops year round without area restriction.

Examining the importance and dynamics of métiers

Métier definitions were applied to fishing trips from 2003 to 2006 to investigate variations and dynamics in relation to number of trips, vessels, landings, and effort. During this time, several métiers became redundant, where trips no longer filled métier criteria. The deepwater shark longlining métier became so in 2004, as did Scottish seining for spat. Tuna longlining occurred intermittently across years. Given their limited size in 2003, each métier was likely to have been highly specialised. Large mesh ray, plaice and black sole beam trawling was a relatively common métier in 2003, but following a continual decline, became redundant in 2006. The remaining métiers persisted over the period, indicating that the analysis and subsequent métier definitions successfully identified recurring patterns in fishing activity within the non-otter fleet.

Fishing Trips and Vessels

Métier allocated fishing trips accounted for between 74-87% of trips annually by this fleet segment, and 84-94% of all vessels operated within at least one métier annually (Table 3.3), both occurring at the upper range in 2006. Vessels can participate in several métiers annually through targeting different species compositions or varying gear configurations between trips. The majority of vessels exhibit fidelity to one defined métier (57% of active vessels), however this decreases if considering non-métier groups (~40%). Those vessels which can be considered polyvalent, annually occur in multiple métiers/non-métiers (up to a maximum of 6 observed in 2005) primarily result from alternative species targeting or mesh size use, or employing several gear types. Vessels alternating gear type typically utilise a combination of gillnets and pots/traps, or gillnets and Scottish seines. Very few beam trawl or dredge vessels employ other gear types, highlighting the specialised nature of these gear types. Vessels can also employ multiple gear types within a trip, such as a bottom otter trawl and pots, although examples of this reported within the logbooks were low over the period (2) and were excluded from the analysis. A small number of vessels occurred exclusively within the non-métier classification. The majority of these occur within the dredge or rare gear groups. In relation to dredging, a small razor shell métier was identified during a previous pilot analysis of the Irish Sea (Davie & Lordan, 2009) which, owing to the métier's high level of speciality and the volume of data analysed, was not identified in this analysis. The same reasoning is applicable to the rare gear groupings which represents a variety of gears occurring at low level usage.

Over the period the greatest increase occurred within the crab and 'other' pot and trap métier, accounting for 52% of trips and 41% of vessels by 2006. These increases were due to an expansion of the pot and trap fleet segment and improved enforcement/reporting practices during the period.

Gillnetting for ray and 'other' in areas VIIa, VIIb, VIIg, and VIIj also increased by over 75% in trip and vessel numbers. Conversely, the small mesh whitefish in VIIa, VIIb, VIIg, VIIj, and VIIk declined by >80% in trips and >60% in vessels. The métier using gillnets to target crab and ‘other’ also declined significantly over the period.

A switch appeared to occur between the two beam trawl métiers targeting megrim and monkfish. Within the large mesh version of this métier trip numbers showed a marked decline, and to a lesser extent vessel numbers (less than 50%). Whereas, trip and vessel numbers increased within the small mesh equivalent. This switch from large to smaller mesh ranges is likely the result of changes in management restrictions continually incentivising smaller meshes. The same magnitude of increase was not observed in the alternative large mesh métier targeting ray and flatfish.

Trip numbers remain stable while participation (numbers of vessels) declined in three metiers; hake and forkbeard GNS, cod GNS, and whiting and haddock SSC, suggesting the remaining vessels carried out a greater number of trips than in the past. While the opposite occurred in SLPD targeted gillnetting where vessel participation increased. Overall little vessel participation stability was observed, one exception was ray and flatfish targeted small mesh beam trawling which persisted with low participation while trips declined indicating vessels carried out progressively more trips within other métiers. Cod longlining has consistently contained only one or two vessels per year. This is likely to be a highly specialised, targeted métier, and unlikely to be able to support great vessel numbers. Although the number of vessels remained stable, trip numbers dropped by 79% becoming the smallest métier of the fleet in 2006.

Landings

Métier landed weights vary, contributing differently to total landings of each species or stock (Table 3.4). The greatest landed weights, throughout the period, were obtained by the crab and ‘other’ pot and trap métier. In 2006, this was over twice that of any other defined métier, with 4,505 tonnes, an increase of 25% on 2003 landings. At the lower spectrum, crab and "other" gillnet resulted in just 2 tonnes of landings. This métier, however, is believed to stem from gear misspecification, or, as stated in the Irish Sea analysis (Davie & Lordan, 2009), recording of one gear when two are used. Two gillnetting métiers landed less than 50 tonnes in 2006; ray and ‘other’, and the small mesh whitefish métier. The former has had consistently low landings, whilst the later exhibited substantial declines.

Landings declined in the majority of métiers, in a number halving or more, suggesting declining quotas or reduced species availability. The greatest reduction (97%) occurred in the small mesh whitefish gillnetting métier mentioned above. Given this contraction, it is likely to become redundant in the near future. Scallop dredging across all areas contracted by 73%, with similar reductions in trip and vessel numbers. It is unlikely that vessels previously dredging for scallops switched to an alternative gear type given the high degree of gear specialisation. Management measures including a decommissioning scheme were in place during the period which reduced the effort and capacity in this segment. However, there were some landings increases within the dredging non-métier, which would suggest a possible change in target species, to for example razor clams. Small mesh whiting and haddock Scottish seine landings halved, with declines also shown in the other Scottish seine métiers. The use of this gear type appears to be declining in an Irish context.

One of the few landings increases noted relate to the whelk pot and trap métier which exhibited the greatest relative increase (109%), indicating métier expansion. Small mesh megrim, monkfish, witch, and lemon sole beam trawling showed a large increase (79%) over the period. By 2006 it represented the second most important métier, contributing 1,652t in landings. A considerable increase in landings within the rare gears category occurred from around 2005, suggesting some fishers began trialling gear types not routinely employed by the Irish fleet. Developments within this group will have to be monitored for emerging métiers. Only one métier, small mesh beam trawling for ray and flatfish, retained similar and consistent landings to those in 2003.

Species compositions show métiers involving beam trawls, gillnets, and Scottish seines contain a wide variety of species, many as chance-catch (Table 3.4), i.e. species not directly targeted but retained onboard and landed in low levels (<10%). Cod for example is a defining species in one métier using these gears, yet it is landed in the majority of métiers. The occurrence of multiple chance-catch species highlights mixed fishery interactions with these gear types. There are less chance-catches and thus fewer species interactions within métiers employing pots/traps, dredges and longlines. These gear types are more specialised, and fishing behaviour is adapted to target specific species. Dredges scrape the sea floor for species which live on, or in, upper benthic sediments. Whereas pots and traps for example, contain bait to attract mobile scavenging species by olfaction. A similar specialised targeting also occurs with longlines; although the longline métiers catch several species, the diversity is far lower than, for example, beam trawling.

Effort

The métier designations considered here focus on effort defined as days-at-sea (days absent from port) as this effort measure is the most often used within European fisheries management regulations. Effort could also be defined in fishing days or fishing hours but such definitions are not detailed here (see Chapter VI). Despite the generality of the European days-at-sea effort definition, it should be noted that the relationship between days-at-sea, fishing days, and fishing hours can vary between métiers due to, for example, fishing location and target species behaviour.

The average trip length for the majority of métiers was between 3 and 7 days-at-sea. There is little difference between fishing days and days-at-sea for most indicating little time is spent steaming to fishing grounds. Cod longlining and hake and forkbeard gillnet métiers have the longest average trip lengths (≥10 days). These métiers are defined by fishing areas further offshore requiring longer steaming times (highlighted by a 2 day difference between averaged days-at-sea and fishing days). At the other extreme, small mesh whitefish gillnetting, and crab and 'other' pot métiers average very short trips (≤2 days-at-sea).

Over the four years examined, overall effort declined within the non-otter trawl fleet however the proportion of effort assigned to métiers increased (71-86%). This indicated that métier definitions encompassed the primary fishing patterns of the fleet segment. Several métiers exhibited substantial increases over the period (Table 3.3). The two pot and trap métiers, targeting whelk and targeting crab and ‘other’, greatly increased in effort during the period, in line with trips and landings already mentioned. Marked effort increases also occurred in ray and 'other' gillnetting, and small mesh megrim, monkfish, witch, and lemon sole beam trawling. As observed for trip and vessel numbers, the increased popularity of the later contrasts with the decline observed in the large mesh beam trawling métier for the same species.

As observed for the characteristics of trip and vessel numbers, little relative métier stability was observed in effort. Whilst hake and forkbeard gillnetting effort remained relatively stable, the lack of stability across other métiers suggests shifting fishing practices. Scallop dredging effort in 2006 declined to about a quarter of that in 2003, following the declining landings, trip, and vessel trends. A second specialised métier exhibiting declines was cod longlining. These two métiers, although contracting, are likely to continue at low levels exploiting small, specific niches within Irish waters.

By far the greatest effort observed in 2006 was expended by the crab and ’other’ pot and trap métier, and by the small mesh megrim, monkfish, witch, and lemon sole beam trawling métier. Each demonstrated increased importance over the period. In contrast, cod longlining and small mesh whitefish gillnetting métiers were of least importance in effort, each totalled less than 50 days-at-sea in 2006, in line with landings, and trip and vessel numbers.

Discussion

An important first step toward achieving sustainable mixed fisheries and healthy ecosystems is to understand fishing activities which can be done by identifying homogeneous groups with similar characteristics, in this case métiers. The key to managing fisheries is to manage fishers and their behaviour (Hilborn, 2007). Having a well informed understanding of the complexity of fisher behaviour is essential to developing effective management strategies and plans.

The non-otter trawl section of the Irish fleet utilises a variety of gear types, across a range of fishing grounds, catching an assortment of species. The result is a diversity of interactions between vessel characteristics and species compositions that gave rise to nineteen métiers. These groupings are in addition to the thirty-three Irish otter trawl métiers previously identified (Davie & Lordan, 2011a). The total number of métiers across the Irish fleet highlights the depth of diversity and complexity. These métiers succeed in segregating the non-otter fleet into homogeneous groupings identifying the dominant fishing patterns, and continued to account for the majority of effort within the fleet segment. A different outlook was observed for landings, where increased use of what had been ‘rare gears’ in 2003 resulted in high volume landings of pelagic species (purse seines). This suggests fisher diversification away from traditional Irish pelagic trawling practices (Davie & Lordan, 2011a). This is likely the combined result of management restrictions encouraging fishers to explore the development of favourable alternative options.

The use of métier definitions to stratify sampling programs, and their utility for management implementation, has already been discussed in Chapter II (Davie & Lordan, 2011a). These same points are relevant to the métiers identified here. As such, the discussion within this chapter considers the utility of métier definitions for revealing particular changes in fisher behaviour, mixed species considerations, and the impacts of external drivers.

The species composition of landings profiles were assumed to represent fishers intended target(s), an assumption applied by many other métier identification studies, with Biseau (1998) constituting one of the earlier examples. Ideally the intended target of a fishing trip would be reported within the logbooks, however experience shows this is unlikely to occur. The alternative approach conducting extensive fisher interviews to ascertain intended targets is both impractical and unlikely to produce the same quantitative data required.

Unlike the otter trawl fleet, landing profiles identified targeting of multiple species to be the exception rather than the rule. The majority of identified target species (two-thirds) were characterised by a single species (group) (e.g. scallops, cod, or deepwater sharks). This can indicate either a high level of species selectivity by many of the fishing gears covered here, or very specific targeting by fishers. The most mixed target groups occurred specifically within gears known to be less selective, i.e. beam trawling, which gave rise to two mixed benthic profiles.

The need to account for both the multi-species and multi-gear interactions within mixed fisheries management is highlighted by this study where the identification of landing profile alone was not enough to identify and define métiers. Identification was only possible in combination with gear type. This is in agreement with otter trawl métier identification (Davie & Lordan, 2011a) and other studies (e.g. Campos *et al.*, 2007). Whilst gear types occurred within multiple métiers targeting different assemblages, similar targets across gear types as seen in the otter trawling fleet (Davie & Lordan, 2011a) was limited. Given the variety of gear types, and differences in fishing methods between them, the variation in species selectivity is unsurprising.

The high single species (group) proportions and low diversity of the three longline métiers likely result from a combination of high gear selectivity and specific spatial and temporal targeting. Longlines use bait to entice fish onto hooks. Consequently, the type of bait used, soak time, diet of target species, distribution of target in relation to bait, as well as the speed and direction of water currents can influence the catch (Sainte-Marie & Hargrave, 1987; Atema 1988; Løkkeborg 1990; Løkkeborg & Johannessen 1992; Engås & Løkkeborg 1994; Løkkeborg & Pina 1997). The two pot métiers use the same highly selective method of fishing as longliners, using olfaction to attract scavenging target species (Sainte-Marie & Hargrave, 1987). The resultant selectivity is a key difference from towed nets where spatial co-existence of species results in greater diversity, sweeping all species unable to avoid the gear back into the net. Thus differences between gear catching methods requires consideration when planning management strategies (Ferro, 2002).

Gillnetting gave rise to the greatest number of métiers, varying in target species. Generally these were defined by a low number of target species. Although there is a potential for gillnets to be unselective, often specific mesh sizes and/or net designs are deployed in specific areas to target particular species resulting in fairly clean fisheries. Danish gillnetting also tend to target single species (Ulrich & Andersen, 2004). Discard observer trips on Irish vessels tend to show lower level discarding from gillnets (Marine Institute & Bord Iascaigh Mhara, 2011).

Including discards in this analysis would alter catch composition and could bias perception of the intended target. However the non-inclusion of discard composition is a potential limitation of this analysis. It would have been advantageous to examine discard profiles in parallel. Historically discard sampling of the Irish fleet was typically on otter trawl gears where discarding was perceived to be most significant (Borges *et al.*, 2005a). More recently with the métier based approach within the DCF sampling programmes have extended to other gears. The Irish *Atlas of Demersal Discarding* (Marine Institute & Bord Iascaigh Mhara, 2011) provides an insight into the very different species mix when catches and not landings are examined by métier. The reality is that the sampling levels for discards (<1% of all trips) make it functionally impossible to carry out an analysis at the scale and coverage here with discards included. Although possible, it is also unlikely that including discards would significantly alter the métier groups identified. Properly defining métiers may in fact improve discard estimation though more appropriate stratification for raising samples, or in conducting sampling in a more appropriate way.

Following extensive discussion and recent public attention, the recently passed Common Fisheries Policy reform (EC, 2013) stipulates that discarding will be reduced or eliminated within European waters for a number of commercial species over the coming years. Implementation of such a regulation will impact on fishing behaviour particularly for métiers where discarding is significant. Another implication of the obligation to land all catches is that landing profiles may become catch profiles in the near future masking intended targets. This will impact on the ability to carry out métier analysis requiring development of new methods to identify targets which may need to be accounted for when tracking métier dynamics into the future. This largely depends on implementation. If the previously discarded catch portion is reported is reported as a separate entity to the retained landings little methodology change will be required and analyses of métier "discarding" profiles may become simpler if the composition is recorded.

It is interesting that beam trawl vessels were observed to switch between two benthic target groups over the time examined. Ray landings for human consumption, for example, have become more prevalent in recent years as traditional species quotas become increasingly restrictive, and public tastes expanded creating market demand (e.g. ray wings). This is an example of the fluidity of fishing and behavioural adaptability of vessels within this fleet, not only in response to management restrictions but also to developing market opportunities. This is an example of where fisher decisions vary fishing pressure on multiple stocks even within the same, quite specialised, gear category.

Vessel length ranges varied particularly in minimum length between métiers. Vessels active in pot and gillnet métiers encompassed the smallest vessel length categories (10-12m). Conversely, beam trawl, dredge, and longline métiers typically consisted of larger vessels (18m+). Variation in minimum vessel length between these métier groups likely relates to differing engine power requirements (linked to vessel length). Greater power is required, for example, to tow beam trawls than for the operation of passive static gears (Galbraith *et al.*, 2004). Jiménez *et al.* (2004) noted a difference between the types of 'Fishing Trip Type' carried out by smaller and larger vessels. Smaller vessels targeted more coastal species and fishing grounds whereas the larger vessels targeted offshore sites. This observation is also true in Irish fisheries as there are examples of larger vessels operating with static gears off shore (e.g. in the long line métier)

Pot gear can be easily utilised by a wide variety of vessels, although many are small, suggesting that the métier is a more inshore coastal fishery and indicated by the large number of under 10m vessels fishing with this gear (Anon, 2006). A small proportion of the larger vessels fish more offshore crabbing areas. This is consistent with three studies highlighted by Tyedmers (2001) that investigate fuel consumption. Similar patterns occur in Scotland's creel and pot activity (Galbraith *et al.*, 2004).

The identified minimum length differed with mesh size range in both beam trawl and Scottish seine métiers. This was an unexpected differentiation, the reason(s) for which could not be identified. In each case both mesh size ranges target the same species indicating intermingling of spatial distribution. The segregation of vessel length categories between métiers implies the length of a fisher's vessel imposes limitations to alternative métier choices. Vessel length is therefore something which should be considered when examining fisher behaviour. The ability to stratify métiers by length categories is already incorporated within the Fcube mixed fisheries simulation model for trawl gears (Ulrich *et al.*, 2011). This is the model currently used to provide ICES mixed fisheries advice, supporting the importance of vessel length differentiation.

The most salient outcome from this study is that the observed métier dynamics, reflected by fluctuations in landings, effort, and participation over time, suggests a lack of stability in métier structure since 2003. The fleet is adapting its fishing practices in response to external pressures, be they biological in relation to species availability (e.g. cod stock declines; ICES, 2007b), economic viability (e.g. rising fuel costs; Poos *et al.*, 2013), or management. The cod long term management plan within the Irish Sea and West of Scotland (EC, 2002; 2003; 2004; 2005) has had a big impact on quota and effort available to some métiers (this is discussed further in Chapter IV). One perverse consequence of the plan observed here were the activity reductions of the larger mesh beam trawl métiers whilst small mesh métiers continued to flourish. Smaller mesh sizes result in greater restriction on the ability of undersize, often juvenile, fish to escape once inside the net, which can result in an increase in discarding practices. The large mesh ray and flatfish targeted beam métier became extinct by 2006. This can be traced to increasingly restrictive effort management regulations for the larger mesh range within the Irish Sea under the cod long term management plan, and the mirrored knock-on effect within the Celtic Sea, as many vessels operated across both areas.

Other examples of observed management impacts include a series of Irish decommissioning schemes which targeted beam trawls and dredgers to permanently remove a number of vessels from the fleet, one scheme having occurred in 2005. Decommissioning removed a large number of what had previously been scallop beam trawlers, essentially eliminating this group, while decommissioning reduced the scale of the scallop dredging métier. Dredging is a specialised fishing method with little switching possible between gears and few Irish alternative target species, although as previously mentioned, razor shell dredging occurs in the Irish Sea (Davie & Lordan, 2009).

The causes of métier dynamics however, are not always easily identified by individual drivers or pressures, and can result from an accumulation of multiple influences. For example the substantial contraction of the small mesh whitefish gillnetting métier while alternative target métiers with the same configuration continue and large mesh métier targeting the same assemblage increase. This implies nether quota, nor effort are restrictive drivers, and market or other factors may be at play.

Conclusion

The multivariate statistical techniques applied to species landings compositions and trip characteristics, developed in Chapter II (Davie & Lordan, 2011a), were again capable of identifying homogeneous groups within the multi-species and multi-gear non-otter fleet. This investigation identified a total of nineteen métiers and provided information on the main characteristics and recent dynamics within this diverse segment. Where possible, relating these to underlying drivers of behaviour, in particular responses to TAC and effort management.

This investigation completes the identification and definition of Irish métiers adding those identified here to those within the otter trawl fleet (Chapter II: Davie & Lordan, 2011a). These Irish métiers can now formulate a base for examining fisher behavioural responses to biological, management and economic drivers within mixed fisheries. These métier definitions can be routinely updated in the future to monitor changes in fisher behaviour and fishery performance over time. Tracking the métier structure and dynamics will be very informative in the development of mixed fisheries management plans with industry and other stakeholders.

Figures

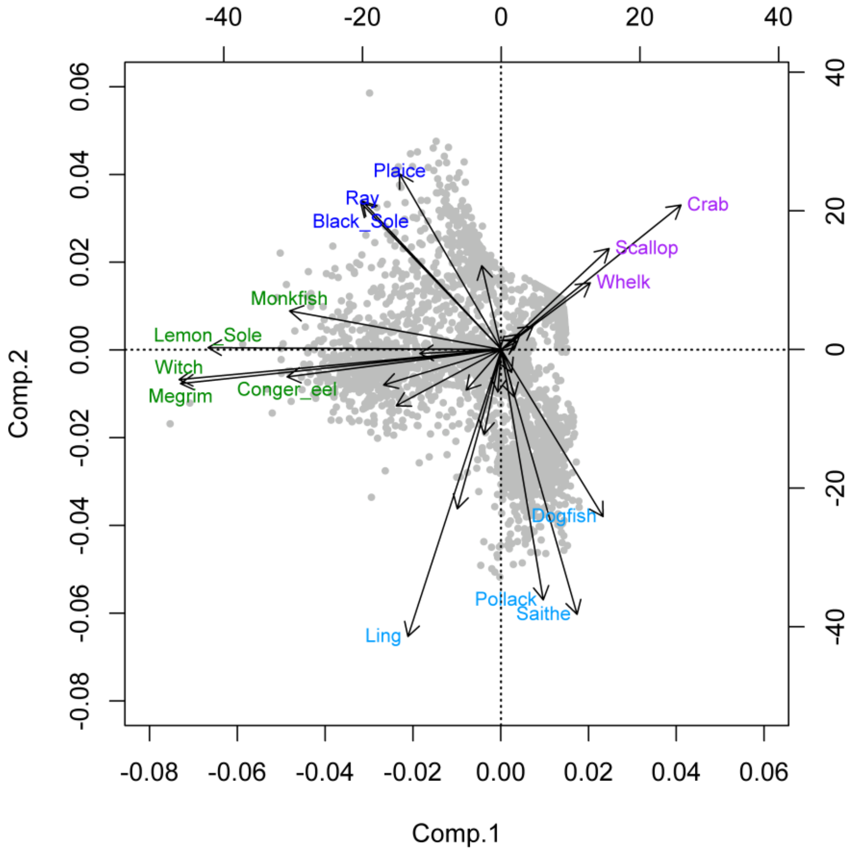

Figure 3.1. Principal Component Analysis scores of the first two axes from fishing trip species proportions within the Irish non-otter trawl fleet, 2003. Only those species considered to influence the axes are labelled. A number of species are differentiated on these axes: flatfish and ray species (blue); crab, scallop and whelk (purple); witch, megrim, lemon sole, monkfish and conger eel (green), pollack and saithe with possible association with ling and/or dogfish (light blue), and *Nephrops* (orange).

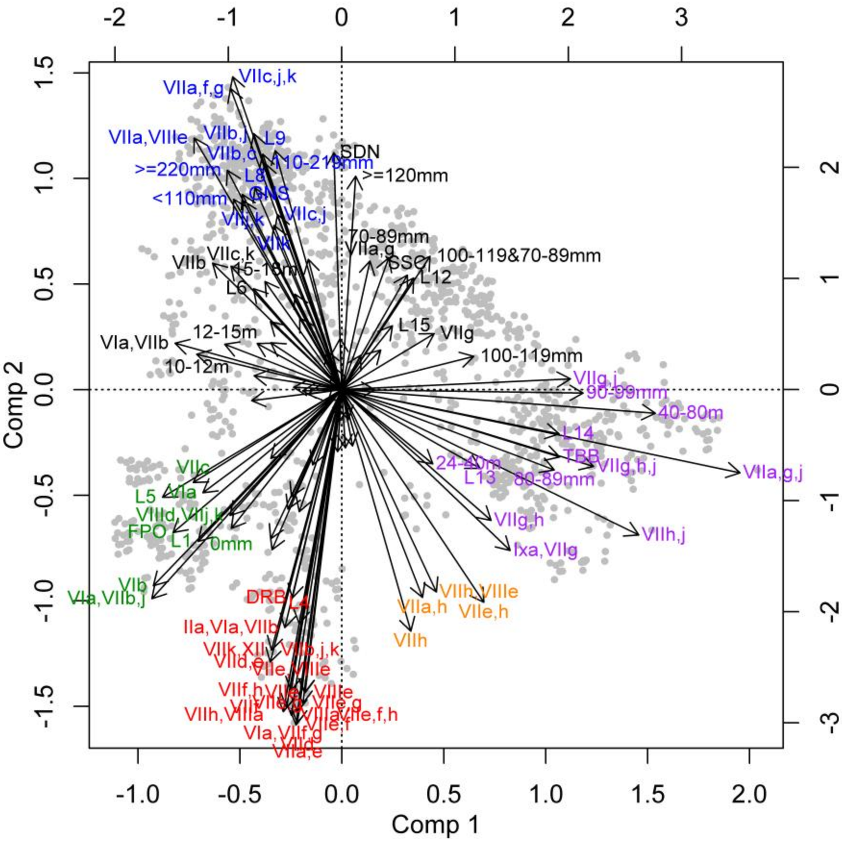

Figure 3.2. MCA scores of the first two axes from fishing trip descriptive characteristics within the Irish non-otter trawl fleet, 2003. Only those factors considered to influence the axes are labelled. Descriptive characteristics: mesh size range (mm); vessel length range (m); month and gear (3 letter code); area (ICES Division); landing profile (see Table 3.1). A number of characteristics are differentiated on these axes: Dredging (DRB) and profile L4 across a wide variety of areas to the south and east (red). While to the left of those are pots (FPO), zero mesh size, and profiles L1 and L5 associated with a variety of areas (green). Mesh ranges <110mm, 110-219mm, and ≥220mm and gillnetting (GNS) associated with the mixed (L8) and slope (L9) profiles, 15-18m vessels and areas more to the west of Ireland (VIIb, VIIc, VIIk) (blue). Beam trawling (TBB) trips are grouped (purple) with L13 and L14 profiles associated with 80-89mm and 90-99mm meshes and larger vessels (24-80m) operating to the south of Ireland (VIIg, VIIj). Those in black show some other associations but are less clearly defined on these axes.

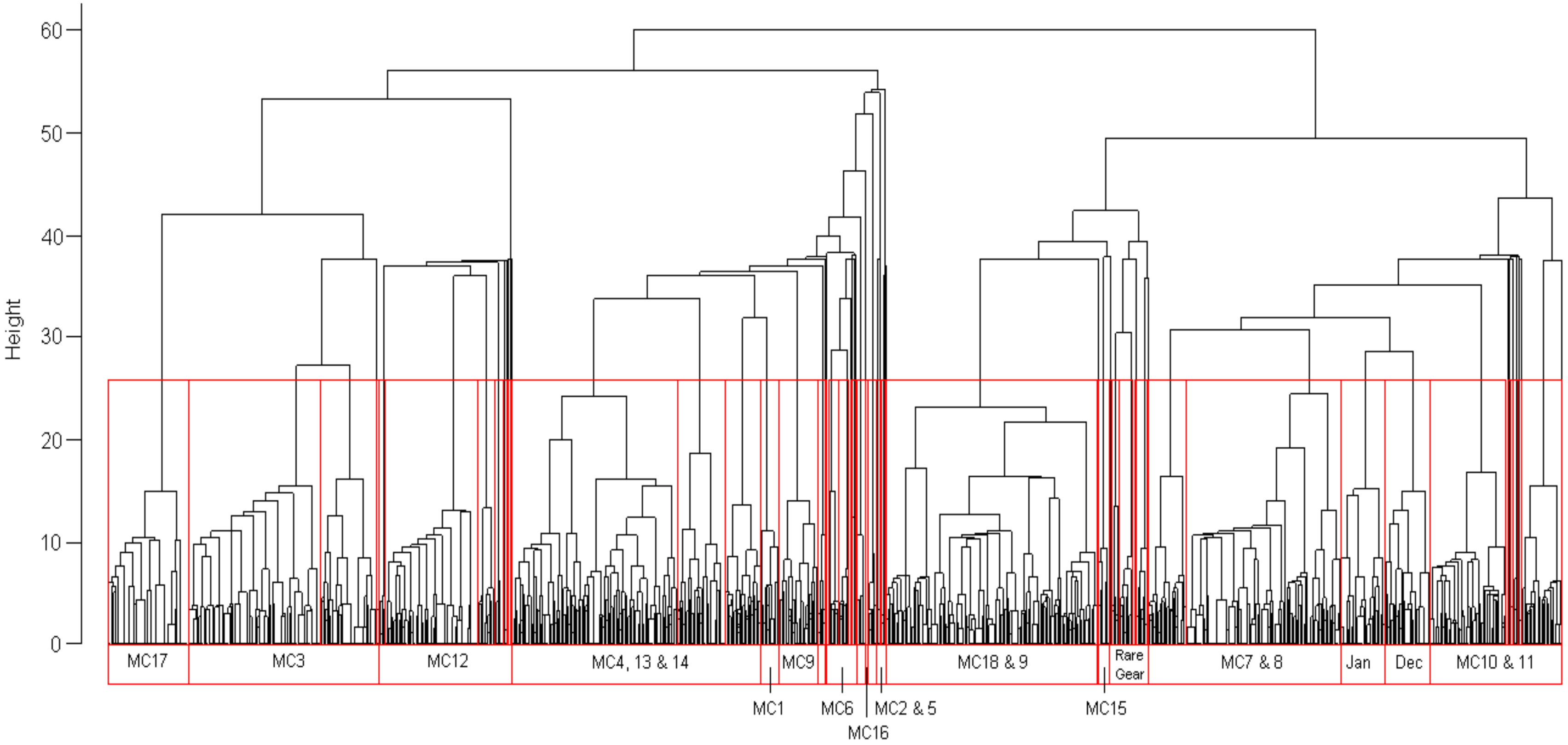

Figure 3.3. Results from HAC of fishing trip descriptive characteristics within the Irish non-otter trawl fleet, 2003. Boxes identify the 73 clusters identified by r^2 values, explaining 77% of the total variation. Labels below clusters correspond to métier IDs (prefixed with MC) detailed in Table 3.2.

Tables

Table 3.1. Landing profiles main target species identified by PCA and HAC of fishing trip species proportions within the Irish non-otter trawl fleet, 2003, detailed with the number of associated trips. A landing profile could not be identified for 8 trips.

Profile	Target Species	Fishing trips
L1	Whelk	231
L2	Sprat	33
L3	Tuna	7
L4	Scallop	397
L5	Crab	705
L6	"Other"	130
L7	Deepwater shark	16
L8	Saithe, ling, pollack and dogfish	685
L9	Hake and forkbeard	49
L10	Mackerel	25
L11	Cod	79
L12	Whiting and haddock	788
L13	Ray, plaice and black sole	322
L14	Megrim, monkfish, witch and lemon sole	725
L15	*Nephrops*	33

Table 3.2. Irish métier definitions of the non-otter trawl fleet, detailing the métier ID, name and the conditions of each métier in relation to species composition and fishing trip descriptive characteristics.

Metier Name		Gear Type	Mesh Size	Vessel Length	ICES Area	Period	Target	Species Composition		
								Lower Species Threshold		Special Conditions
1	Cod GNS VIIa,g	GNS	ALL	10-24m	VIIa VIIg VIIa.g	Jan-Apr	Cod		≥30% Cod	
2	Cod longlining	LONGLINE	-	24-40m	I IIb	Nov-Apr	Cod		≥60% Cod	
3	Crab & Other FPO All areas	FPO	-	10-40m	ALL	ALL	Crab & Other	Or,	≥60% Crab ≥50% Other	&, <20% dogfish <10% all other species
4	Crab & Other GNS VIIa,b,g,j	GNS	<110 & 0	10-15m	VIIa VIIb VIIg VIIj	ALL	Crab & Other	Or,	≥45% Crab ≥50% Other	<20% dogfish &, <10% all other species
5	Deepwater shark longlining	LONGLINE	-	24-40m	VIa VIIc VIIk	May-Nov	Deepwater shark		≥70% Deepwater shark	
6	Hake & Forkbeard GNS VIIb,c,g,j,k	GNS	ALL	10-40m	VIIb VIIc VIIg VIIj VIIk	ALL	Hake & Forkbeard	Or,	≥30% Hake ≥30% Forkbeard	
7	MMWLS Large TBB VIIg,h,j	TBB	≥90	24-80m	VIIg VIIh VIIj	ALL	MMWLS	Or,	≥20% Megrim ≥25% Monkfish ≥15% Witch ≥10% Lemon Sole	If witch or lemon sole: <10% Plaice &, <15% Black Sole <30% Ray Species
8	MMWLS Small TBB VIIa,e,g,h,j	TBB	80-89	18-40m	VIIa VIIe VIIg VIIh VIIj	ALL	MMWLS	Or,	≥20% Megrim ≥25% Monkfish ≥15% Witch ≥10% Lemon Sole	If witch or lemon sole: <10% Plaice &, <15% Black Sole <30% Ray Species
9	Ray & Other GNS VIIa,b,g,j	GNS	ALL	10-40m	VIIa VIIb VIIg VIIj	Apr-Aug	Ray Species & Other	Or,	≥30% Other ≥30% Ray Species	<45% Crab <25% Saith <25% Ling &, <25% Pollack <30% Cod in VIIa,VIIg, VIIa.g Jan-Apr <30% Hake & Forkbeard in VIIb, VIIg, VIIj related
10	RPBS Large TBB VIIa,g	TBB	≥90	24-80m	VIIa VIIg	ALL	RPBS	Or,	≥30% Ray Species ≥10% Plaice ≥10% Black Sole	<20% Megrim &, <25% Monkfish
11	RPBS Small TBB VIIa,g,h,j	TBB	80-89	18-40m	VIIa VIIg VIIh VIIj	ALL	RPBS	Or,	≥30% Ray Species ≥10% Plaice ≥15% Black Sole	<20% Megrim &, <25% Monkfish
12	Scallop DRB All Areas	DRB	-	18-40m	ALL	ALL	Scallop		≥80% Scallop	

Table 3.2. Continued.

Metier Name		Gear Type	Mesh Size	Vessel Length	ICES Area	Period	Target	Species Composition					
								Lower Species Threshold			Special Conditions		
13	SLPD Large GNS VIIa,b,g,j,k	GNS	110-219	10-40m	VIIa VIIb VIIg VIIj VIIk	ALL	SLPD	Or,	≥25%	Saith	&,	<30%	Cod in VIIa,VIIg, VIIa.g Jan-Apr
									≥25%	Ling		<30%	Hake & Forkbeard in VIIb, VIIg, VIIj VIIk related
									≥25%	Pollack		<30%	Other
									≥30%	Dogfish		<30%	Ray Species
14	SLPD Small GNS VIIa,b,g,j,k	GNS	<110	10-40m	VIIa VIIb VIIg VIIj	ALL	SLPD	Or,	≥25%	Saith	&,	<30%	Cod in VIIa,VIIg, VIIa.g Jan-Apr
									≥25%	Ling		<30%	Hake & Forkbeard in VIIb, VIIg, VIIj related
									≥25%	Pollack		<30%	Other
									≥35%	Dogfish		<30%	Ray Species
15	Sprat SSC VIa & VIIa	SSC	70-89	12-18m	VIa VIIa VIa.VIIa	Oct-Dec	Sprat		≥95%	Sprat			
16	Tuna longlining	LONGLINE	-	18-40m	VIIh VIIj	Aug-Sep	Tuna		100%	Tuna			
17	Whelk FPO VIa,VIIa	FPO	-	10-24m	VIa, VIIa, VIa.VIIa	ALL	Whelk		≥90%	Whelk			
18	Whiting & Haddock Large SSC VIIa,b,g,j	SSC	≥90	18-40m	VIIa VIIb VIIg VIIj	ALL	Whiting & Haddock	Or,	≥35%	Whiting			
									≥35%	Haddock			
19	Whiting & Haddock Small SSC VIa,VIIa,b,g,j	SSC	70-89	12-40m	VIa VIIa VIIb VIIg	ALL	Whiting & Haddock	Or,	≥30%	Whiting			
									≥35%	Haddock			

Table 3.3. Annual fishing trips, vessel participation and days-at-sea effort within non-otter trawl métiers, 2003–2006 with relative change over the period within brackets (% increase or decrease).

		2003			2004			2005			2006		
Metiér Name	ID	Trips	Vessels	Effort	Trips	Vessels	Effort	Trips	Vessels	Effort	Trips	Vessels	Effort
Cod GNS VIIa,g	1	65	18	177	77	15	257	46	11	224	70 (8)	14 (-22)	240 (36)
Cod longlining	2	14	1	149	7	2	63	1	1	10	3 (-79)	1 (0)	25 (-83)
Crab & Other FPO All areas	3	565	19	2,318	949	25	2,942	1,027	35	3,394	2,277 (303)	65 (242)	4,320 (86)
Crab & Other GNS VIIa,b,g,j	4	100	5	159	7	1	7	0	0	0	16 (-84)	2 (-60)	27 (-83)
Deepwater shark longlining	5	16	1	187	0	0	0	0	0	0	0 (-100)	0 (-100)	0 (-100)
Hake & Forkbeard GNS VIIb,c,g,j,k	6	69	15	506	87	15	524	81	11	508	74 (7)	10 (-33)	559 (10)
MMWLS Large TBB VIIg,h,j	7	191	8	1,126	126	6	842	166	7	1,139	55 (-71)	5 (-38)	373 (-67)
MMWLS Small TBB VIIa,e,g,h,j	8	259	12	1,587	240	19	1,723	383	18	2,599	423 (63)	20 (67)	2,789 (76)
Ray & Other GNS VIIa,b,g,j	9	39	9	168	52	9	244	61	10	237	86 (121)	16 (78)	264 (57)
RPBS Large TBB VIIa,g	10	122	7	650	25	5	145	10	4	59	0 (-100)	0 (-100)	0 (-100)
RPBS Small TBB VIIa,g,h,j	11	188	14	1,067	105	13	697	155	15	901	111 (-41)	12 (-14)	687 (-36)
Scallop DRB All Areas	12	381	20	1,875	372	17	1,942	218	12	914	133 (-65)	6 (-70)	427 (-77)
SLPD Large GNS VIIa,b,g,j,k	13	210	24	1,111	148	17	829	62	17	360	220 (5)	31 (29)	869 (-22)
SLPD Small GNS VIIa,b,g,j,k	14	241	24	961	144	19	593	175	20	783	41 (-83)	8 (-67)	47 (-95)
Sprat SSC VIa & VIIa	15	19	3	33	0	0	0	0	0	0	0 (-100)	0 (-100)	0 (-100)
Tuna longlining	16	5	3	35	0	0	0	4	2	43	0 (-100)	0 (-100)	0 (-100)
Whelk FPO VIa,VIIa	17	230	7	307	160	4	169	374	9	649	421 (83)	15 (114)	968 (215)
Whiting & Haddock Large SSC VIIa,b,g,j	18	221	14	1,030	169	10	808	199	12	913	227 (3)	11 (-21)	859 (-17)
Whiting & Haddock Small SSC VIa,VIIa,b,g,j	19	428	18	1,505	287	12	1,085	224	11	864	203 (-53)	8 (-56)	730 (-51)
Annual Total		3,363	222	14,951	2,955	189	12,870	3,186	195	13,597	4,360 (30)	224 (1)	13,184 (-12)

Table 3.4. Average non-otter trawl métier landings species composition (%) with average total landed (t), 2003–2006.

	Metier Name	Cod GNS VIIa,g	Cod longlining	Crab & Other FPO All areas	Crab & Other GNS VIIa,b,g,j	Deepwater shark longlining	Hake & Forkbeard GNS VIIb,c,g,j,k	MMWLS Large TBB VIIg,h,j	MMWLS Small TBB VIIa,e,g,h,j	Ray & Other GNS VIIa,b,g,j	RPBS Large TBB VIIa,g	RPBS Small TBB VIIa,g,h,j	Scallop DRB All Areas	SLPD Large GNS VIIa,b,g,j,k	SLPD Small GNS VIIa,b,g,j,k	Sprat SSC VIa & VIIa	Tuna longlining	Whelk FPO VIa,VIIa	Whiting & Haddock Large SSC VIIa,b,g,j	Whiting & Haddock Small SSC VIa,VIIa,b,g,j
	ID	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
	Average weight landed (t)	154	231	4,132	13	83	265	679	1,281	67	159	550	1,373	635	398	20	3	438	1,066	1,315
Average percentage (%)	Blue Whiting								0.0										0.0	
	Boarfish																			
	Cardinalfish																			
	Cod	65.2	81.4	0.0			5.5	4.9	5.5	1.4	5.2	3.8	0.0	2.7	3.0			0.0	2.5	2.4
	Conger eel	0.0		0.1		0.6		2.7	1.5		0.6	0.2		0.0	0.0				0.2	0.0
	Crab			97.5	92.9		0.0		0.2	5.0		0.1	0.0	0.5	0.1			0.1		
	Deepwater Shark					89.6									0.2					
	Dogfish	2.7		0.5		0.1	7.2	0.1	0.2	3.9		0.7		31.6	35.8			0.0	0.6	0.7
	Pilchard																			
	Forkbeard					0.4	3.8	0.0	0.0	0.4				1.1	0.0					
	Grenadier														0.0					
	Haddock	3.1	13.0		0.2		2.8	6.4	7.4	1.4	1.5	1.8		3.3	3.3				17.6	17.8
	Hake	3.5		0.0			50.2	2.8	2.0	1.3	0.4	0.3		6.7	3.9				5.5	3.5
	Herring	0.1					0.0	0.0						0.1	0.1				0.0	0.0
	Horse Mackerel						0.1												0.1	
	John dory	0.3					0.2	0.7	0.6	0.1	0.2	0.2		0.3	0.3				0.4	0.3
	Lemon Sole	0.3		0.0				4.2	4.5		2.1	1.8	0.0		0.0				1.1	1.5
	Ling	5.6	0.1	0.0	0.1	0.9	7.4	5.0	5.4	1.2	2.2	0.9		9.1	8.0				1.2	1.1
	Mackerel	0.0		0.0			0.1	0.0		0.2				0.1	0.2				0.0	0.0
	Megrim	0.9					0.7	33.2	25.9	0.3	1.8	1.5	0.1	0.5	0.9				4.1	3.2
	Monkfish	2.1		0.0	0.1		2.7	13.7	18.8	18.4	4.4	6.1	0.4	2.3	1.2				2.7	2.2
	Nephrops			0.0			0.2	2.9	2.9		0.3	0.2		0.1	0.1				0.1	0.2
	Other	0.7	5.5	1.8	6.4	8.4	2.1	2.7	2.8	25.0	3.0	5.3	0.2	1.3	0.5			0.0	0.8	1.0
	Plaice	0.0		0.0				0.5	1.2	0.1	7.1	17.2	0.0	0.0	0.0				0.8	0.6
	Pollack	9.8		0.0	0.2		8.5	2.6	2.0	1.5	1.4	0.5		23.6	21.6			0.0	1.3	1.3
	Ray	0.3		0.0			0.3	6.0	6.9	36.6	62.1	44.7	0.0	0.2	0.7			0.0	0.8	0.8
	Saithe	3.9	0.0	0.0			6.7	0.8	0.1	2.2	0.9	0.2		12.8	16.5				0.7	0.6
	Scallop			0.0				0.2	1.2	0.0	0.2	3.0	99.2		0.2					
	Sole Black	0.2					0.0	0.8	2.6	0.1	4.5	10.3	0.0	0.1	0.0				0.0	0.0
	Sprat															100.0				
	Squid						0.2	0.1	0.1	0.8	0.6	0.1	0.0	0.8					1.4	1.0
	Tuna							0.0							0.0		100.0			
	Whelk			0.0				0.0	0.0									99.9		
	Whiting	1.3		0.0			1.2	1.7	1.1	0.2	0.9	0.3		2.9	3.2				57.7	61.1
	Witch	0.1						8.1	7.1		0.6	0.9		0.0	0.1				0.3	0.5

Chapter IV: Examining changes in Irish fishing practices in response to the cod long-term plan

Published:

Davie, S., and Lordan, C. (2011). Examining changes in Irish fishing practices in response to the Cod Long-Term Plan. ICES Journal of Marine Science, 68: 1638–1646.

Presented:

Davie, S., and Lordan, C. (2010). Examining changes in Irish fishing practices in response to the Cod Long-Term Plan. Fishery Dependent Information: Making the Most of Fisheries Information, Galway 23-26 August 2010

Abstract

In 2009, there were marked changes in Irish demersal fishing effort owing to the implementation of a new cod long-term plan (CLTP). This replaced previous top-down cod recovery plans, first implemented in 2002, which set days-at-sea limits for fishing vessels. The new plan specifies a harvest control rule, annual effort ceilings for EU Member States, and rules for adapting fishing effort. It encourages cod avoidance, but leaves Member States to allocate effort between individual vessels. During 2009, effort was allocated through a series of pilot schemes in Ireland. These can be considered as an evolution towards co-management. Industry and state authorities worked closely together to develop strategies for effort management and cod avoidance. The impact of recent effort-management measures on the Irish fleet, fishery, and métiers affected by the CLTP was examined. Vessel movements within and between métiers are described and discussed, and unintended impacts resulting from the implementation of management schemes are highlighted. In future, possible fishers' responses to policy initiatives should be considered prior to implementation to minimize potentially adverse consequences.

Keywords

cod, cod long-term plan, demersal fisheries, effort management, métiers

Introduction

The fishing pressure exerted on cod stocks in European waters has long been considered to be unsustainable. As a result, several stocks have declined to dangerously low levels. In an effort to reduce fishing mortality, the European Union (EU) has adopted various management initiatives in the Irish Sea (ICES Division VIIa), west of Scotland (VIa), North Sea (IV) and Kattegat (IIIaS).

Under the Common Fisheries Policy, total allowable catches (TACs) were established and progressively reduced, yet stocks continued to decline. In 2003, effort management was introduced in conjunction with TACs encompassing the west of Scotland (EC, 2002) and further expanded in 2004 to include the Irish Sea (EC, 2003). This top-down scheme specified the number of days individual vessels were permitted to be at sea, varying with area and gear configuration, with the aim of reducing fishing mortality (EC, 2004). In many cases, the days-at-sea allowance decreased annually, particularly for gear configurations traditionally used to target whitefish, such as bottom otter trawls with codend mesh sizes of 100mm or more. Despite these measures, there was little evidence of commensurate reduction in fishing mortality according to ICES stock assessment (ICES, 2010b).

In 2008, the EU Fisheries Council adopted a cod long-term plan (CLTP; EC, 2008a). The plan aims to recover stocks and achieve sustainable exploitation at a target fishing mortality (0.4) corresponding to the maximum sustainable yield, by managing demersal fishing pressures within several areas. This was implemented in February 2009 (EC, 2009a). The CLTP contains harvest- and effort-control rules, implementation rules, and potential derogations to encourage the development of cod-avoidance measures. It specifies effort ceilings for EU Member States, developed using historical international fishery dependent data. The effort is defined as the vessel engine power (kW) multiplied by the days spent at sea, summed over the fleet, giving kW days-at-sea as the unit. The ceilings are partitioned into fishing gear groups for each area covered by the plan. Member States decide individually how effort is to be allocated to their fishers. The ceilings become increasingly restrictive over time for types of cod-catching gear until recovery is achieved. The five gear groups covered by the CLTP are described in the relevant Council Regulation (EC, 2009a) as follows:

i. bottom trawls, Danish seines, and similar towed gear (excluding beam trawls) of codend mesh size ≥100mm (TR1), ≥70mm and >100mm (TR2), and ≥16mm and, 32mm (TR3);
ii. beam trawls of mesh size ≥120mm (BT1), and ≥80mm and >120mm (BT2);
iii. gillnets and entangling nets (excluding trammel nets; GN1);
iv. trammel nets (GT1);
v. longlines (LL1).

Irish fishers primarily use bottom otter trawls, and to a lesser extent beam trawls, gillnets, and demersal seines, to target various demersal fisheries. Combined, these gears account for ~70% of all Irish fishing effort, the remainder being primarily split between pelagic, potting, and dredging gears. Large-mesh beam trawls, trammel nets, and longlines are rarely used by Irish vessels. The Irish Sea and west of Scotland areas fall under the CLTP effort restrictions and are important fishing grounds for the Irish demersal fleet.

In 2009, Ireland endeavoured to follow the spirit of the regulation by taking actions to reduce cod mortality by 25% or more. The Irish administration actively encouraged vessels to adopt fishing practices that would avoid cod catches. To the west of Scotland, this included fishers avoiding grounds where cod aggregations were known. For example, ICES rectangle 39E3 was voluntarily avoided by Irish fishers in 2009, with subsequent closures under national regulation, 1 February to 31 March 2010, and 1 October 2010 until 31 January 2011. Gear trials were carried out in the Irish Sea incorporating separator panels and grids in otter trawls to improve species selectivity. The most active fishery in the Irish Sea (for *Nephrops*) was subsequently given incentives of additional effort to employ these devices.

Several pilot allocation schemes were implemented to divide effort between individual vessels, primarily based on recent track records. The state-retained control and private transfers of effort allocations between vessels were not allowed. The first scheme, from 1 February to 30 April 2009, was the most restrictive. Conservative allocations were assigned to ensure adequate effort remained for later in the year, allowing vessels to re-enter the fleet. Two subsequent schemes, 1 May–31 October 2009 and 1 November 2009–31 January 2010, were adaptations based on the experiences and effort uptake from the previous period. These were less restrictive, and unused effort from the previous period was redistributed, in most cases giving fishers additional effort allocations as time progressed. The schemes and avoidance measures were developed by policy-makers and control authorities, in close consultation with industry and supported by scientific analysis of fishery-dependent data.

Here, we explore the impact of this latest form of effort management, by examining changes to the Irish fleet, fishery, and métiers affected by the CLTP (a métier is a group of fishing trips carried out by similar vessels within a fishery; ICES, 2003). Vessel movements within and between métiers are described and discussed. The results focus on CLTP areas where Irish demersal fishers are most active, namely west of Scotland and in the Irish Sea. Identifiable changes outside the CLTP remit, which are believed to have occurred as a consequence of its implementation, are highlighted.

Methods

The investigation is based on the examination of fishery dependent data from Irish logbooks and vessel monitoring systems (VMS). The logbook data, from the Integrated Fisheries Information System (IFIS) database, were provided by the Irish Department of Agriculture, Fisheries and Food. The information encompasses all fishing trips by Irish vessels ≥10m from 2003 to 2009. Irish VMS data from 2005 to 2009 were provided by the Irish Naval Services (FMC).

Irish métiers were determined prior to this investigation by statistically segmenting fishing trips into homogeneous groupings based on species composition profiles, seasons (using month as a proxy), fishing areas, and vessel characteristics, including gear type, mesh size range, and vessel length. Details of a similar methodology are provided in Davie and Lordan (2009).

Logbook and VMS data were integrated using the methodology described in Gerritsen and Lordan (2011). A simple speed rule was applied to identify the majority of fishing operations relating to trawl gear, where speeds between 1.5 and 4.5 knots were considered to be fishing activity. VMS positions relating to fishing activity were then integrated with catch and effort data from logbooks via a vessel identifier and the date.

Integrated logbook and VMS data allow analysis of fisheries-dependent data on a fine spatial scale.

Data manipulation and analysis were carried out using the software Microsoft SQL Server 2008 Management Studio software and the R language and environment for statistical computing (R Development Core Team, 2008).

Results

Within the west of Scotland (VIa) and Irish Sea (VIIa) areas, regulated effort generally declined in 2009, and most ceilings were not reached (Table 4.1). TR1 to the west of Scotland is the only exception, showing an increase of ~25%, exceeding the 2009 allocation by >60%. However, Ireland was permitted to transfer effort between gear categories (EC, 2008a), and effort was thus transferred from the primarily unused TR2 category to TR1, adjusting the effort ceilings.

In addition to the implemented effort ceilings, several vessels were removed permanently from the Irish fleet by the end of 2008, through a decommissioning scheme. This had little effect in the west of Scotland, but in the Irish Sea a large quantity of effort was removed from the regulated gear categories (Table 4.1). More than half the 2008 BT2 effort was attributable to vessels that were subsequently decommissioned. Around one quarter of TR1 and TR2, as well as 13% of GN1 effort, was removed at that time, and these decommissioning reductions should be taken into account when considering changes in effort patterns.

For the west of Scotland during 2009, codend mesh sizes >120mm were prohibited east of a Division VIa management line (shown in Figure 4.1), unless targeting *Nephrops* under derogations detailed in EC (2009a). The TR2 gear category delivered much reduced effort in 2009, attaining only 3% of the permitted allocation by December. Most vessels utilising TR2 gear in 2008 fished with larger mesh sizes in VIa during 2009, thus transferring to the TR1 category and resulting in the increased TR1 effort. These vessels also fished outside VIa, including ICES Divisions VIIb and VIIj, and several of these Divisions showed reduced TR2 effort coupled with increased TR1 effort in 2009 (Figure 4.2).

There were a number of changes within the west of Scotland area TR1 category. Effort during the earlier months of 2009 was reduced from the levels of the two preceding years, with February being the most affected (Figure 4.3). However, effort increased later in the year. The spatial distribution was also affected, with more effort in water deeper than 200m, west of the VIa management line, and also to the east in an area typically fished by TR2 gear (Figure 4.1). In terms of the species targeted by the TR1 gear category, two dominating métiers provide useful information (Figure 4.4a): (i) mixed whitefish (pollack, saithe, cod, whiting, and dogfish; PSCWD), dominated by larger landings of saithe in 2009 (Figure 4.5), and (ii) mixed slope species (ling, witch, forkbeard, and hake; LWFH), dominated by higher hake landings in 2009 (Figure 4.5). Large effort increases were observed within these métiers, 317% and 97%, respectively. In addition, many trips were not assigned to a métier in the area, because variable trip-level species compositions yielded no clearly recurring target species patterns. For these trips in 2009, haddock landings (which previously dominated) declined, whereas landings of monkfish and megrim increased (Figure 4.5).

In 2009, TR2 effort within the Irish Sea was 35% less than in 2008 (Table 4.1), and 31% below the effort ceiling by December. *Nephrops* were the primary target, shown by the dominance of two *Nephrops* directed otter trawl métiers, "mixed *Nephrops*" and "*Nephrops*" (Figure 4.4b); the latter has lower landings of other species. Combined, these two métiers accounted for ~85% of effort in 2008 and 2009. During the final quarter of 2009, three vessels began to use sorting grids to reduce fish bycatch while targeting *Nephrops*. All trips by vessels using grids were classified within the *Nephrops* métier. There was no clear change in spatial effort distribution of these métiers over ICES rectangles, but temporally, the monthly TR2 effort level dropped during the first half of 2009, particularly between February and April (Figure 4.6). Previously, effort peaked in summer (June–August) when *Nephrops* are more easily caught. The 2009 summer peak was reduced and later than normal.

Comparisons of 2009 TR2 effort with that in 2007 and 2008 revealed changed spatial patterns. The TR2 effort in February and March 2009 declined in the Irish Sea and increased in the northern Celtic Sea (VIIg), which was also the case in June and July (Figure 4.7). Combined, those vessels expended 70–94% of their monthly effort of TR2 gear, otherwise favouring TR1 gear within Division VIIg.

TR1 effort in the Irish Sea declined over most of 2009, with just 70% uptake of the 79,246kW effort ceiling by December. Despite this decline, there was little evidence of a change in the monthly effort pattern, or the spatial distribution compared with previous years. A number of different métiers operate within the Irish Sea TR1 category, some targeting whitefish (PSCWD), rays, and flatfish, and some Scottish seining for whiting and haddock. Although little change was observed in the spatial or temporal distributions within the Irish Sea, records for 2009 show that these TR1 vessels spent more time in additional, alternative areas within the same fishing trip.

The uptake of gillnet (GN1) effort was the highest of the regulated gears in 2009, 80% of the 24,713kW ceiling by December. Within the Irish Sea, GN1 effort would primarily be deployed in the first quarter, often targeting cod, but it was much reduced in 2009. The effort in February was the lowest in recent years (Figure 4.8a), 88% less than in 2008. The fishery tends to take place across the VIIa/VIIg border, close to the southeast coast of Ireland. Effort within VIIg during February was also relatively low and hence unlikely to have been fished as an alternative. The distribution of GN1 effort remained similar to earlier years, primarily within ICES rectangles 33E2 (decreased in 2009) and 33E3 (increased in 2009). The distribution within VIIg also remained consistent, though with increased effort in 32E2.

There was a large change in the métiers making up the GN1 category in 2009. From 2006 to 2008, the primary gillnet métier targeted cod, delivering 89% of the total effort in 2008 (Figure 4.4c), but the level declined dramatically in 2009, to 34%. There was a substantial effort increase (~35%) in the relatively small métier targeting hake and forkbeard, which is not based within the Irish Sea, but operates in multiple ICES Divisions within a fishing trip. The large increase in the effort allocated to this métier signifies the movement of vessels from the Irish Sea into the Celtic Sea and its surrounding waters.

Beam trawling with ≥80mm and <120mm mesh (BT2) saw very modest (32%) uptake of the 507,923kW allowance by December. Substantial effort was removed through vessel decommissioning by the end of 2008 (66%). Indeed, the fleet has been subject to a number of decommissioning schemes in the 5 years prior to 2008. In most months, therefore, effort was less than in previous years, as would be expected from a substantially reduced fleet. There is little consistency in the monthly effort levels between years for this gear category, although there seems to be a greater reduction in the first quarter (Figure 4.8b). Effort distribution did not change from that in 2008, continuing within the central Irish Sea, and there was no change in métier composition, still dominated by ray and flatfish target species.

Discussion

There were notable behavioural changes in the Irish demersal fleet during 2009 within the west of Scotland and Irish Sea fisheries. The changes result directly from implementation of several management and technical measures, mainly associated with the CLTP (EC, 2008a).

Fishery managers do not manage the resource, but rather the fishers who target the resource. In single species TAC management, it is the fishers who decide how long and where to fish, given the bounds of quotas. This is not the case in effort management schemes, however. In the previous days-at-sea system, the EU made these decisions by placing an upper limit on vessel activities. Within the revised scheme, although the EU sets the effort allocation, the Member State decides how much time individual fishers may spend in controlled areas. The involvement of stakeholders within the national management process is a step towards co-management, where those directly influenced by management have an integral role in deciding how the fisheries they depend on can become sustainable. Stakeholder knowledge and the benefits of their involvement have long been topics for discussion (Jentoft & McCay, 1995; Johannes *et al.*, 2000; Rossiter & Stead, 2003), and such stakeholders are slowly being incorporated, unlocking and utilizing their knowledge. Fixed parameters within the regulation, such as the effort-control rule, mean that industry engagement has focused on the objective of reducing cod mortality, thus developing an effective effort management framework. Industry stakeholders have been the main drivers in trialling separator grids and panels and in investigating area closures that can reduce cod mortality. In Australia, the Fisheries Research and Development Corporation examined co-management in relation to their fisheries (Anon, 2008) stating that "the co-management implementation process is a lengthy one, since it is ultimately about building mutual trust and responsibility based on performance and risk management". The small step in Ireland towards co-management recorded here has been a move in this direction. Although the process of agreeing the measures to be taken has lengthened, it has opened the channels of communication between managers and other stakeholders and has increased cooperation and support by industry, something that tends to be lacking in many regulatory schemes.

The overall rate of effort uptake throughout 2009 was low, and by the end of the year, Irish effort ceilings had not been reached. During the first pilot scheme (1 February–30 April 2009), the usage of regulated gears in the Irish Sea and west of Scotland was less than in the same period of earlier years, revealing some disruption to normal fishing behaviour. The first month of the new regulation (February) was the most affected, with the effort, in some cases, less than half of previous levels. Throughout this period, fishers were clearly feeling the effects of the uncertainty, and were conserving effort allocations for times when fishing returns were expected to be better. Later in the year, however, the pilot schemes became less conservative, because of the low uptake during the earlier part of the year, and effort usage increased.

Many factors can influence effort uptake. In the case of the beam trawl fleet, a decommissioning scheme removed vessels that accounted for around two-thirds of the effort in 2008. Consequently, that category delivered the lowest uptake (32%), and individual allocations caused little restriction on the remaining vessels because an excess of effort was available to them. The BT2 category, however, contributes only a small proportion of Irish cod landings.

Unlike beam trawling, the subdivision of effort within other gear categories resulted in many vessels being restricted by their allocations, e.g. Irish Sea gillnetting early in 2009. The Irish Sea *Nephrops* fleet, which is the main TR2 activity, was particularly hard-hit by the restrictive allocations, in contrast to the previous cod recovery plan (EC, 2004), managed through days-at-sea, where the rules for equivalent vessels were not perceived to be restrictive (STECF, 2009). Following gear trials, a few *Nephrops* vessels within the Irish Sea TR2 category began using separator panels (~15) and sorting grids (~4) in the fourth quarter, to increase their individual effort allocations. These technical measures are similar to Swedish grids which have been shown to reduce the fish component of catches (Valentinsson & Ulmestrand, 2008; Drewery *et al.*, 2010). During the Irish trials, fish catches, including cod, dropped by ~85%, and most of the *Nephrops* were retained (D. Rihan, pers. comm.). Adoption of such technical measures was therefore considered to be a very effective means of cod avoidance. However, the few vessels participating in 2009 were unlikely to have had a measurable impact on the cod stock or the overall catch composition of the TR2 category. The uptake of the modified gear by fishers is a business decision taken at an individual vessel level; the loss of revenue (~30% in the Irish case) through reduced commercial fish and *Nephrops* landings needs to be balanced against the restrictiveness of the effort allocation and/or fishing opportunities elsewhere.

The Irish Sea *Nephrops* fishery usually follows the seasonal behaviour of *Nephrops*, increasing effort when the catchability is at its highest, during neap tides in summer. In earlier years, there was a minor peak in effort around March, and the main fishing period ran from June to August. In 2009, the main seasonal peak was delayed to August/September, and the drop in effort earlier that year likely resulted from fishers "saving" their effort allocation for later, when they expected better catchability of *Nephrops*. Changes in fishing patterns can have marked economic consequences. Irish *Nephrops* landings declined by around 800t (~25%) in 2009 compared with levels of the previous two years. The effort reduction within the Irish Sea by the main TR2 category would have reduced fishing pressure on a wide variety of stocks, not just cod. Effort restrictions within a mixed species fishery limit fishing mortality not only on the species in need of recovery, but on all other species caught with the same gear (targeted catch, bycatch, and discards), likely benefitting other stocks. A similar suggestion has been advanced by Andersen & Rice (2010) in relation to community effects of rebuilding plans.

Some TR2 effort normally expended in the Irish Sea was displaced to other *Nephrops* fisheries, including those in ICES Division VIIg. The displacement of effort to areas beyond those regulated by the CLTP could have a negative impact on other stocks through increased fishing pressure, but in VIIg during 2009 the overall annual effort also dropped as a result of the decommissioning. Moreover, the seasonal distribution of effort changed in VIIg, burgeoning during the first half of the year, resulting in a different exploitation pattern from that traditionally observed.

Some reduction in the Irish Sea TR2 effort can be explained by the 2008 decommissioning scheme; this included TR2 vessels accounting for ~25% of the 2008 effort. However, decommissioning is unlikely to explain the changes recorded here in terms of monthly effort patterns. Furthermore, the behavioural changes are not attributable to reduced availability of the targeted *Nephrops*, because there was little change in the status of that stock in 2009 (ICES, 2010b).

The decline in the west of Scotland TR2 activity in 2009 resulted in just 3% of the effort ceiling being used. This stems from the technical measures implemented in 2009 preventing the use of TR2 mesh sizes unless targeting *Nephrops* (EC, 2009a). Mixed demersal fish, rather than *Nephrops*, had previously been the prime target of Irish vessels in the area. Effort displacement into surrounding areas was not evident, however, because the TR2 effort by vessels previously active in VIa declined in both adjoining areas (VIIb and VIIa); instead, those vessels switched to a larger mesh size (TR1) operating in VIa and elsewhere.

In contrast to other categories, the total TR1 effort in VIa increased in 2009 by ~25%. This would have caused the original ceiling to be exceeded by >60%, but the transfer of effort from the largely unused TR2 category to TR1 (EC, 2008a) allowed the effort to remain below the adjusted ceiling (72% of the limit). The additional TR1 effort was distributed in two main areas: the original TR2 grounds on the Stanton Bank and west of the VIa management line. In 2009, 45% of the Irish TR1 and TR2 fishing effort was west of that line, promoting cod avoidance by fishing at depths >200m. Although catches of large cod can be made at those depths, indeed up to ~400m, the landings declared in 2009 were small. This does, however, increase the fishing pressure on slope species, particularly monkfish and megrim, which both yielded increased landings.

The effort ceiling for gillnetting within the Irish Sea is relatively low, and the individual allocations were particularly conservative in February, when the core fishery targets cod. The fishery is mostly close to the VIIa/VIIg boundary, depending on the spatial distribution of Celtic Sea cod in the spawning season. Gillnet landings of cod from VIIa were much lower in 2009, but that was not the case in the adjacent VIIg. Therefore, a reduction of cod fishing mortality in the Celtic Sea may have transpired as an unintended impact, rather than being the intended mortality reduction of the overall Irish Sea stock.

Fishing is a dynamic industry in which economic, biological, and management changes induce tactical and strategic decisions and are reflected by modified fishing behaviour. The Irish demersal fleet is no exception. When individual effort allocations were restrictive, the vessels would move to alternative fishing grounds rather than tie-up, as happened in response to an area closure in the North Sea (the plaice box; Poos & Rijnsdorp, 2007). The Irish demersal fleet is highly dynamic, with individual vessels switching easily between métiers, gear configurations, and fishing grounds. Vessels with previous experience of fishing elsewhere, as seen here, are more likely to move to alternative grounds, whereas those with a previously strong area preference are more likely to stop fishing (Poos & Rijnsdorp, 2007). The importance of previous experience within particular fishing grounds is also suggested by the modelling of fisher location choice (see Hutton *et al.*, 2004). The displaced Irish effort in 2009 did not lead to significant increases outside the areas regulated by the CLTP, mainly because the impacts were negated by the decommissioning scheme. In future, however, any displacement of effort could result in adverse consequences for stocks, ecosystems, and environments in areas outside those of the CLTP, such as in the Celtic Sea or on slope species beyond 200m deep west of Scotland. Similar effects have been recorded after effort was displaced from newly assigned closed and marine protected areas (Hilborn *et al.*, 2004; Suuronen *et al.*, 2010), diminishing the intended beneficial effects on stock recovery (Kelly *et al.*, 2006; Suuronen *et al.*, 2010). Increased pressure in previously low effort areas may be detrimental to surrounding ecosystems and environments (Dinmore *et al.*, 2003). The reduction of available effort and its displacement to alternative areas demonstrated by the Irish fleet could have negative impacts on alternative stocks and species.

The results of this analysis have highlighted both predictable and unforeseen consequences of restrictive management measures. In Division VIa, for example, the large shift from shelf to slope fisheries was predictable. Less predictable, however, was the switch of so many TR2 vessels to TR1 in 2009, rather than to areas outside the CLTP. The response of TR2 vessels in the Irish Sea, spending more time fishing other *Nephrops* grounds, was largely predictable, although the seasonal shift in effort pattern and the extent to which effort was reduced were not foreseen. The previous effort level in the Irish Sea TR2 category dropped by 35% relative to 2008, and was only 76% of the ceiling set. Some of this behaviour can be explained by fishers wishing to establish a track record in areas outside the CLTP, such as in the Celtic Sea, in anticipation of a future extension of effort regulations. There were also behavioural changes within individual fishing trips. More vessels fished multiple, different grounds within a trip, evidence of instability in their normal behaviour caused by restrictive effort management.

Overall, the 2009 CLTP allocation ceilings were not reached. Irish cod landings in 2009 dropped by more than 50% in the west of Scotland and by 32% in the Irish Sea from 2008 declared figures. These areas showed low discard rates on observed trips (4% and 11%, respectively; gears combined). Reduced landings, combined with few discards, are believed to have delivered Irish cod-mortality reductions better than those stipulated by the CLTP for 2009. However, Irish catches are a small proportion of the total cod catches from the Irish Sea (12% of the landings, and 6% of the removals as stated in the ICES stock assessment; ICES, 2010b). West of Scotland, the percentages are even less (2% of the landings, and 0.6% of estimated removals; ICES, 2010b). Therefore, the expected reductions in partial fishing mortality attributable to the Irish fleets will only be beneficial to the cod stock if the CLTP has resulted in similar reductions by fleets of other countries.

Effort was mainly displaced rather than reduced (although decommissioning negated this impact in 2009). Retrospective exploration of fine-scale changes of behaviour in response to management action will illustrate the effectiveness of the action, and identify potential unwanted consequences. However, the type of analysis presented here should also be conducted at an international level to understand the overall impacts better. Of course, this statement would be true for any large-scale management measures encompassing multinational fleets.

A currently expanding area of research is the prediction of complex, multifaceted fleet and fisher responses to management scenarios through simulation and modelling. Examples include random utility models (Vermard *et al.*, 2008; Andersen *et al.*, 2010), individual-based models (Bastardie *et al.*, 2010), and dynamic-state models (Poos *et al.*, 2010). These are aided by retrospective analyses of responses, which can provide valuable insight into decision-making that is not always rational or logical. Many of the current approaches simplify various aspects of the dynamics. Increasing the model complexity by incorporating more factors would also cause more uncertainty (Bence *et al.*, 2008). However, response prediction can be improved through better data collection and developing modelling techniques further, such as using Bayesian approaches, which are evolving to incorporate facets such as socio-economic and political dimensions.

Acknowledgements

We thank the Department of Agriculture, Fisheries and Food for supplying Irish logbook data and the Irish Naval Services for supplying VMS data, and Norman Graham, Dominic Rihan, and Rick Officer for their helpful input and comments. The comments and suggestions of the anonymous reviewers and editors on an early draft are also appreciated.

Figures

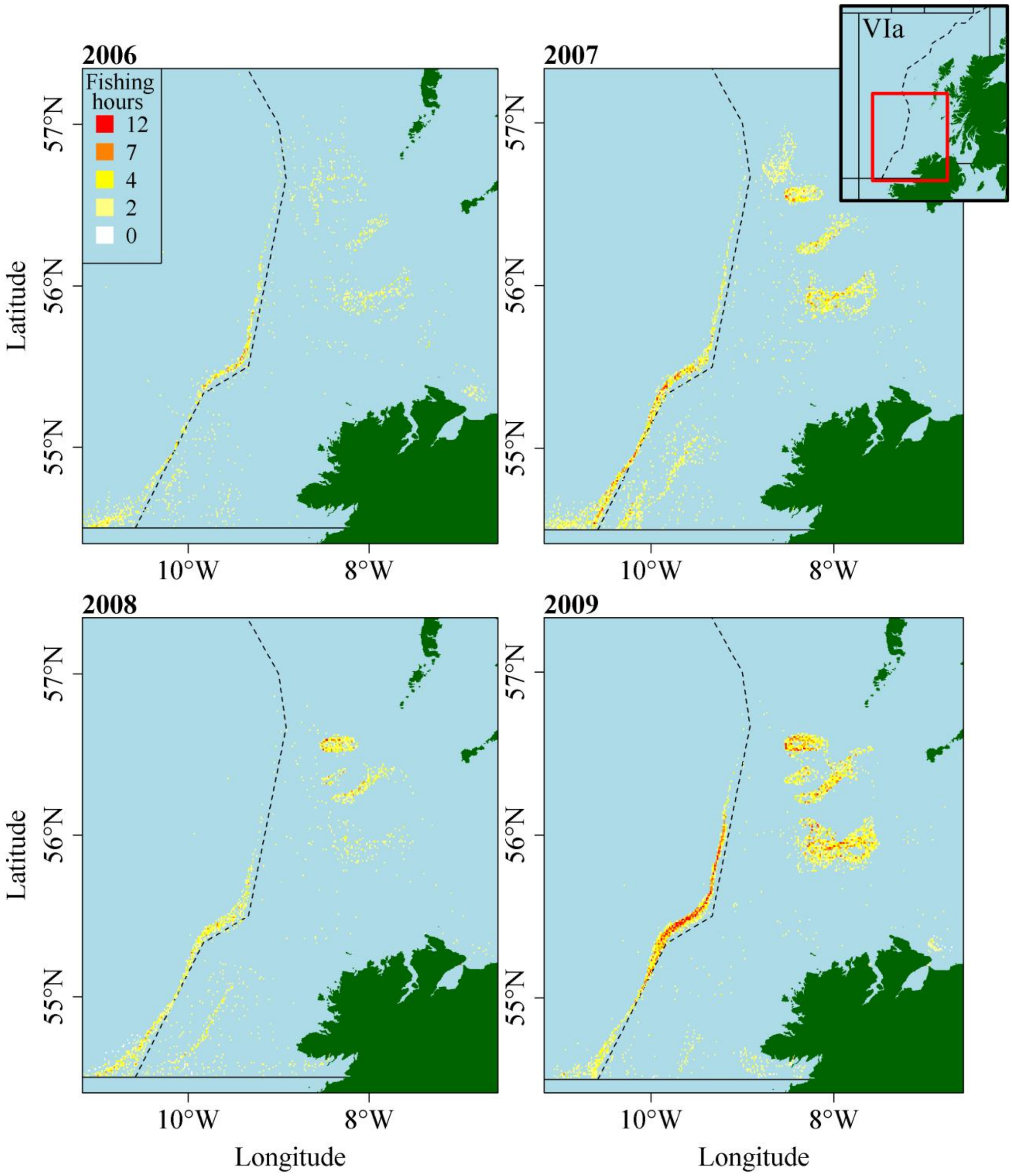

Figure 4.1. Irish VMS-based TR1 (bottom trawls, Danish seines, and similar towed gear of codend mesh size ≥100mm) fishing effort as hours per square nautical mile, 2006–2009, west of Scotland. The inset shows the plotted area within the red box in relation to the west of Scotland area (ICES Division VIa). The dashed line depicts the Division VIa management line, as detailed in EC (2009a).

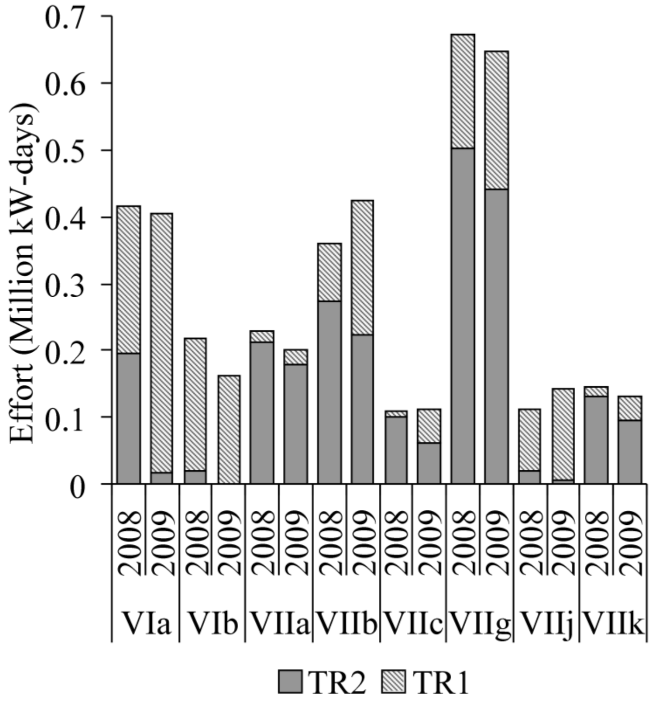

Figure 4.2. Fishing effort (kW days-at-sea) by Irish vessels fishing west of Scotland (ICES Division VIa) with TR2 gear (bottom trawls, Danish seines, and similar towed gear of codend mesh size ≥70mm and <100mm) during 2008. The comparison with 2009 shows the transfer of effort in VIa between the TR1 and TR2 gear categories.

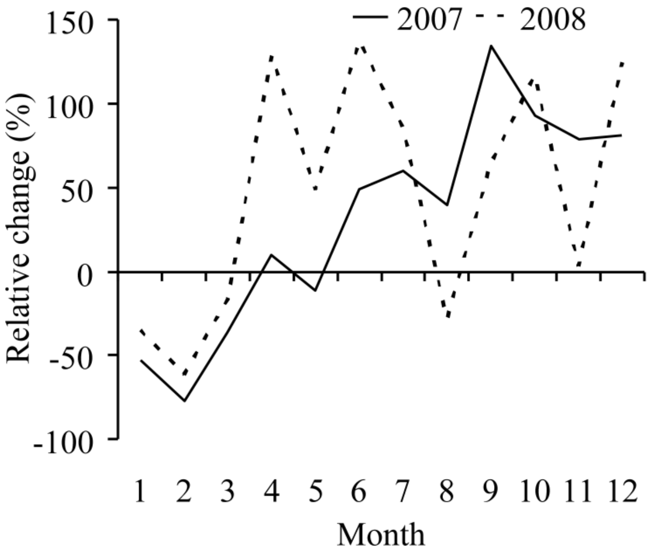

Figure 4.3. Changes in the monthly TR1 category effort (kW days-at-sea) within the west of Scotland area (ICES Division VIa) during 2009, relative to the same month in 2007 and 2008.

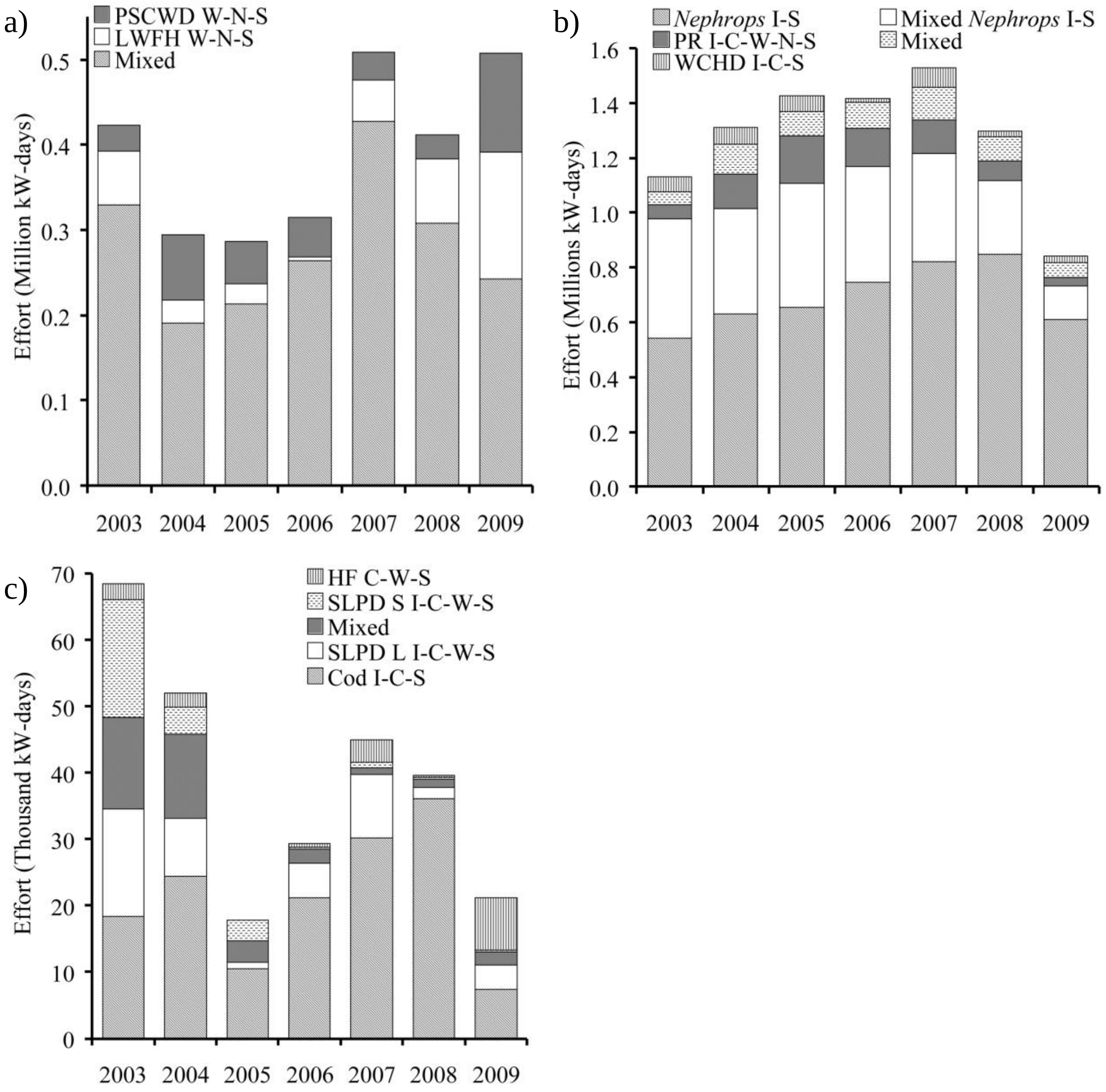

Figure 4.4. Fishing effort (kW days-at-sea) of the main métiers within the Irish fleet, 2003–2009, for the categories (a) west of Scotland TR1, (b) Irish Sea TR2, and (c) Irish Sea GN1. PSCWD refers to pollack, saithe, cod, whiting, and dogfish; LWFH to ling, witch, forkbeard, and hake; WCHD to whiting, cod, haddock, and dogfish; SLPD to saithe, ling, pollack, and dogfish; PR to rays and flatfish; and HF to hake and forkbeard. Area descriptions end in S, and those prefixed with W refer to the west of Ireland, N to the north of Ireland, I to the Irish Sea, and C to the Celtic Sea.

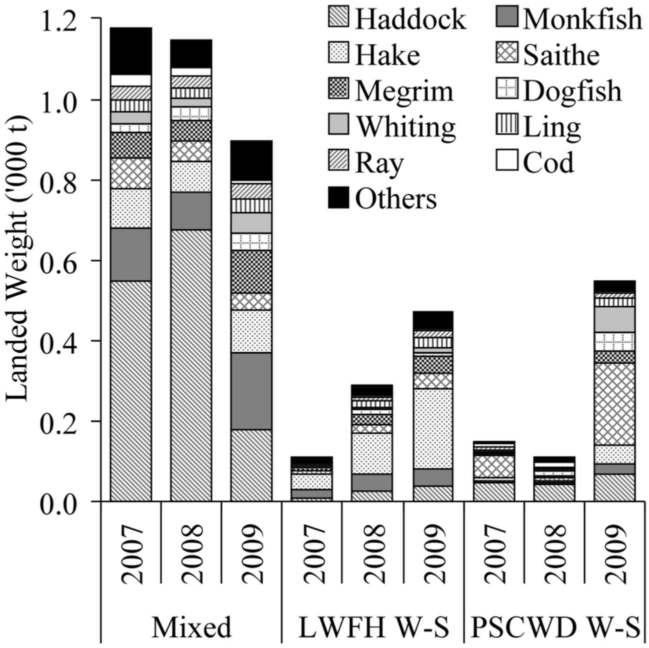

Figure 4.5. Top ten species, by live weights, in TR1 landings (thousand tonnes) for the main Irish métiers fishing in the west of Scotland area (ICES Division VIa), 2007–2009. The remaining species landed are grouped as others. LWFH refers to ling, witch, forkbeard, and hake; PSCWD to pollack, saithe, cod, whiting, and dogfish; and W-S to waters west of Ireland.

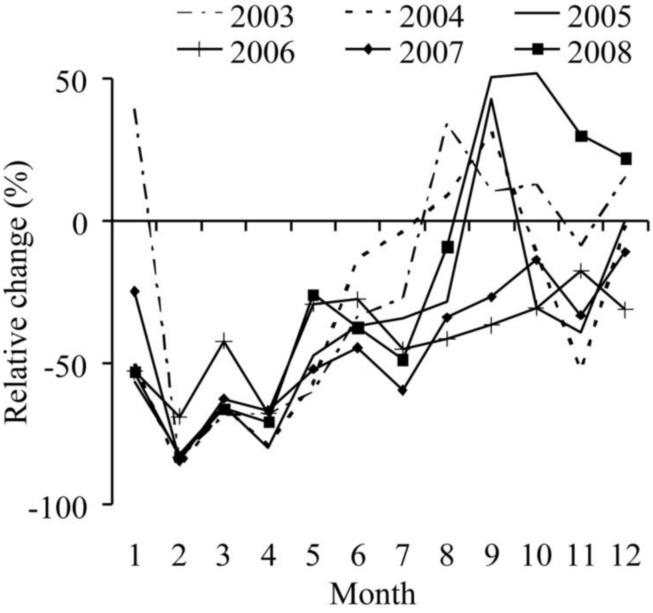

Figure 4.6. Monthly fishing effort in the Irish Sea (ICES Division VIIa) effort by the Irish TR2 fleet (kW days-at-sea) during 2009 relative to 2003–2008.

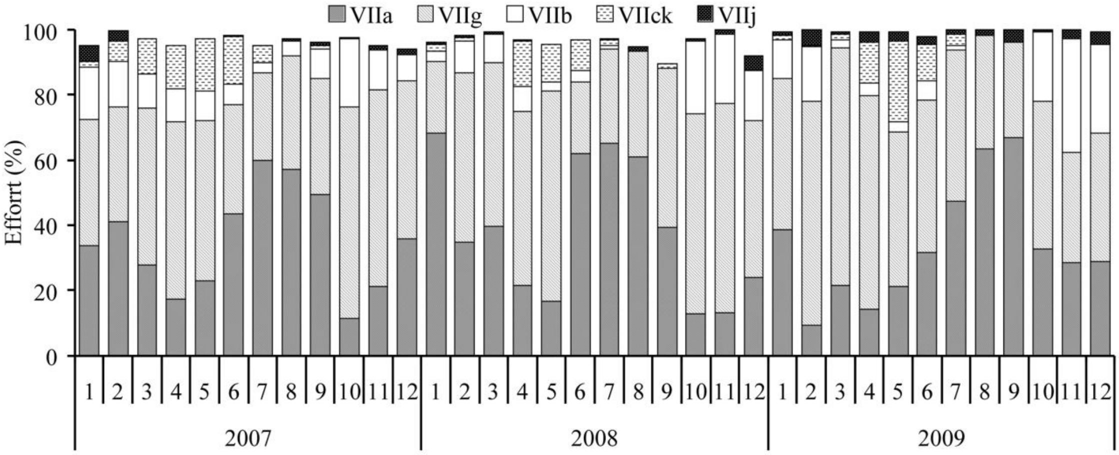

Figure 4.7. Monthly percentage distribution of the TR2-category effort by area, 2007–2009, deployed by Irish TR2 vessels operating within the Irish Sea (ICES Division VIIa).

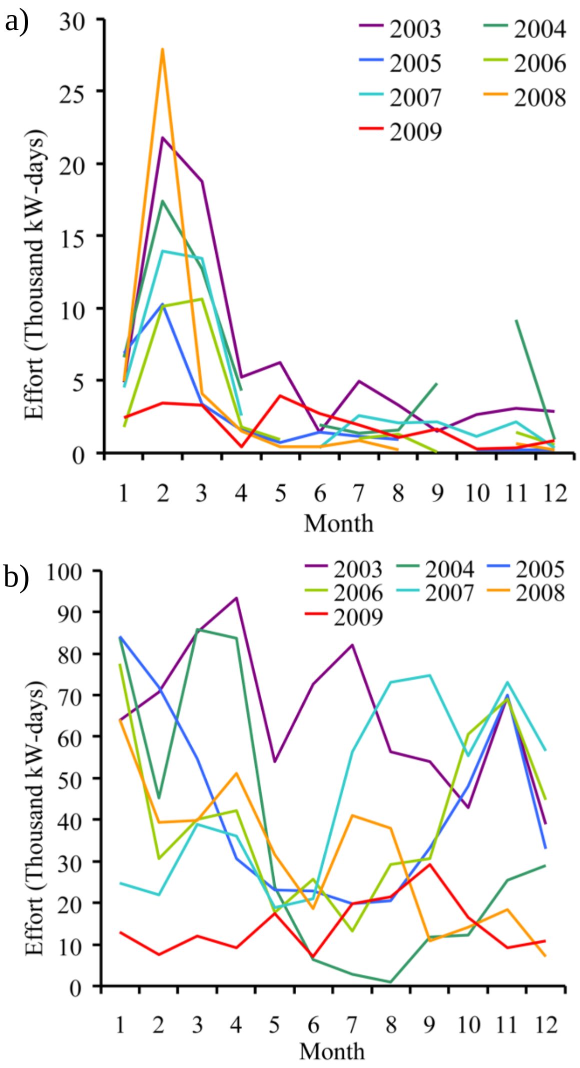

Figure 4.8. Irish Sea (ICES Division VIIa) monthly kW days-at-sea effort by the Irish fleet, 2003–2009 for (a) GN1 and (b) BT2 gear categories.

Tables

Table 4.1. The west of Scotland (VIa) and Irish Sea (VIIa) kW days-at-sea for the CLTP gear categories effort groups, as defined in the text; Council Regulation No.1342/2008, 2003–2009, with details of 2009 effort ceilings allocated to Ireland (EC, 2009a), uptake from January to December 2009 (%), and the 2008 effort by subsequently decommissioned vessels (removed; %).

Area	Effort Group	2003	2004	2005	2006	2007	2008	2009	Effort Ceiling (kW)	Uptake (%)	Removed (%)
West of Scotland	TR1	496 438	316 478	308 680	323 880	530 291	435 213	549 302	310 005	163%	0%
	TR2	1 039 254	967 586	767 637	712 743	384 398	196 959	17 989	481 938	3%	0.2 %
	TR3	2 198		342	160	317	11 321	1 323	21 327	0%	0%
	BT1									NA	0%
	BT2		28 827	5 068	6 335				3 914	0%	0%
	GN1	19 967	20 763	192	3 554	13 348	9 949	3 276	6 400	44%	0%
	GT1			5 410	449				1 946	0%	0%
	LL1	7 200	18 400	3 000		9 750			1 013	0%	0%
	Total	1 565 057	1 352 054	1 090 329	1 047 121	938 104	653 442	571 890	826 543	63%	
Irish Sea	TR1	358 717	134 382	87 264	84 551	140 395	73 005	60 348	79 246	70%	23%
	TR2	1 194 559	1 345 089	1 464 650	1 458 922	1 582 409	1 311 141	853 165	1 120 977	69%	28%
	TR3	900	90	3 305	960		436		9 646	0%	0%
	BT1									NA	0%
	BT2	783 381	411 353	511 814	481 404	550 534	374 493	173 927	507 923	32%	66%
	GN1	76 613	60 551	26 671	29 533	45 084	40 958	22 213	24 713	80%	13%
	GT1						1 327	1 237			0%
	LL1		800				149		62	0%	0%
	Total	2 946 207	2 775 422	2 503 899	2 401 100	2 754 585	2 196 165	1 533 442	1 742 567	58%	

Chapter V: Modelling fuel consumption of fishing vessels for predictive use

Submitted for publication:

Davie, S., Minto, C., Officer, R., Lordan, C., and Jackson, E. *In review*. Modelling fuel consumption of fishing vessels for predictive use. ICES Journal of Marine Science.

Abstract

Fuel costs are an important element of the models used to analyse and predict fisher behaviour for application within the wider mixed fisheries and ecosystem approaches to management. This investigation explored the predictive capability of linear and generalised additive models in providing daily fuel consumption estimates for fishing vessels given knowledge of their length, engine power and fleet segment (annual dominant gear type). Models were fitted to Irish fishing vessel data collected between 2003 and 2010. The predictive capabilities of the five best models were validated against previously un-modelled 2011 data.

The type of gear used by a fleet segment had an important influence on fuel consumption. Passive gear segments indicated consistently lower consumptions, while pelagic gears showed consistently higher fuel consumptions, above those of both dredges and beam trawls traditionally considered to be heavy fuel consumers.

Of the formulated models, the best fit to test data was a generalized additive model (GAM) with by-gear type smooth functions of standardized vessel length and engine power. All five models demonstrated good predictive capability for the best sampled segments (demersal and pelagic trawlers). A simpler GAM without gear effects on smoothed terms showed on average the closest predictions with the least bias. Fuel consumption for the dredger fleet segment was not well predicted by any model investigated.

Key words

Fuel consumption; fuel price; fuel cost predictions; fishing vessels; modelling; GAM; fishing gear

Introduction

Fishing, like any other business, aims to generate profits through achieving greater revenues than costs. Individual fishers hold a detailed understanding of the factors influencing their business, such as fishing location, gear configuration, and fuel costs. Scientists do not have such detailed information and must reconstruct or predict this knowledge from the information available.

Fuel represents one of the largest costs associated with individual fishing trips, while the actual proportion attributable to fuel varies greatly between fisheries (Sumaila *et al.*, 2008): within Hong Kong's commercial fisheries fuel amounts between 30% and 60% of total costs (Sumaila *et al.*, 2007), South East Australian trawlers report fuel costs of between 18% and 25% while the proportions were lower (5%-10%) for Danish seiners (FERM, 2004). Variation in fuel costs have also been reported between European fisheries: Irish demersal trawlers have ranged from 15% to 38% of total costs over recent years, varying both annually and with vessel length (unpublished data); Cheilari *et al.* (2013) state average fuel costs represented 29% of total costs in 2008 across 54 fleet segments; Bastardie *et al.* (2013) detail variation in the fuel costs of Danish fisheries between 2005 and 2010.

Since the Arab oil embargo of 1973 (Yergin, 1991), fuel "supply scares" have resulted in rapid fluctuations in fuel prices. The most recent event occurred between early 2007 and mid 2008 when fuel doubled in price. Such scares have prompted analyses of the energetic performance and economic vulnerability of a wide range of fisheries (see Tyedmers, 2001 and Tyedmers *et al.*, 2005 for examples). The most recent price fluctuation stimulated further investigations into fuel use within the fishing sector. From an economic perspective, Cheilari *et al.* (2013) evaluated the economic performance and energy efficiency of the EU fleet. Abernethy *et al.* (2010) examined the impact of fuel price on the structure, behaviour and vulnerability of the UK's southwest fishing fleet. Others have considered increased fuel prices from a more biological perspective. For example, Arnason (2007) conceptualises excessive fishing pressure could be reduced as a result of lower profitability (from higher fuel costs) further hypothesising that such reductions in pressure could aid fish stock recovery. However, Arnason highlights that this can be negated if governments increase fuel subsidies, such as the 38 cent per litre rebate described in Australian trawl fisheries by Chenhall and Magnet (2008). The points made by Arnason (2007) are further supported by Sumaila *et al.* (2008) who believe that positive reductions in fishing pressure due to increased fuel prices are reduced, if not completely negated by increasing fuel subsidies. Such variability illustrates the importance of fuel costs as a driver of fisher behaviour and choices.

The fuel consumption of a fishing vessel varies depending on a variety of factors and conditions, for example vessel size, age, and condition, engine power, vessel speed and gear configuration, sea state and weather conditions (Driscoll & Tyedmers, 2010; Schau *et al.*, 2009; Tyedmers, 2001).

Previous investigations have also examined fuel consumption associated with fleets, fisheries, gears and specific species or stocks over time. Schau *et al.* (2009) developed fuel-use coefficients expressed as a value of fish per volume of fuel used. Tyedmers (2001) related the results of fish per fuel volume of various studies to their equivalents in terms of obtainable energy. This conversion into values of protein energy yield (Joules) and output (tonnes) allowed respective comparison between fisheries, and other protein producing sectors such as agriculture. While other studies generate fish per fuel volume values and convert these into their equivalent greenhouse gas emissions (e.g. CO_2 weight per volume of fuel) to address the implications of such emissions (e.g. Driscoll & Tyedmers, 2010).

Bio-economic models that examine the choices and responses of fishers to management impositions within mixed fisheries should include fuel as an important explanatory variable. Many such analyses utilise increasingly complex models to analyse and predict fisher behaviour. The importance of financial drivers to the decision making processes in fisheries is increasingly acknowledged and incorporated (Andersen *et al.*, 2010; Gourguet *et al.*, 2013; Marchal *et al.*, 2011; Ulrich *et al.*, 2007). However, these analyses often do not relate specifically to fuel consumption, but rather incorporate measures of fuel usage (e.g. total expenditure or price per quantity) as proxies for fishing cost. Disaggregating estimates of input variables within fishery simulations, e.g., by vessel length and engine size, should lead to increased model accuracy and enhanced predictive capabilities.

This investigation utilised annual Irish fuel cost data to estimate linear and generalized additive models that describe, and subsequently predict fuel consumption per day for different fleet segments (gears) by vessel length and engine power combinations. Model outputs were designed for subsequent use in decision support tools to inform the development of mixed fisheries management plans by enumerating potential economic consequences and behavioural adaptations in response to management measures.

Materials and Methods

Data

Europe’s implementation of fisheries Data Collection Regulations (DCF; EC, 2001) and Member State’s subsequent commitment to the Data Collection Framework (EC, 2008e) has increased the quantity and quality of economic data collected from the fishing sector. Individual Member States are required to collect a variety of detailed economic variables from a sample of the fleet considered representative of the overall fishing sector. More general economic data, such as total fuel costs and fuel consumption are also collected.

Economic data on fishing vessels within Ireland are collected by Bord Iascaigh Mhara (BIM) as part of Ireland’s commitment to the Data Collection Framework (DCF). Information collected includes annual income and expenditure figures, including annual fuel cost, from a sample of individual vessels. Questionnaires are sent to all ≥10m active vessels on an annual basis. Sampled vessels constitute those who completed and returned the questionnaire. These data were used in conjunction with the annual number of days-at-sea associated with the vessel (as the number of days absent from port) available from logbook entries, provided by the Department of Agriculture, Food, and the Marine to calculate an average fuel cost per day for ≥10m vessels sampled between 2003 and 2011.

The annual estimate of fuel cost (in Euro) per vessel was divided by the vessel's effort (measured as days-at-sea) within the same year. This resulted in a fuel consumption cost per day-at-sea regardless of vessel activity (steaming or fishing). Within this investigation it was necessary to assume the same fuel consumption rates for fishing days and steaming days. Unfortunately separate, detailed information on fuel consumption rates for steaming and fishing were not discernable for this investigation. It was not possible to accurately determine how much time vessels spent on either activity, nor how to derive this from the aggregated values of total annual fuel cost. Whilst not ideal, this assumption enabled analysis. Furthermore, the final intended use is to provide fuel consumption over complete trips, accounting for all fuel usage within a fishing trip. The segregation between fleet segments may help to reduce some of the variability in travelling distances between trips which occur for example between those employing pots, demersal trawl gear, or pelagic gears.

The resulting dataset contained 637 anonymous records including vessel length (rounded down to the nearest 0.5m), engine power (rounded down to the nearest 5kW), vessel annual fleet segment (Table 5.A1; defined using DCF dominance criteria[7]; hereafter referred to as gear), fuel cost per day-at-sea (Euro), and a fuel per day-at-sea (litres) value (here after referred to as fuel per day) derived from per day fuel cost divided by the average overall annual fuel price per litre provided by BIM (Table 5.A2). Average fuel price per litre was not available for 2003, and was assumed to be the same as in 2004. Data from years 2003 to 2010 were used for model fitting. Samples for 2011 (most recent year available) were reserved for testing the predictive capabilities of the fitted models.

Three samples with unrealistic, extreme per day fuel costs were removed (euro per day: 0.00, 0.32 and 49,000). Furthermore, the two polyvalent gears classifications PGO and PMP, contributing 1 and 2 samples respectively were removed from the final models. Exploratory modelling had resulted in high by-gear leverage for these samples due to the small sample sizes.

Analysis

Methods of data visualization are described first followed by a description of linear and additive models fit to the 2003-2010 fuel per day data. Finally, the predictions of the best fitting set of linear and additive models are compared with un-modelled 2011 fuel

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[7] A vessel is allocated a gear annually based on the gear with the highest number of fishing days within the year (i.e. over 50% of fishing days), if no gear dominates the vessel is allocated to one of 3 polyvalent segments (all mobile gears, all passive gears, mixed mobile and passive gears), from http://datacollection.jrc.ec.europa.eu/dcf-fish/eco/dsgr visited 12/03/2013

per day data to test predictive capability. All analyses were carried out within the R statistical environment version 2.15.2 (R core development team, 2012) and included use of the following specific functions and packages: dredge (MuMIn; Barton, 2013), gam (mgcv; Wood, 2006), and normalmixEM (mixtools; Benaglia *et al.*, 2009).

Data visualisation

Fuel per day values of sampled vessels 2003-2010 were visualised by gear for vessel length and engine power (Figure 5.1a and b, supplementary material depicts gears separately) to examine relationships between fuel usage and vessel characteristics. A clear relationship is observed between vessel length and engine power when plotted by gear (Figure 5.1c, depicted separately in supplementary material), highlighting a correlation which should be considered within the modelling process.

Fuel per day plots (Appendix A and B on pages II and III) by vessel length and engine power indicated power-curve relationships between fuel per day and vessel characteristics, with increasing variability with mean response in a log-normal fashion. These suggest that a log-linear model with normally distributed errors on the log scale may be appropriate. This relationship will down weigh the influence of more extreme samples which appear as outliers.

Modelling

Log-linear models

Sample data from 2003-2010 were used to develop a set of candidate models for predicting per day fuel consumption based on vessel length and engine power characteristics for different gear types. Based on the log-linear relationship identified during data visualisation the continuous variables of fuel per day, vessel length, and engine power were converted to natural logarithmic values.

Preliminary linear model fits using only the categorical explanatory variable "year" accounted for a small but significant amount of the variability of the response as indicated by a slight reduction in AIC values (Akaike, 1974) (AIC without year: 1778, with year: 1172). However, the inclusion of year to models incorporating engine power or vessel length actually resulted in increased AIC values (by 5.8 and 8.8 respectively). To further test the apparent negligible importance of year, it was included within the full linear model tests. No improvement in AIC value was obtained for the additional model complexity of its inclusion. As such, year was not considered to be an important variable and removed from the modelling process. This is intuitive given vessels are unlikely to alter annually in length or in engine power beyond minor alterations in efficiency, however some engines may deteriorate over time due to age and condition this did not appear to occur between the available samples. The following initial log-linear model of fuel per day by length, power and gear was applied:

$$\log(F_i) = a_{0,G[i]} + a_1 \log(L_i) + a_2 \log(E_i) + a_3 \log(L_i)\log(E_i) + \varepsilon_i \qquad (1)$$

Where F_i is fuel per day, L_i is vessel length, E_i is engine power, G is gear (categorical variable with 10 levels: Table 5.A1), and i is the ith observation (i.e., average fuel per day for a given year and vessel). A high level of correlation was identified between the variables vessel length and engine power (0.71; Figure 5.1), which was reflected in high correlation of the parameter estimates. The variables were standardized by subtracting the mean and dividing by the standard deviation. This decreased the magnitude of most correlations although resulted in a greater direct negative correlation of the parameters. The model was expanded to include the full 3-way interaction (excluding PGO and PMP gear types due to high leverage), described as:

$$\log(F_i) = a_{0,G[i]} + a_{1,G[i]} \log(SL_i) + a_{2,G[i]} \log(SE_i) + a_{3,G[i]} \log(SL_i)\log(SE_i) + \varepsilon_i \qquad (2)$$

Where SL_i and SE_i are the standardised vessel length and engine power, respectively. Within this model there were 19 possible sub-model combinations for the three variables. These preliminary models are listed in Table 5.A3. However, examination of the relationship between the predicted and observed fuel consumption values (Figure 5.2) suggest data do not conform to a strict linear relationship.

Generalized additive models

To investigate linearity assumptions, a Generalized Additive Model (GAM) (Hastie & Tibshirani, 1986, 1990; Wood, 2006) with integrated smoothness estimation was fitted (Model 3), modelled as:

$$\log(F_i) = a_{0,G[i]} + s_1(\log(SL_i)) + s_2(\log(SE_i)) + \varepsilon_i \qquad (3)$$

Where s_1 and s_2 are smoother functions (thin plate regression splines). Examination of the fitted GAM k-index (basis dimension of the smoother) indicated that although the GAM model provided a good fit for the data (low AIC value), residual patterns were present. This indicated that not all patterns within the data were accounted for by the covariates using low basis dimension smoothing. This could be remedied by increasing the space over which the smoothers could operate (increasing k value to 100) however it was considered more appropriate to specifically account for the course of the pattern.

A GAM was applied accounting for interaction between vessel length and engine power (Model 4):

$$\log(F_i) = a_{0,G[i]} + s_1(\log(SL_i), \log(SE_i)) + \varepsilon_i \qquad (4)$$

Where s_1 here is a 2-dimensional surface thin-plate spline (Wood, 2006). Although this model generated a lower AIC value, it was considered to be over fitted to the specific data being modelled, and thus may have reduced predictive capability (see: Model Application section below). Surface plots were used to visually compare the two GAM model fits (Figure 5.3).

The final fit trials included gear as part of the smoothing function of the GAM. This was trialled for both GAM models, the 2 smoother model (Model 5: Equation 5) and single 2-d smoother model (Model 6: Equation 6):

$$\log(F_i) = a_{0,G[i]} + s_{1,G[i]}(\log(SL_i)) + s_{2,G[i]}(\log(SE_i)) + \varepsilon_i \qquad (5)$$

$$\log(F_i) = a_{0,G[i]} + s_{1,G[i]}(\log(SL_i), \log(SE_i)) + \varepsilon_i \qquad (6)$$

To enable the single 2-d smoother version to run successfully, the space over which the smoother operated was reduced (k=10) from that applied in Model 4 (k=100) to prevent over parameterisation.

Model testing

To test the ability of formulated models to predict fuel consumption the vessel lengths, engine powers and gears were taken from the 49 fuel per day samples obtained in 2011. Not all the gear types modelled were contained within the 2011 dataset. Samples were available for DFN, DRB, DTS, FPO, and TM gears. Only one sample for SSC was available and was excluded to ensure confidentiality. Predictions were made using 5 models; the best fitting linear model and the 4 GAM models. Vessel length and engine power of the 2011 samples were logged and standardised using the mean and standard deviation values obtained during standardisation of the 2003-2010 dataset to which the models were fitted. Proportional errors as (predicted value - true value)/true value and mean absolute proportional errors (MAPE) were calculated to compare the predictive capability of the five chosen models.

Results

Modelling

GAM models achieved lower AIC values than the series of linear models (Table 5.A3). Of the GAMs, those incorporating gear within the smoother function (Models 5 and 6) achieved lower AIC values than Models 3 and 4 (Table 5.1). However, the by gear single 2-d smoother version (Model 6) did not perform as well as Model 5, which would suggest Model 6 is over parameterised.

GAM Model 5 showed the best fit to the test fuel consumption data. This model has two smoother functions incorporating gear; over vessel length and over engine power. Details of the coefficients and smoother terms are given in Tables 5.2 and 5.3 respectively. The diagnostic plots for this model (Figure 5.4) indicate that the residuals do not strictly conform to the normal distribution. This was investigated post-hoc by applying a scale finite mixture model (McLachlan & Peel, 2000) to the residuals. The mixture model indicated that two distributions were present within the residuals: 90% of which were normally distributed with a small variance, with the remaining 10% constituting a more dispersed distribution (Figure 5.5).

Model testing

Proportional errors ((predicted-true)/true) for the five tested models (the best fitting linear model and the 4 GAM models) are visualised in Figure 5.6 and average proportional errors in Table 5.4. Demersal (DTS) and pelagic (TM) trawl gears were the best sampled gears throughout the modelling and prediction period. This is reflected in the closeness of fuel predictions given by MAPE values of ~0.45-0.53 for DTS and ~0.5-0.55 for TM (Table 5.4). This is combined with low levels of bias for each of the models when predicting fuel consumption for these two fleet segments (Figure 5.6). There is greater variability between models for the remaining gears. Dredges (DRB) show the widest range and the poorest predicted fuel usages (Table 5.4, Figure 5.6). Model 6 grossly overestimates fuel consumption for the dredging sector. The GAMs incorporating a single 2-d smoother show no better capability, if not reduced capability to predict fuel consumption than the simpler GAM and linear models for the less sampled gears (Table 5.4). The tested models have similar performances in relation to average proportional errors. Models 1 and 3 perform best, although only slightly better than Model 4. Each exhibited comparatively small proportional error ranges and means close to zero. Those GAM models including gear as an interaction are poor predictors of DRB gear fuel usage. In the majority of cases the MAPEs are positive indicating an overestimation of fuel consumption.

Discussion

Model

A general additive model incorporating gear within the smoother terms for both length and engine power was found to be the best descriptor of fuel consumption (Model 5) out of the alternatives applied and tested here. The model implies a more complex relationship than a simple scaling of fuel consumption between gear and the vessel characteristics. Variation in fuel consumption between gear and fishing practice were also observed in other studies (Schau *et al.*, 2009; Tyedmers *et al.*, 2005; Winther *et al.*, 2009). Our model indicates that vessels employing passive gears such as pots and gillnets require less fuel than those deploying mobile gears (Table 5.2). This is consistent with those studies reviewed by Tyedmers (2001), and more recently by Abernethy *et al.* (2010), who identified higher fuel consumption with towed gears and larger vessels. Bastardie *et al.* (2013) found that seiners out-competed trawlers when targeting the same species. This is understandable given that while towing gear ~95% of fuel is used to tow the gear with the remainder propelling the vessel (BIM, 2009). This penalty is not incurred by vessels setting passive gears into the water and leaving them for a period of time. Longlining is an exception within the passive gear group. In the current analysis longlining was shown to have higher fuel consumption than other passive type gears. Tyedmers (2001) also found longlines to have a higher fuel consumption (given as litres per HP*sea day) than other gear types, including a combined trawl and dredge group. In relation to Irish longlining, increased fuel consumption in comparison to other passive gears may relate to the typically more offshore fishing grounds exploited by longliners requiring greater steaming distances. Furthermore, the nature of longline gear deployment and retrieval in conjunction to location of fishing grounds result in longline vessels tending to be larger than those employed in gillnetting or potting, giving rise to a greater energy (fuel) input. Longlining was found by Tyedmers (2001) to have higher energy intensity (litres/tonne) than other passive gears, due to the relatively high energy inputs (fuel) and low levels of fish landed (despite their sometimes high monetary value).

Pelagic gears were the most fuel demanding fishing method identified within this investigation. This was slightly counter intuitive. One would think dredge gears, which incur the resistance of sea floor sediment, would have greater fuel consumptions through greater drag. However, the high fuel intensity indicated for pelagic gears may relate to high volume catches entering the mid-water net creating greater drag and additional effort maintaining position in the water column with the additional weight of catch. As our results are calculated on a per day at sea basis, a more plausible explanation would be that pelagic vessels exert substantially more effort searching for fish shoals, and also travel greater distances in often higher powered vessels (as also suggested by Schau *et al.*, 2009 and Winther *et al.*, 2009). Furthermore, greater cruising speeds to reach markets faster and thus provide a fresher, more valuable product (Reid *et al.* (2011) would require greater fuel consumption, as would running the seawater refrigeration units which many pelagic vessels possess (Reid *et al.*, 2011).

Residual distributions from all the models evaluated indicate violation of assumed normality. An investigation of the residual distribution through the application of scale mixture models, indicated that two distributions were apparent; one of normal distribution (mean of zero and standard deviation 0.407), the other containing far broader tails (mean of zero and standard deviation 1.352). The mixture proportions were identified as 90% normal with 10% over dispersion contamination. This could be interpreted as 90% of responding fishers having provided accurate estimates of annual fuel and effort usage, whilst 10% of submitted estimates do not accurately reflect likely fuel consumption from annual fuel and effort figures. This reporting could result from a number of sources including submission of under- or over- estimated fuel costs or effort. Cost data are presented by accountants and thus have a higher likelihood of being accurate representations of annual fuel costs. Fuel data may be distorted by the application of an average fuel price if the prices paid by a fisher varied constantly from the average. In addition, although the reporting variable for fuel excludes lubrication oil, some vessels may report it within the total. Furthermore, distortion may result from inaccuracies within the reporting of days-at-sea effort within the logbooks. The non-normal distribution could further be investigated through the application of mixed distribution models at the modelling stage. Whilst such approaches are at the forefront of CPUE modelling research (Thorson *et al.*, 2012), this type of modelling was beyond the scope of the present investigation, particularly given the relatively low level of contamination and would be more likely to affect uncertainty rather than the mean parameter values. Investigation of mixture models for this type of analyses may be a fruitful avenue for further research.

During the initial stages an un-transformed power curve relationship was indicated between the vessel characteristics scaled by gear types. However the formal log linear relationship of fitted linear models (Table 5.A3) appeared too restrictive to adequately describe the relationships within our data. The flexibility of the linear relationship within GAMs provided a more appropriate fit. The complexity of GAM models applied increased to highlight that better fitting models were possible but that these may have been over fitted to the specific variability within the training data rather than capturing persistent effects. For example increasing the k-index (basis dimension of the smoother) increases the space over which smoothers operate to account for residual patterns.

Furthermore, whilst application of a GAM with 2-d smoother in which vessel length and engine power interacted resulted in a better fit to the data, this was achieved at the expense of increased complexity and a reduced ability to predict unknown fuel consumptions (Table 5.4), the overall goal of the investigation.

Prediction

The performance of several models were tested for their capability to predict the observed fuel per day consumption values given knowledge of un-modelled 2011 vessel length, engine power and annual fleet segment (DCF definition) data. The candidate models included the best linear model and all four of the GAM models, including those believed to be over fitted. Overall two models outperformed the rest. Surprisingly, this included the best fitting linear model (Model 1). However, the underlying validity of applying a strict linear relationship was questionable and highlighted by the better fit of GAM models to the test data. The other was Model 3, the simpler GAM without gear variation within the smoother terms for length and engine power. This confirms the belief that the GAM models incorporating 2-d smoothers and those where smoothers varied by gear were over fitted to the test data. Therefore Model 3 was chosen as the most appropriate for predicting fuel consumption.

Models varied in their ability to predict fuel consumption between gears. The least variable predictions with near zero proportional error were for demersal (DTS) and pelagic (TM) trawl gears. These groups contained the greatest sample numbers within the testing data. These two fleet segments represent the largest capacity within Ireland, with the demersal trawl fleet receiving the greatest research focus. This highlights the importance of sample size and that of collecting data across the whole fleet, not just from vessels of primary interest. Several of the candidate models applied to the 2011 test data showed poor capability to predict dredge gear (DRB) fuel consumption. An unsurprising result given dredgers constitute a relatively small group of heterogeneous vessels which target a variety of shellfish across different fisheries. However, dredge samples were limited in 2011 to just two. Furthermore, predictive testing was not possible on all modelled gears, with samples unavailable for beam trawls, one from Scottish seines (not presented due to confidentiality). Ideally, candidate models would have been tested on a greater number of samples across all fleet segments to increase the confidence in average predictions.

Perspectives

Previous fisheries energy consumption and emission studies have often focussed on small sample numbers of interviewed fishers and conducted for specific purposes. The results from such studies are presented as fuel usage per fish weight landed (e.g. Schau *et al.*, 2009), equivalent emissions per fuel usage (e.g. Driscoll & Tyedmers, 2010; Ziegler & Hansson, 2003), or expressed in terms of energy (e.g. Cheilari *et al.*, 2013; Tyedmers, 2001). Such estimations can be relative and changeable over time for numerous reasons including fluctuating species abundance and/or fuel prices (Schau *et al.*, 2009). Therefore such values do not readily lend themselves for manipulation into input variables for alternative applications. This investigation however, took a more general modelling perspective to facilitate prediction of fuel consumption to the wider fleet, through usage of the more general data unit of fuel per day (litres/sea day) consumption rates. Therefore the resulting rates can still be utilised as the basis for energy efficiency and emission estimates that form the focus of other studies.

Furthermore, our fuel consumption prediction outputs can also be used to generate fuel consumption figures at fishing trip, vessel, or fleet level for integration as an economic variable within mixed fisheries bio-economic models on fisher choice and behaviour in which the economics of fuel use and price is becoming a more widely acknowledged driver. For example Suuronen *et al.* (2012) note that while fuel prices increase the fishing industry will suffer losses in profitability, with some conventional bottom trawl, beam trawl, and dredge fisheries becoming uneconomic, forcing fishers to consider changes to their fishing practices. They argue that fuel consumption and costs of the fishing sector could be substantially lowered by adoption of low impact and fuel efficient technological improvements and as well as behavioural adaptations. Behavioural adaptation to rising fuel costs was examined by Poos *et al.* (2013) within the Dutch beam trawl fleet. Through modelling the trade off between fuel savings and catch losses Poos *et al.* (2013) focussed on vessels adapting their speed to reduce fuel consumption. An Irish guide designed to advise the Irish fishing industry on energy efficiencies (BIM 2009) also refers to the determination of optimal speeds for highest fuel efficiency. The integration of fuel costs into fisher choice and decision models is thus needed, and demonstrated by Bastardie *et al.* (2013). The availability of a model capable of predicting fuel consumption will also enable fuel consumption and fuel price to be incorporated, and varied, independently within bio-economic models and response simulations. Such applications will likely increase the ability and utility of such models for predicting choices in fishing behaviour.

Conclusion

The GAM model (Model 3) constructed within this analysis is capable of estimating fuel per day consumption for several different fleet segments (gears) utilising vessel length and engine power. The type of gear used by a fleet segment has an important influence on fuel consumption. The greatest difference occurs between towed pelagic and passive gears. These daily fuel consumption predictions could be used for existing applications (such as translation into abundance calculations per litre, or emissions estimates) or used to estimate the fuel component of running costs within bio-economic models designed to examine drivers of fisher and fleet behaviour.

Acknowledgements

The authors would like to thank the Irish Department of Agriculture, Food and the Marine for providing logbook information and Bord Iascaigh Mhara for providing fuel cost data. Much of the data collection and analysis carried out here was supported by the European Commission through the Data Collection Framework. Some of the analysis and write up was supported with INTEREG funding as part of the GEPETO project. Authorship sequence reflects levels of contribution through the "sequence-determines-credit" approach. Author contributions: data configuration: SD, EJ; data analyses: SD, CM, EJ; manuscript: SD, CM, RO, CL, EJ.

Figures

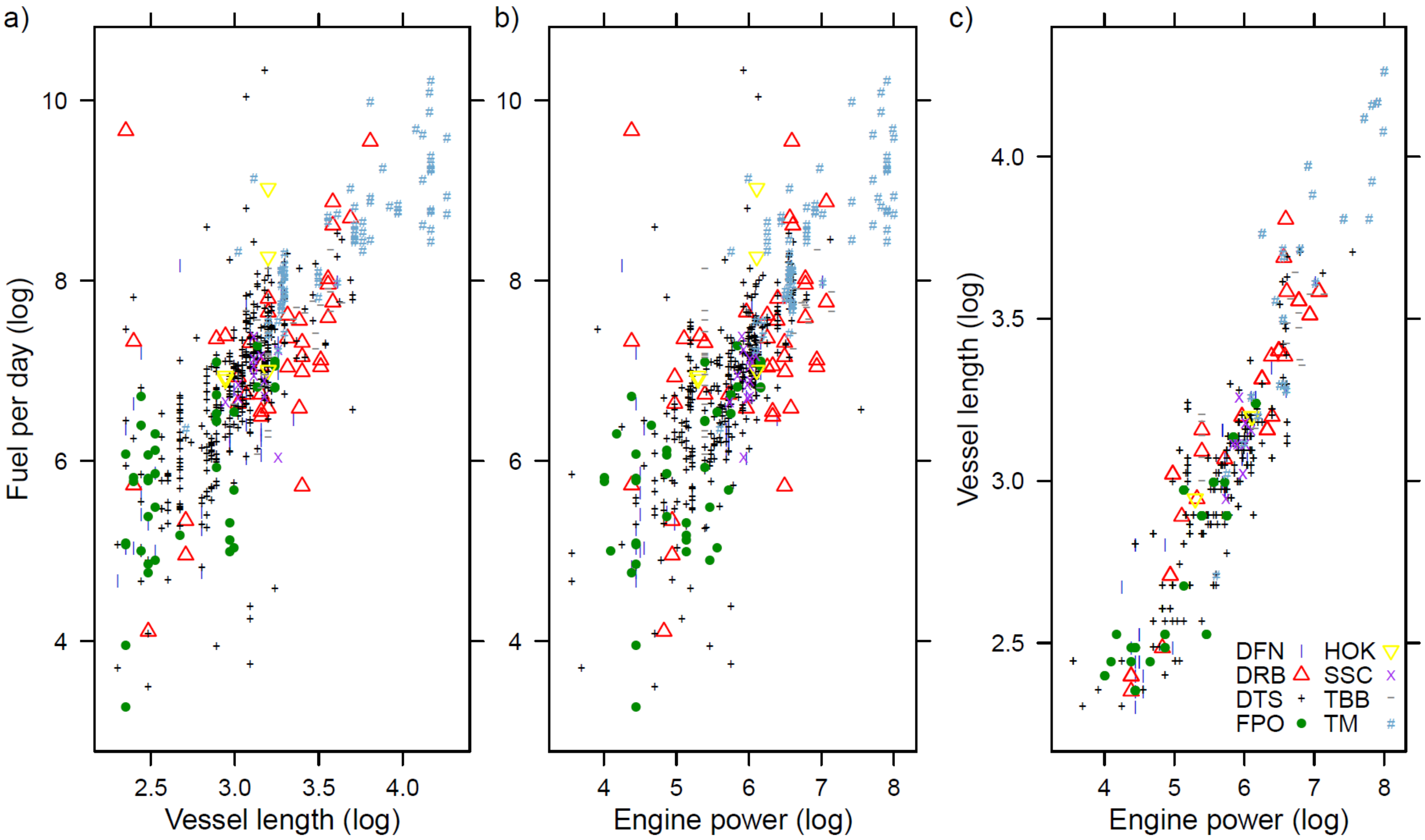


Figure 5.1. Sampled vessels 2003-2010 fuel per day consumption for different gears by a) vessel length and b) engine power in addition to c) the relationship between vessel length and engine power. Depicted on the natural logarithmic scale.

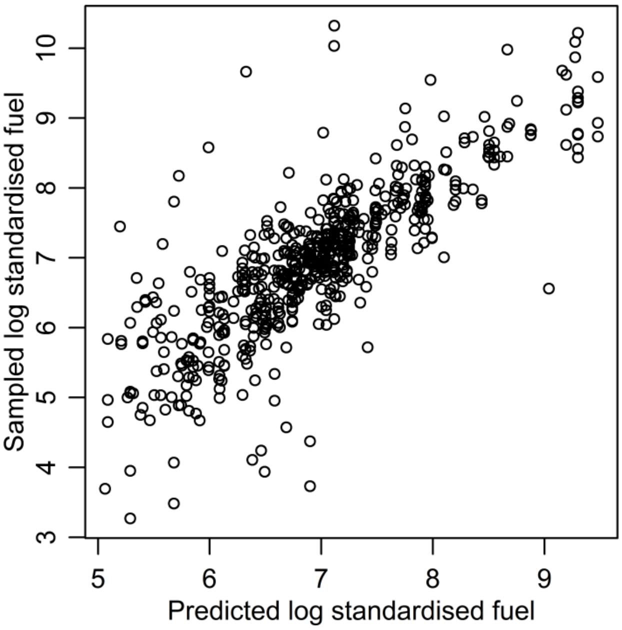


Figure 5.2. Relationship between observed and predicted values of log standardised fuel per day consumption for the linear model with lowest AIC: the first model in Table 5.1.

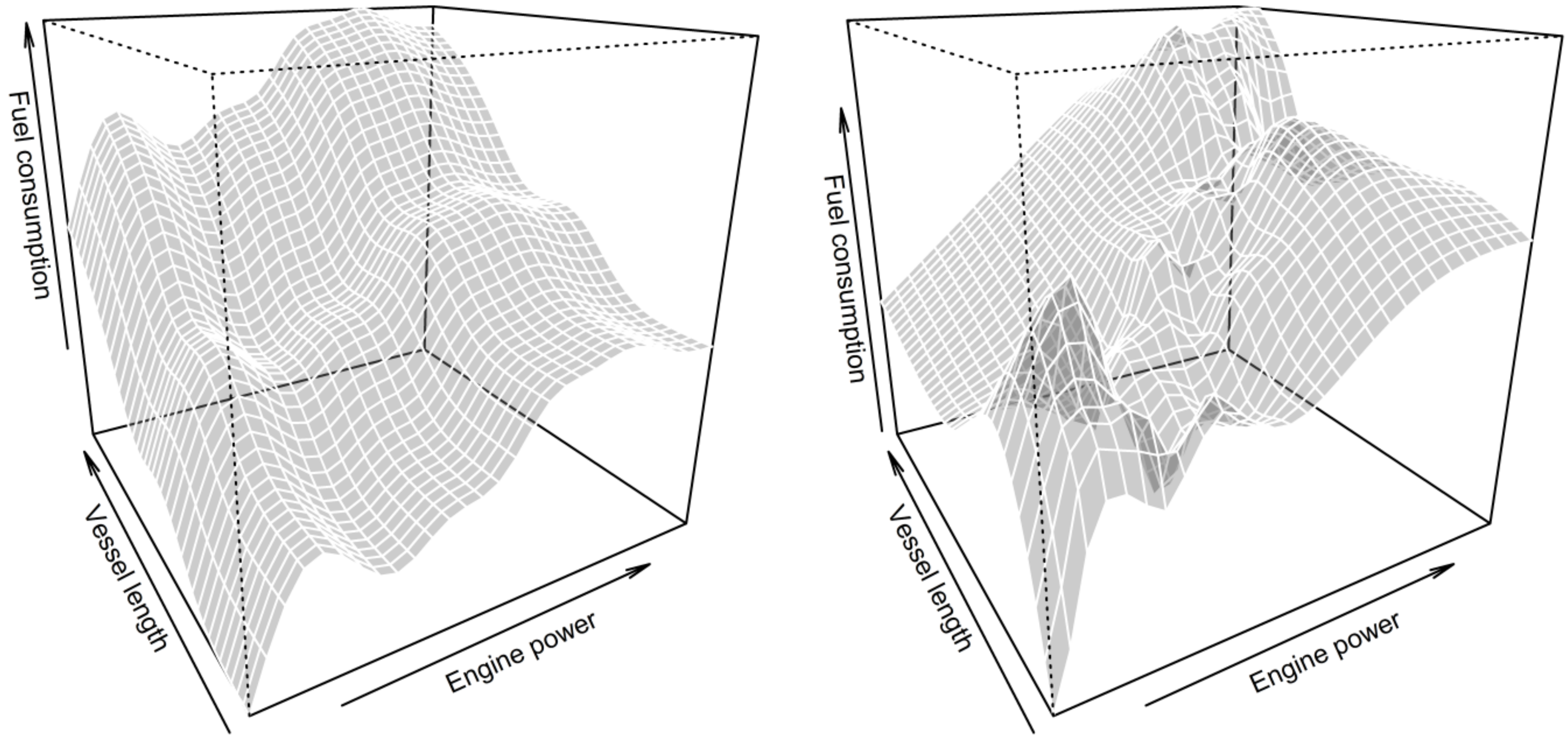


Figure 5.3. Surface plots of GAM model fits for Model 3 (left) and Model 4 (right).

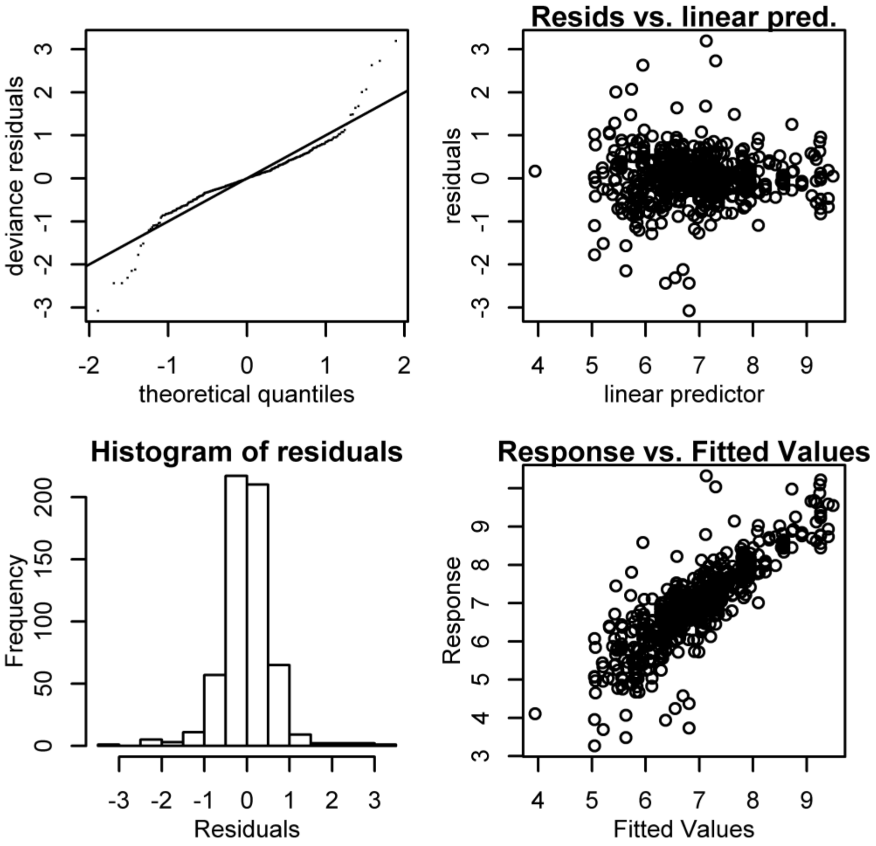


Figure 5.4. Diagnostic plots from GAM model, Model 5.

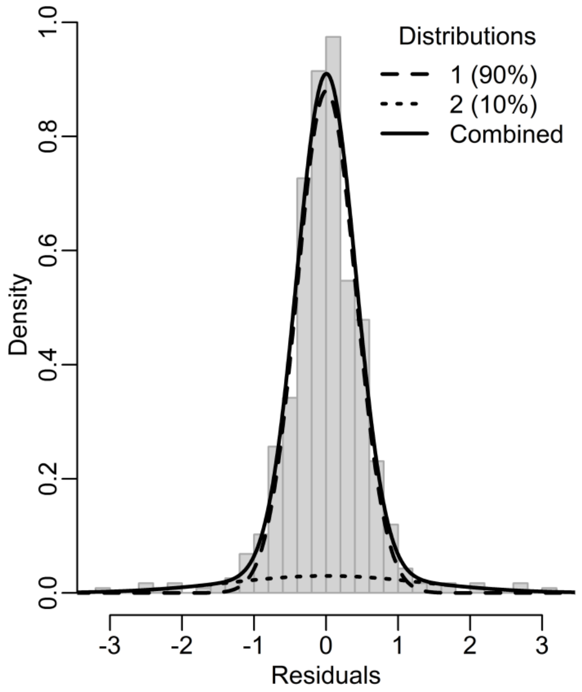


Figure 5.5. Residuals histogram of Model 5 GAM model fit displaying results of scale mixture model broken down by identified mixed distributions.

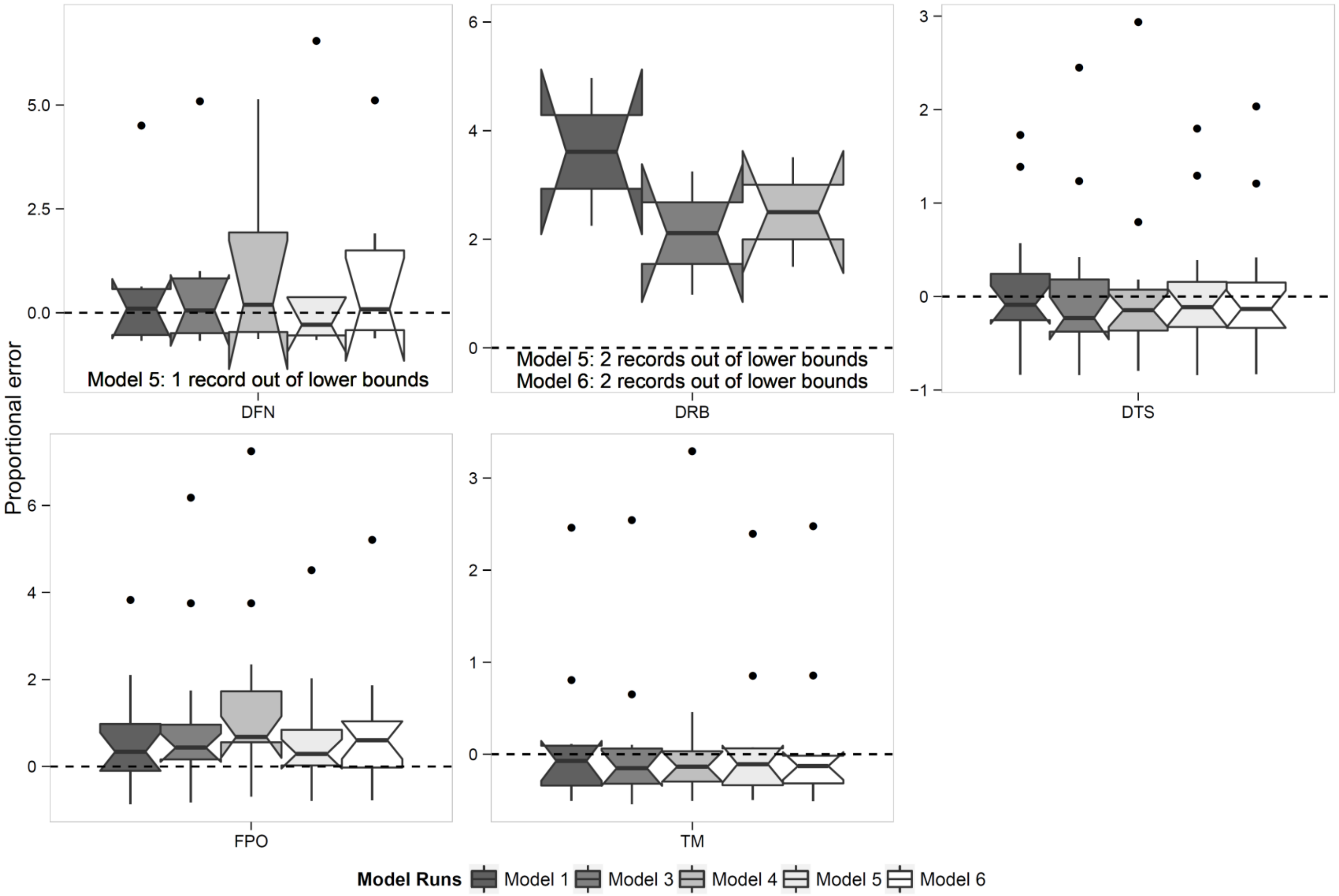


Figure 5.6. Proportional errors of the five models predicted fuel consumptions to those reported in 2011 by gear types. Median depicted with the upper and lower quartiles correspond to the 25th and 75th percentiles.

Tables

Table 5.1. Summary of trialled GAM model outputs, detailing degrees of freedom (df), log likelihoods, AIC values and difference in AIC to best fitting model. With SE_i as standardised engine, SL_i as standardised length, and G as gear.

ID	Model	Log likelihood	df	AIC	ΔAIC
3	$a_{0,G[i]} + s_1(\log(SL_i)) + s_2(\log(SE_i)) + \varepsilon_i$	-561.730	27	1177.459	63.81
4	$a_{0,G[i]} + s_1(\log(SL_i), \log(SE_i)) + \varepsilon_i$	-469.4139	108	1154.828	41.18
5	$a_{0,G[i]} + s_{1,G[i]}(\log(SL_i)) + s_{2,G[i]}(\log(SE_i)) + \varepsilon_i$	-404.8250	152	1113.650	0.00
6	$a_{0,G[i]} + s_{1,G[i]}(\log(SL_i), \log(SE_i)) + \varepsilon_i$	-319.5617	241	1121.123	7.47

Table 5.2. Coefficients resulting from GAM Model 5.

Parameter	Estimate	Standard Error	t value	Pr(>|t|)
Intercept	6.6483	0.65126	10.208	<2e-16
Gear				
DRB	0.28937	0.76229	0.38	0.704
DTS	0.17844	0.65443	0.273	0.785
FPO	0.03809	0.74107	0.051	0.959
HOK	0.99448	18.11197	0.055	0.956
SSC	0.12718	0.72515	0.175	0.861
TBB	0.36292	0.69587	0.522	0.602
TM	0.95591	0.66659	1.434	0.152

Table 5.3. Smooth terms resulting from GAM Model 5.

Smooth terms	edf	Ref.df	F	p-value
s(log(SL))*DFN	1	1	0.576	0.448355
s(log(SL))*DRB	7.4037	7.8352	11.116	2.35E-14
s(log(SL))*DTS	2.9679	3.7377	4.878	0.001084
s(log(SL))*FPO	2.4626	2.9331	0.791	0.494347
s(log(SL))*HOK	0.302	0.302	0	0.994931
s(log(SL))*SSC	1	1	0.058	0.810068
s(log(SL))*TBB	1	1	0.708	0.400462
s(log(SL))*TM	1	1	12.058	0.000556
s(log(SE))*DFN	6.4768	6.9902	2.842	0.006451
s(log(SE))*DRB	1	1	0.019	0.889493
s(log(SE))*DTS	7.2833	7.9123	7.834	6.86E-10
s(log(SE))*FPO	2.1817	2.6601	1.267	0.27875
s(log(SE))*HOK	0.6999	0.6999	0.001	0.980715
s(log(SE))*SSC	1	1	0.227	0.633812
s(log(SE))*TBB	1	1	0.444	0.505597
s(log(SE))*TM	1	1	0.11	0.739931

Table 5.4. Mean absolute proportional error as (predicted-true)/true) by fleet segment for each of the 5 tested models.

Model	DFN	DRB	DTS	FPO	TM
Model 1	1.17	3.61	0.47	0.85	0.51
Model 3	1.31	2.11	0.54	1.17	0.51
Model 4	1.54	2.50	0.50	1.61	0.56
Model 5	10.06	81.94	0.45	0.83	0.50
Model 6	1.42	3.41E+06	0.46	0.96	0.51

Appendix A

Table 5.A1. Details of gear codes (DCF fleet segments), and the gear types to which they refer. * Demersal seine (SSC) gear under the DCF is included within the demersal trawl (DTS) category. For the purposes of this investigation, demersal seiners were examined as a separate group owing to likely differences in fuel consumption.

Gear code	Gear description
DFN	Drift and/or fixed netters
DRB	Dredgers
DTS	Demersal trawlers
SSC*	Demersal seiners
FPO	Pots and/or traps
HOK	Hooks
MGO	Other active gears
MGP	Polyvalent active gears only
PG	Passive gears only for vessels < 12m
PGO	Other passive gears
PGP	Polyvalent passive gears only
PMP	Mixed active and passive gears
PS	Purse seiners
TM	Pelagic trawlers
TBB	Beam trawlers

Table 5.A2. Average annual fuel price per litre 2003-2011 applied in analyses, provided by BIM. N.B. 2003 price was not available at time of analysis and was assumed to be the same as 2004.

Year	fuel Euro/l
2003	0.329
2004	0.329
2005	0.420
2006	0.490
2007	0.490
2008	0.636
2009	0.418
2010	0.534
2011	0.660

Table 5.A3. Summary of linear model fits, detailing the model degrees of freedom (df), log-likelihood, AIC value and difference in AIC to the best fitting model. The first line represents the best fitted model (Model 1) subsequent models ordered by increasing AIC value. With *F* as fuel per day, *SE* as standardised engine, *SL* as standardised length, and *G* as gear. N.B. Degrees of freedom in models containing interaction between vessel length and engine power are two less than expected due to limited number of HOK samples with differing length:power combinations.

Model	df	likelihood	AIC	ΔAIC
$a_{0,G[i]} + a_1 \log(SL_i) + a_{2,G[i]} \log(SE_i) + a_3 \log(SL_i)\log(SE_i) + \varepsilon_i$	19	-576.57	1192.483	0.00
$a_{0,G[i]} + a_1 \log(SL_i) + a_{2,G[i]} \log(SE_i) + \varepsilon_i$	18	-578.60	1194.409	1.93
$a_{0,G[i]} + a_{1,G[i]} \log(SL_i) + a_{2,G[i]} \log(SE_i) + a_{3,G[i]} \log(SL_i)\log(SE_i) + \varepsilon_i$	31	-564.43	1194.444	1.96
$a_{0,G[i]} + a_{1,G[i]} \log(SL_i) + a_{2,G[i]} \log(SE_i) + a_3 \log(SL_i)\log(SE_i) + \varepsilon_i$	25	-573.61	1199.548	7.06
$a_{0,G[i]} + a_{1,G[i]} \log(SL_i) + a_{2,G[i]} \log(SE_i) + \varepsilon_i$	24	-575.62	1201.383	8.90
$a_{0,G[i]} + a_1 \log(SL_i) + a_2 \log(SE_i) + \varepsilon_i$	11	-590.83	1204.113	11.63
$a_{0,G[i]} + a_{1,G[i]} \log(SL_i) + a_2 \log(SE_i) + \varepsilon_i$	18	-583.59	1204.390	11.91
$a_{0,G[i]} + a_1 \log(SL_i) + a_2 \log(SE_i) + a_3 \log(SL_i)\log(SE_i) + \varepsilon_i$	12	-590.61	1205.766	13.28
$a_{0,G[i]} + a_{1,G[i]} \log(SL_i) + a_2 \log(SE_i) + a_3 \log(SL_i)\log(SE_i) + \varepsilon_i$	19	-583.37	1206.083	13.60
$a_0 + a_1 \log(SL_i) + a_2 \log(SE_i) + \varepsilon_i$	4	-608.58	1225.221	32.74
$a_0 + a_1 \log(SL_i) + a_2 \log(SE_i) + a_3 \log(SL_i)\log(SE_i) + \varepsilon_i$	5	-608.45	1227.014	34.53
$a_{0,G[i]} + a_{1,G[i]} \log(SE_i) + \varepsilon_i$	17	-596.58	1228.242	35.76
$a_{0,G[i]} + a_{1,G[i]} \log(SL_i) + \varepsilon_i$	17	-597.37	1229.811	37.33
$a_{0,G[i]} + a_1 \log(SL_i) + \varepsilon_i$	10	-604.94	1230.273	37.79
$a_{0,G[i]} + a_1 \log(SE_i) + \varepsilon_i$	10	-605.51	1231.403	38.92
$a_0 + a_1 \log(SL_i) + \varepsilon_i$	3	-623.40	1252.834	60.35
$a_0 + a_1 \log(SE_i) + \varepsilon_i$	3	-633.56	1273.163	80.68
$a_{0,G[i]} + \varepsilon_i$	9	-746.87	1512.057	319.57
$a_0 + \varepsilon_i$	2	-881.01	1766.039	573.56

Supplementary

The following supplementary material is available at ICESJMS online.

The below three figures are by gear breakdowns of those within Figure 5.1 of the paper providing greater clarity of detail. Fuel per day consumption is depicted individually by the gears of sampled vessels, 2003-2010, by: vessel length, engine power, and the relationship between vessel length and engine power. Plotted on the natural logarithmic scale. Gear codification is detailed within Table 5.A2 of the appendix. PGO and PMP gear types are excluded due to low sample numbers.

Figure 5.S1. Fuel per day consumption by vessel length.

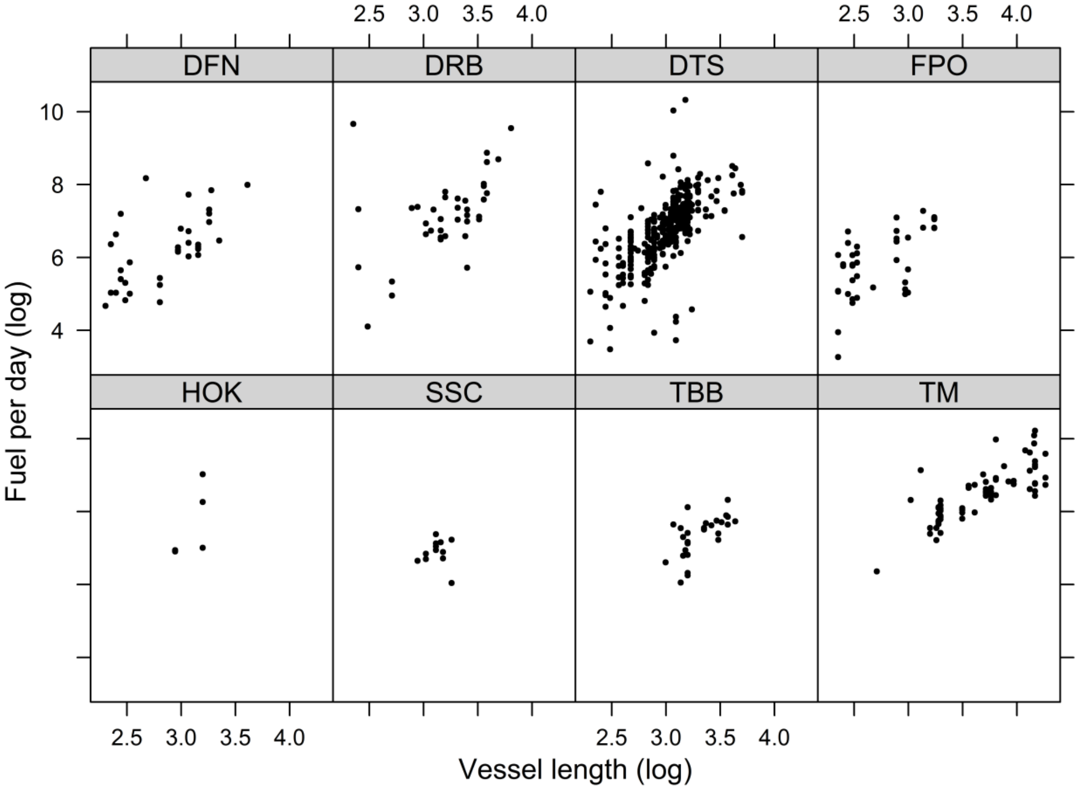


Figure 5.S2. Fuel per day consumption by engine power.

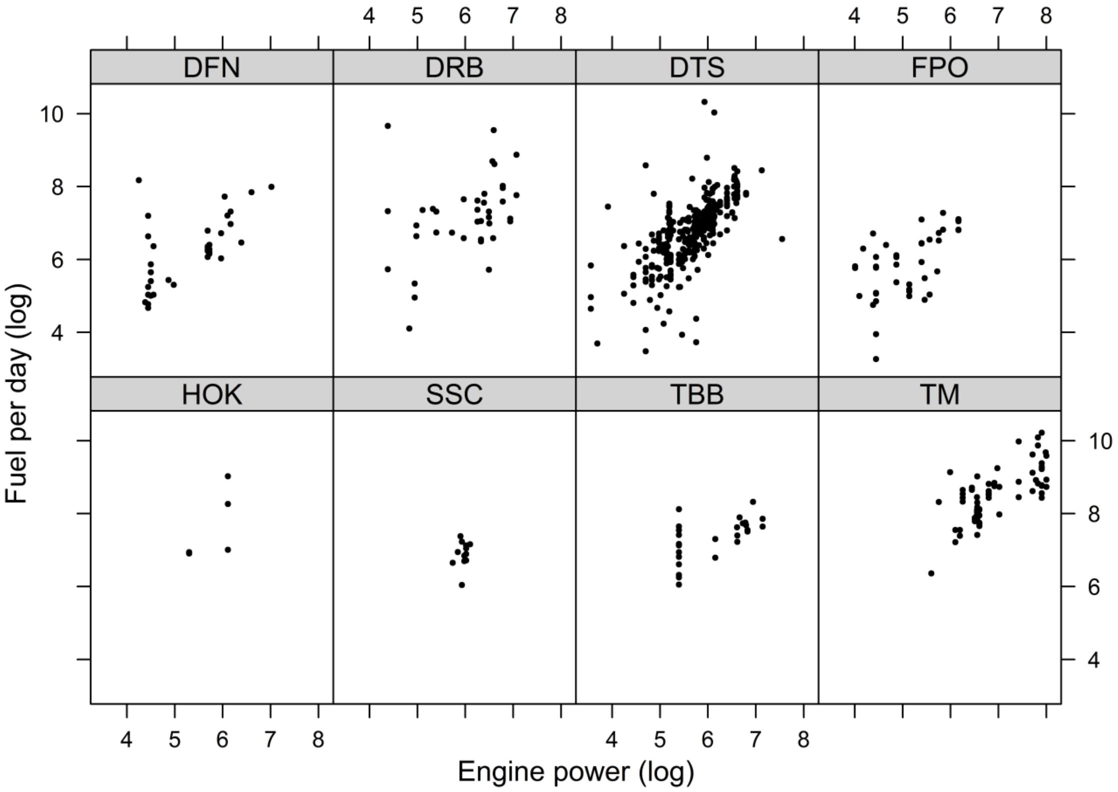
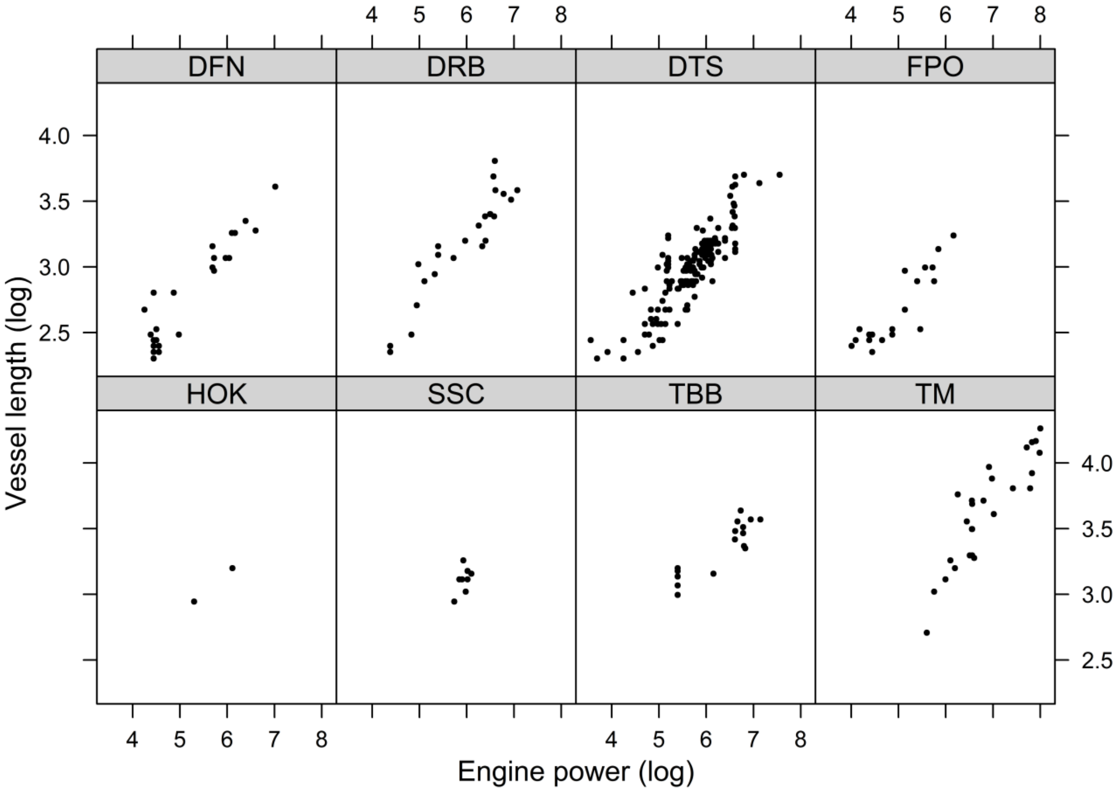


Figure 5.S3. The relationship between sampled vessel length and engine power.



Chapter VI: Defining value per unit effort in mixed métier fisheries

Submitted as:

Davie, S., Minto, C., Officer, R., and Lordan, C. *In review*. Defining value per unit effort in mixed métier fisheries. ICES Journal of Marine Science.

Abstract

The value achieved from time spent at sea is an important driver of fishing operation decisions and fishing behaviours. A time series of Irish first sale prices and total per trip landings values is presented for the first time. These time series highlight heterogeneity in prices and values achieved by the Irish fleet spatially and temporally, as well as variability with targeting (métier groupings). Through the calculation of total per trip values this investigation found catch rate was affected by individual vessels which encompass both variation in vessel characteristics and skipper effects, species targeting, annual variability, and fishing effort.

A linear mixed effects model incorporating within-group variance between métier groupings was fitted to produce value per unit effort (VPUE) estimates accounting for these variables. Kilowatt fishing days (as the days on which fishing operations were reported multiplied by vessel engine power) were found to be the most appropriate effort measure when generating VPUE. Furthermore, the traditionally applied measure of effort, fishing hours, performed poorly in formulation of VPUE.

The model detailed here can be used to standardise value of first sale per fishing trip using averages of each variable to produce an index of VPUE in the region. Indexing can facilitate direct comparison between fishing trips to monitor and detect change in a key metric for the industry.

Key words

Fish price; fishing value; value per unit effort; mixed effects models; temporal trends

Introduction

Maximising the value returned from time spent at sea is an important imperative of commercial fishing operations and hence, a driver of fishing decisions and behaviours. Variation in the landings prices at first sale obtained for specific species (also called ex-vessel prices (Sumaila *et al.*, 2007; Swartz *et al.*, 2012)), can alter fisher behaviour (Marchal *et al.*, 2007; Sumaila *et al.*, 2007). The achievable price of a species will determine the level of investment fishers are prepared to make in order to catch it (Pinnegar *et al.*, 2002), or whether they attempt to catch it at all (Bastardie *et al.*, 2013). Influenced by species prices and the predicted value of trips, fishers may adopt alternative strategies perceived as more profitable (Marchal *et al.*, 2007), for example through targeting different species or grounds, or through use of different gear.

Species prices fluctuate in response to market demand (Pinnegar *et al.*, 2002). The quantity, quality, and variety of species available can also influence values. A glut of landings of one species for example can ‘flood’ the market, lowering prices and thus value to fishers. An anecdotal example is Celtic Sea cod from February to March when spawning stocks are targeted. Conversely, insufficient landing of a species creates a market shortage that inflates prices. Such price inflation can occur though quota restrictions or bad weather, lowering the quantities or quality of species available (Abernethy *et al.*, 2010; Bastardie *et al.*, 2013; Pinnegar *et al.*, 2002).

As the value achieved on a fishing trip is influenced by factors including duration, fishing grounds, and target species, direct comparison between trips can be misleading, and sometimes inappropriate. Standardising trip values to a ‘per unit effort’ (PUE) measure removes the influence of variable trip duration from the value achieved, giving a value per unit effort (VPUE) measure (analogous to catch per unit effort (CPUE)). VPUE essentially incorporates economic factors into CPUE, reflecting fishers imperative to maximise profit. Continuing the analogy, achieved values hence apply only to the landings portion of the catch, whilst discards have zero value.

Whilst CPUE can be a good measure for variability in species stock biomass, this is only appropriate if catchability remains constant (Gulland, 1983) and is not always the case (Campbell, 2004; Harley *et al.*, 2001). It is widely acknowledged that processes introducing bias through varying catchability or availability must be accounted for to ensure proportionality between CPUE and total stock size. This is the underlying concept of standardising catch rates (Campbell, 2004).

Fluctuations in catch rates can bias perceptions of VPUE in the same way as in CPUE. A variety of factors influence species catchability either directly or indirectly by changing the effect of effort (Maunder *et al.*, 2006; van Oostenbrugge *et al.*, 2002). These factors include gear/vessel attributes such as engine power (Rijnsdorp *et al.*, 2000 (cited in Quirijns *et al.*, 2008)) and gross tonnage (Parente, 2004), increases in gear efficiency through technological innovation (van Oostenbrugge *et al.*, 2002), age- or size-specific selectivity, gear saturation (Maunder *et al.*, 2006), and the recently acknowledged influence of fuel prices (Tidd, 2013). Other factors include skipper and/or crew skill (Mahévas *et al.*, 2011), changes in seasonal and spatial distribution (Campbell, 2004; Mahévas *et al.*, 2011; Tidd, 2013), targeting behaviour of the fleet (Maunder *et al.*, 2006; Quirijns *et al.*, 2008; Tidd, 2013), and management-induced responses (Maunder *et al.*, 2006; Quirijns *et al.*, 2008) such as quota restrictions, as well as the influence of economic related decisions (Campbell, 2004).

Measures of PUE and its standardised forms can be affected by the selection of effort unit (Borges *et al.*, 2005b; van Oostenbrugge *et al.*, 2002). Where commercial CPUE data are used in stock assessment it is important to ensure that effort is accurately enumerated otherwise it may lead to bias or poor precision in the assessment (Tidd, 2013). It is also important for management, particularly where input controls are used. Accurate enumeration of effort has the same importance in VPUE estimation. Identifying a suitable effort unit for use in PUE calculations facilitates the appropriate standardisation allowing direct comparisons between fishing trips which vary in space, time, target, gear and other factors. It is therefore imperative to determine the most appropriate effort term to use when calculating VPUE. Given the increasing desire to reflect the economic nature of fishing when modelling of fisher choice and behaviour, it is especially important to evaluate the influence of value-based variables. This investigation aimed to develop a unit which could be used to represent the turnover of fishing activity by:

- Calculating Irish price at first sale (€ per kg) values to examine spatial and temporal trends for several gear and species target groups for:
    - Species landed into Ireland, and

    - Total first sale values achieved per trip (VPT; € per kg);
- Exploring several factors known to influence catch rates and value per trip;
- Standardising per trip value to account for these factors.

Materials and Methods

Data

Irish logbook data for vessels ≥10m in total length from 2003 to 2011 were made available from the Integrated Fisheries Information System (IFIS) database, provided by the Department of Agriculture, Food and the Marine. For each fishing trip the following data were retained: landing date, fishing area (ICES division or subdivision), gear type, mesh size, estimated live weight (raised from landed weight using conversion factors when not landed whole) and price per kilo of all species declared.

The price per kilo is linked to the form (e.g. whole, gutted, filleted, tails) of the species when landed resulting in varying weights and prices dependent on state. To remove this variability, available prices were scaled to the estimated live weight of landings (using the same conversion factors as above). Exploratory analyses for each species or group of species (e.g. *Rajiformes*) identified price ranges, determined outliers, and the extent of missing values. Within the dataset price information was first made available in 2003, although commencing at different times for the various species, the last of which was made available at the beginning of 2004. For a number of species the method of recording price appeared to change in 2008. The style of price recording shifted from an almost constant value within a port to a more dynamic method within the Irish centralised logbook databases (sales notes) resulting in greater variation since 2008, in line with developing control and enforcement regulations (EC, 1993; 2006; 2009b).

Instances with missing price information (70,195 records representing 8% of all records, 57,911 of which from 2003-2004) and outlier prices (3,419 equating to >0.4%) were replaced with an average value to retain as much data as possible. Examples of original prices are given in Appendix C. To gain the most accurate average price, a series of data options were used with decreasing resolution for interpretation of missing values and replacing outlying values. The series ran in the following order:

Landing date, fishing division, landing port, species ID[8]

Landing year, fishing division, landing port, species ID

Landing year, fishing division, species ID

Landing year, species ID

Landing year, higher species aggregation[9]

As prices were not recorded across the whole of 2003 with some not beginning until 2004, a number of 2003 prices remained unfilled even after these aggregated averages were completed. For these unfilled instances, data from 2003 were combined with 2004 data to generate averages in the above aggregations without the inclusion of year. Unfilled prices across the dataset were then filled, were possible, using an average price across the higher species aggregation alone (relating to 27 trips). This left 60 instances of unfilled price (primarily due to unusual species reported). For completeness at the subsequent trip level these were filled with an arbitrary, fixed first sale price of 1 €/kg. This represented a relatively low to mid range price for a number of species. The completed price database was used to calculate the value of each species landed (kg weight x price) within a fishing trip, then summed across species to give a total value per trip (€).

Three effort measures were obtained from the logbooks on a per trip basis:

1. Days at sea: the number of days a vessel was absent from port;
2. Fishing days: number of days where fishing operations were reported within a trip
3. Fishing hours: the time reported to have been spent fishing.

As a quality control, reported instances of fishing hours exceeding 24 were replace with the maximum of 24h, such instances occurred in approximately 2.3% of trips. A small number of trips (0.6%) were excluded where declaration sheet records and operational sheet records could not be paired, for example due to mismatched gear/mesh/division information, thus missing fishing days or hours.

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[8] Based on FAO’s ASFIS List of Species 3alpha code (http://www.fao.org/fishery/collection/asfis/en last visited 11/04/2013)

[9] Common name/group e.g. monkfish (*Lophius spp* and *Lophius Piscatorius*) and rays (*Raja clavata, Leucoraja fullonica, Raja brachyura, Raja montagui, Leucoraja naevus, Amblyraja radiata, Raja undulata, Rajiformes, Raja fyllae, Raja spp*)

Furthermore, each fishing trip was assigned to a particular métier according to the classifications in Davie and Lordan (2011a) for otter trawls and the unpublished classifications in Chapter III for remaining gears obtained using the same methodology. Due to overall métier complexity, métiers were grouped into one of the following "métier groups" based on gear and species aggregations: *Nephrops* (Neph), demersal (Dem), pelagic (Pel), slope (Slope), deepwater (Deep), other trawl (OT), Scottish seiner (SSC), beam trawl (TBB), dredges (DRB) and passive gears including gillnets, pots, longlines (Pa). Incomplete records constituting ~1.1% of the dataset were excluded. The bulk of these resulted from missing gear and/or mesh size information, or trips recording gear types rarely employed by Irish vessels (for example, purse seines). Vessel characteristics could not be identified for four trips. Finally, three trips with a total rip value of less than €1 were considered unrealistic and also removed. This resulted in the availability of 144,190 fishing trips across the years 2003 to 2011 for analysis. A small number of trips occurring early in the time series were assigned to the Deep métier group (243 trips), the result of a declining fishery. This métier group was excluded from the modelling processes due to absence of data across the whole period.

Modelling

The goal of modelling was to explore factors which may explain part of the variability in the achieved first sale value per trip data such as effort, year and métier effects. As an initial starting point and investigate the best descriptor of value per unit effort, a linear model was fitted to the total value achieved per trip accounting for year and the different métier groups as:

$$\log(VPT_i) = a_{Y_i M_i} + \varepsilon_i$$

where the response variable is value per trip (VPT), Y is year incorporated as a categorical variable, M is métier grouping and ε_i are the random residuals initially assumed normally distributed with zero mean and constant variance (lm function within the stats package; R core team, 2012). To increase variation explained by the model it was expanded to include an effort variable, which was included both as a variable with a free parameter and as an offset where the parameter is fixed at one. These two parameter types were trialled for each of the three effort units (days at sea, fishing hours, and fishing days), and their kilowatt effort variations were each applied as effort measures. Separate effort and engine power variables and the effort offset combination equivalents were fitted to explicitly account for vessel power (size) independent of effort. The possible interaction between effort measure and engine power was fitted in addition to offset combinations.

Examination of the fitting diagnostics for all models revealed "heavy" tails on the Q-Q plots, indicating over-dispersed residuals. This occurred not only for this best fitting model, but for all those tested. Whilst comparison of the residual distribution to a random normal distribution showed some alignment, residuals tended to be narrower and taller than a single normal distribution. The over-dispersed pattern within the tails of the residual distribution could have resulted from vessel effects, indicating that some fishers performed better than others. To test this theory, a series of linear mixed effects models (Pineheiro & Bates, 2000) through R package "nlme" were applied allowing for random influence of individual vessels. The mixed effects model allows the use of both fixed and random effects within the same analysis (Tidd, 2013). The first of these models applied fishing days and engine power separately, given as:

$$\log(VPT_i) = b_{V_i} + a_{1Y_iM_i} + a_2 \log(E_i) + a_3 \log(P_i) + a_4 \log(E_i)\log(P_i) + \varepsilon_i$$

where the response variable is value per trip (*VPT*), *Y* is year, *M* is métier group, *E* is effort measure, *P* is vessel engine power in kW, *V* is individual vessels, b_v are vessel random effects assumed normally distributed, and ε_i are the random residuals. The second combined these into a single kilowatt fishing days variable. As further investigation, the mixed effects model was expanded to include kilowatt fishing days, and the influence of year on vessel random effects. These model formulations did not account for the observed over-dispersion in the residuals distribution although the severity was reduced. Differences in the residual variances between métier groups was investigated as an alternative cause of the observed over-dispersion as some métier groupings contain a greater level of variation in VPT.

Results

Visualisation

Prices at first sale for species (groups) landed by the Irish fleet vary in response to factors including time, métier, catching area, and the port of landing. Many species show annual and inter-annual fluctuations over the period as well as variations between métiers and areas caught. *Nephrops*, for example, show relatively stable prices caught from ICES areas VIIa, VIIg and VIIj as well as VIIb for the *Nephrops* métier (Figure 6.1). However there were large fluctuations over the earlier period from the slope métier in VIIb, and the *Nephrops*, other otter trawls and slope métiers in VIIc and VIIk which can be linked to the Porcupine *Nephrops* fishery. These prices became more stable at a reduced level since 2008 with the introduction of sales notes.

Annually, there is a great deal of variation between the total value achieved per trip (VPT) (Figure 6.2), although this is smaller for both Scottish seines and beam trawlers. Pelagic trips achieve far higher trip values than any other métier group. Dredges (DRB) demonstrate a distinct declining trend in trip value and decreased trip variation, whilst Scottish seines and beam trawls indicate a small value increase between 2003 and 2011. Other métiers such as *Nephrops* (Neph) and other otter trawls (Ot) appear more constant, though with large variance. Several métiers show a dip in trip value during 2009-2010 seasons.

Seasonal patterns of métier groups are highlighted by visualising the average monthly trip value (Figure 6.3). Two distinct patterns are observed, those demonstrating higher value trips in summer months (e.g. Neph, Dem, SSC), and those with more valuable trips over winter months (Slope, Pa, and Pel).

The *Nephrops* métier typically shows greater value during the summer months. However seasonal variation in value has reduced. 2009 was a poor year while value in 2011 appeared to have recovered to higher than previous values. The demersal métier experienced a bad value winter over 2009-10. The seasonal variation continues throughout the period for this group even increasing in severity in 2010-11. Scottish seiners follow the same seasonal pattern and have an increasing trend in value per trip, but they do not demonstrate the same declines around 2009 as the *Nephrops* and demersal métiers. While beam trawls also indicate a general increase in trip value, the value of these trips decreased around 2009-10. The seasonality of this group is less defined. Dredging (DRB) values dropped suddenly and substantially at the beginning of 2006. The seasonal pattern within this métier had previously been unclear, however within the last two years slightly higher values were achieved in summer months compared to winter.

Poor value summer seasons were observed within the slope group between 2007 and 2009. The group showed recovered, or even increased trip values in 2010 and 2011, with particularly valuable trips at the turn of 2011. The other otter trawl (OT) group, which also showed more valuable winters, experienced a particularly high value period in the winter of 2007/08. Trip values achieved by the pelagic métier increased after 2005, and were distinguished by disparity between high value winters and low value summers. This disparity reduced in the latter two to three years with high value winter trips becoming less extreme, and the occurrence of higher value summer trips. May of 2010 was an unusually and particularly high value month. The passive gear métier (Pa) demonstrated the same high winter, low summer seasonal pattern as the pelagic group. The overall value trend within this group declined, particularly with winters achieving much lower values from the end of 2008.

Modelling

Development

The initial linear model fit to total value achieved per trip accounting for year and métier groups indicated a poor level of explained variation (R^2 = 38%, p-value <2.2e-16, 146,337 residual degrees of freedom). The AIC values (Akaike, 1974) declined upon incorporating an effort measure variable (Table 6.A1). Offsetting effort did not improve model fit. Of the effort measures tested fishing effort in hours was shown to be the poorest effort measure, when compared to sea days and fishing days, the latter of which performed best. Models in which engine power were explicitly accounted for independent to effort measure gave lower AIC values than combined kilowatt effort equivalents when including an interaction between effort measure and engine power.

Mixed effects models applied as an alternative to simple linear models gave rise to a large AIC decrease, particularly with the inclusion of vessel as a random effect. The further development of random effects indicated comparatively minor fit improvements. The most complex of these trials incorporating year and kilowatt fishing days into random vessels effects obtained the lowest AIC value. However, the degrees of freedom increased significantly reflecting the increased complexity of the model suggesting an over fitting to the data.

From the variety of models fitted the presence of over-dispersion in the residuals distribution continues to persist, resulting in heavy tails, more so in the lower tail. Given the number of observations (143,947) it is likely that alternative error distribution assumptions would have little effect on the mean parameter estimates but rather would affect their standard errors. This will result in less conservative estimations of uncertainty here.

Model selection

Four models were considered most relevant due to AIC value, degrees of freedom and level of over-dispersion. For these, the coefficient representing effort was examined. Ideally this would be a value of 1, achieving unity, and thus allowing direct division of *VPT* by effort when considering the other variable attributes included in the model. Between the candidate models this value varied from 0.987 to 1.847 (Table 6.1). Those models with separate terms for fishing days and engine power resulted in higher coefficients for fishing days than those models where fishing days and engine power were re-combined into values of kilowatt fishing days. The two models incorporating random vessel effects gave values close to one, of these the model containing within-group differing variance was chosen due to the combination of AIC value and close unity of effort coefficient (1.044). Fixed effects coefficients for this model are depicted in Figure 6.4.

Discussion

First sale price and value

This investigation presents for the first time a time series for first sale prices and subsequent total per trip landings values for Irish fisheries. The two time series highlighted the heterogeneity in prices and values achieved by the Irish fleet spatially and temporally, and also the variation between métier groupings. Such variability is reflected in the distribution of effort over space and time, also observed by Bastardie *et al.* (2013).

Nephrops was presented here as a clear example of how first sale prices have changed. For example, the larger *Nephrops* landed in earlier years from the Porcupine fishery (primarily within ICES divisions VIIc and VIIk) were shown to consistently achieve higher prices per kilo than *Nephrops* fisheries in the Irish Sea (ICES, 2012a). However prices dropped after 2008 due to reduced market demand at the onset of the economic downturn, and an excess quantity of *Nephrops* in frozen storage.

Irish pelagic species typically have comparatively low first value prices however the fisheries obtain the highest per trip values. This is consistent with observations made by Sethi *et al.* (2010) on global fisheries developments; since 1950 the species preferentially targeted by fishers have been those with high profit potential attributes (i.e. those with high catch biomass or those inhabiting shallow, obtainable habitats). The Irish pelagic fisheries represent the highest catch biomass. Bastardie *et al.* (2013) found that the decision to go fishing for larger vessels, associated with pelagic fleets, was also highly influenced by fish prices.

Some interesting variations in trip value occurred within a number of the métier groups, particularly within dredging, pelagic, and seining fisheries over the period investigated. Drops in dredge and passive trip values occurred. These declines result from decreased per kilo prices over time, in particular scallops in dredging, and crab and whelk in the passive grouping. Within the pelagic métier grouping, 2006-7 showed higher trip values than other years because of high per kilo values for herring (2005-2007) combined with a peak in mackerel prices in 2007, while an above average monthly spike occurred in

2010 relating to large volumes of *Sardinella* landed from distance fishing in CECAF areas.

The measures of price elasticity provided by Swartz *et al.* (2012) suggest that first sale prices are relatively inelastic to supply and *vice versa* for a large number of fisheries (as exhibited by the lack of correlation between catch volumes and price). Consistent with this finding, Batardie *et al.* (2013) suggest that price more strongly influences fishermen than the prospect of large catch abundance. Within pelagic fisheries high volumes of generally lower value species are caught, anecdotally however, price is maximised by targeting the most valuable size grades.

Modelling VPUE

The fitted mixed effects linear model with within-group variability incorporated several variables known to impact catch rates, where individual vessels were included as random effects. Several previous studies into the standardisation of catch and effort data utilised random effects for *vessel* and for *vessel and year* interactions whilst examining fishing power (Bishop *et al.* 2004; Helser *et al.* 2004). Random vessel effects were explored to account for between-vessel variability which would allow for variation in catchability due to individual characteristics between vessels not explicitly accounted for elsewhere within their models. Incorporating both vessel and year as random effects accounts for vessel variation over time due to increased engine power or technological capability, and human effects (Mahévas *et al.*, 2011; Marchal *et al.*, 2007), i.e. individual fisher performance will differ due to varying efficiency in their "foraging behaviour", and their varying levels of knowledge of the fisheries and their own gear. More recently, Tidd (2013) included a vessel random effects variable to explain variance in landings per unit effort associated with gear, seasonal and area effects as well as variation in efficiency and capacity. Tidd (2013) believed that ignoring vessel effects could have produced negatively biased LPUE estimates.

This investigation tested both vessel and the interaction between vessel and year as random effects along with the time spent fishing. Our inclusion of vessel as a random effect resulted in a large reduction in AIC implying a large variation between individual vessels in their ability to generate value from a trip. Inclusion of vessel as a random effect essentially incorporates a number factors which differ between vessels but are not explicitly accounted for as parameters within the model, for example, vessel characteristics like engine size and vessel gross tonnage important in other studies (e.g. Parente, 2004). Human effects due to skipper and/or crew (Mahévas *et al.*, 2011; Marchal *et al.*, 2007) were also accounted for. A further rationale for incorporation of vessels as random effects relate to the individual economic circumstances of fishers; the influences of unique revenues, costs, debts and profits would be expected to individually affect vessel activities. The inclusion of other variables as random effects within this investigation reduced the AIC although the reduction was not as pronounced as that resulting from the inclusion of vessel. This may be related to the low probability that vessels markedly increased their power or efficiency during the relatively short time series examined.

Parente (2004) carried out multiple linear regressions on the Portuguese coastal seine fleet in 1997. Several vessel characteristics were found to have little or no influence on CPUE in their study, namely: construction year, depth, vessel length overall, and vessel breadth. These variables were not included within this investigation as depth, vessel breadth and construction year were not available for all vessels and vessel length was highly correlated to engine power. The fixed effects of the final model however did include year, métier group and kilowatt fishing days. Year was used to account for variation in underlying species availability, and for annual variation and inflation in first sale prices which would result in variation in per trip values.

Métier groupings act as a proxy for a number of effects, primarily relating to fisher targeting behaviour. Considerable variation was identified between métier groups. This is consistent with the results of previous LPUE analyses that detected significant differences in fishing power related to differing targeting behaviour (Mahévas *et al.*, 2011; Quirijns *et al.*, 2008). The requirement to include between-métier variation within the residual error further highlights differences between the métier groupings. Greater variance and a larger number of negative residuals were observed in the pelagic métier. These appear to generate much of the inflated negative tail observed in the overall residuals. The presence of larger negative residuals implies a greater variation in trip values for this métier than others and a higher occurrence of trips with lower than expected values. These may be caused by an underreporting of catches on trips which then reduce the reported values obtained. An alternative possibility may be differences in fisher behaviour of the pelagic métier compared to others. This would be fitting given the differences in fishing practice. Pelagic fishers go out, target a number of shoals, then head back to port while in other métiers such specific targeting is not possible and a greater amount of time is spent with nets in the water over a greater number of days before returning. By accounting for targeting behaviour through broad métier groups, seasonal changes and spatial variation in fisher behaviour are inherently incorporated where other studies have explicitly included seasonal proxies or spatial areas (e.g. Mahévas *et al.* 2011). Seasonal variation examples within our dataset include the pelagic fisheries, occurring primarily during winter months, and summer peaks in *Nephrops* targeting (Davie and Lordan, 2011a). The different otter trawl métier groups of pelagic, demersal, *Nephrops* and slope métier groups typically cover different fishing grounds (unpublished data from vessel monitoring systems information). Quirijns *et al.* (2008) identified only modest inter-annual variations in micro-spatial indices and concluded that bias introduced by not explicitly accounting for such micro-scale variation in targeting would not significantly affect CPUE. Had area been specifically included, the finest spatial scale available to our analyses would have been ICES rectangles, an appropriate scale for a number of cases. The slope métier group, for example, spans multiple rectangles tracing the edge of the continental shelf west of Ireland. Other métier groups contain multiple discrete grounds and rectangles, such as the *Nephrops* métier. Fine spatial detail is something which could be further investigated in the future through the use of data from vessel monitoring systems, which record vessel positions in latitude and longitude. Variation in gear type is incorporated within métier groupings where each métier group contains a single gear type, with the exception of the passive gear group.

Kilowatt fishing days were determined through model explorations to be the most appropriate effort measure to apply when calculating value per unit effort. This effort measure is formulated by multiplying the number of days on which fishing operations were reported within logbooks by the associated vessel's engine power. The inclusion of kilowatt power within the effort measure accounts for engine size and therefore any efficiency changes which could have caused interpretation biases in long-term trends. Evaluation of engine power as a separate variable was trialled and found to improve model fit (indicated by lower AIC value). However, the effort measure coefficient was much higher when effort and engine power were included separately (values of over 1.8 compared to 0.98). A coefficient value of one would validate a direct division of per trip value by the effort measure given a set of modelled terms. The further the coefficient from 1 the lower the capacity for direct division. The interpretation is more complex when engine power is considered separately, creating a surface for the coefficient rather than a single value.

Kilowatt fishing days were compared against several other effort measures; fishing days without consideration of vessel power, fishing hours, kilowatt fishing hours, days at sea, and, kilowatt days at sea. The latter two effort units are often used in effort management regulations such as those effected for cod recovery within the Irish Sea and West of Scotland since 2003 (Davie & Lordan, 2011b; EC, 2002, EC, 2003, EC, 2004; EC, 2008a). The time reported actually spent fishing (fishing hours) and kilowatt fishing hours have traditionally been used as the effort measure in the computation of per unit effort. The former is a usual input to the commercial catch or landings per unit effort abundance indices used to tune stock assessments (ICES, 2012a), and as an auxiliary variable for raising discards to fleet and fishery level (Allain *et al.*, 2003; Borges *et al.* 2005b). Given that hours actually spent fishing represents the most specific measure of effort, and the importance of fishing hours in other PUE calculations, we had expected this unit to also be applicable to VPUE calculation, however it was not. Tidd (2013) used fishing hours for nominal vessel landing rates (LPUE) believing, as was thought here, that management decisions based on effort measured in hours would provide a less crude measure which closely relates to actual fishing activity. A possible explanation for the poorer performance of fishing hours within this investigation could be as a result of inaccurate recording of hours within the logbooks. Whilst our finding that fishing hours was in fact the poorest effort measure for VPUE calculation was unexpected, application of fishing days as a more appropriate alternative effort measure appears to be logical. Value is only generated on days when fishing operations occur, and days spent steaming, strictly speaking, do not generate revenue as fishing does not occur. Although in a broader sense, steaming days could be considered to generate revenue if moving to alternative grounds where higher value catches can be obtained.

Summary

The variability in the data observed in this investigation is not uncommon (as stated by Tidd, 2013). Fisher behaviour varies, encapsulated here by random vessel effects, leading to variation in the values and effective effort obtained between trips. Tidd (2013) also notes that managers applying effort limitation need to be aware of the variability in catchability of individual fishers operating within fisheries that utilise the same stock. Accounting for variation in catchability is particularly important when fleets concentrate their fishing effort in areas of high densities, potentially altering perceptions of stock abundance. This is especially relevant within mixed fisheries where market conditions, fishing costs and management regimes alter fisher targeting behaviour (Quirijns *et al.*, 2008). For example, effort restrictions can motivate fishers to increase their profit efficiency through achievement of higher VPUEs, to compensate for the lower availability of effort. For management to be more effective in reducing fishing mortality attention should be shifted from nominal effort to consider the factors which contribute to effective effort. Properly accounting for variability in vessel characteristics, targeting, and seasonal and area effects should result in improved effort management (Tidd, 2013).

Each of the three economic variables presented here (price at first sale, total value per trip, and value per unit effort) could be useful measures of revenue for consideration in fisheries management. We concur with Marchal *et al.* (2007) that fish prices (and trip values) provide only partial information on the economic incentives driving fishermen’s decisions. Of the other economic influences on fisher behaviour, fuel cost is a primary driver at the operational level. Therefore, the ability to produce catchability adjusted estimates of VPUE is vital for inclusion along with cost information into bio-economic models that describe fisher behaviour, and attempt to predict behavioural responses to future management.

Conclusion

Through the calculation of species prices at first sale and total per trip values this investigation found catch rate was affected by a number of different factors. These included an effect of individual vessels which encompass both variation of vessel characteristics and skipper effect, species targeting, annual variability, and fishing effort. Kilowatt fishing days were found to be the most appropriate effort measure when generating VPUE. Furthermore, the traditionally applied measure of effort, fishing hours, performed poorly in formulation of VPUE.

The linear mixed effects model detailed here can be used to standardise value of first sale per fishing trip using averages of each variable producing an index of value per unit effort. This index can facilitate direct comparison between fishing trips which can be applied in monitoring and detecting changes. Such VPUE indices' can also be used as a proxy for turnover within bio-economic modelling of fisher choice and behaviour. VPUE may also be used as driver within simulations predicting behavioural responses to future management, informing the debate on current and future fisheries management initiatives.

Acknowledgements

The authors would like to thank the Irish Department of Agriculture, Food and the Marine for providing logbook information. Thanks to Hans Gerritsen for his advice and guidance on visualising price information. Authorship sequence reflects levels of contribution through the "sequence-determines-credit" approach. Author contributions: data configuration: SD; data analyses: SD, CM; manuscript: SD, RO, CM, CL.

Figures

Figure 6.1. *Nephrops* average monthly price per kilo achieved at first sale over the period 2003-2011 by métier group and ICES division. Categories with minimal landings across the time series have been excluded.

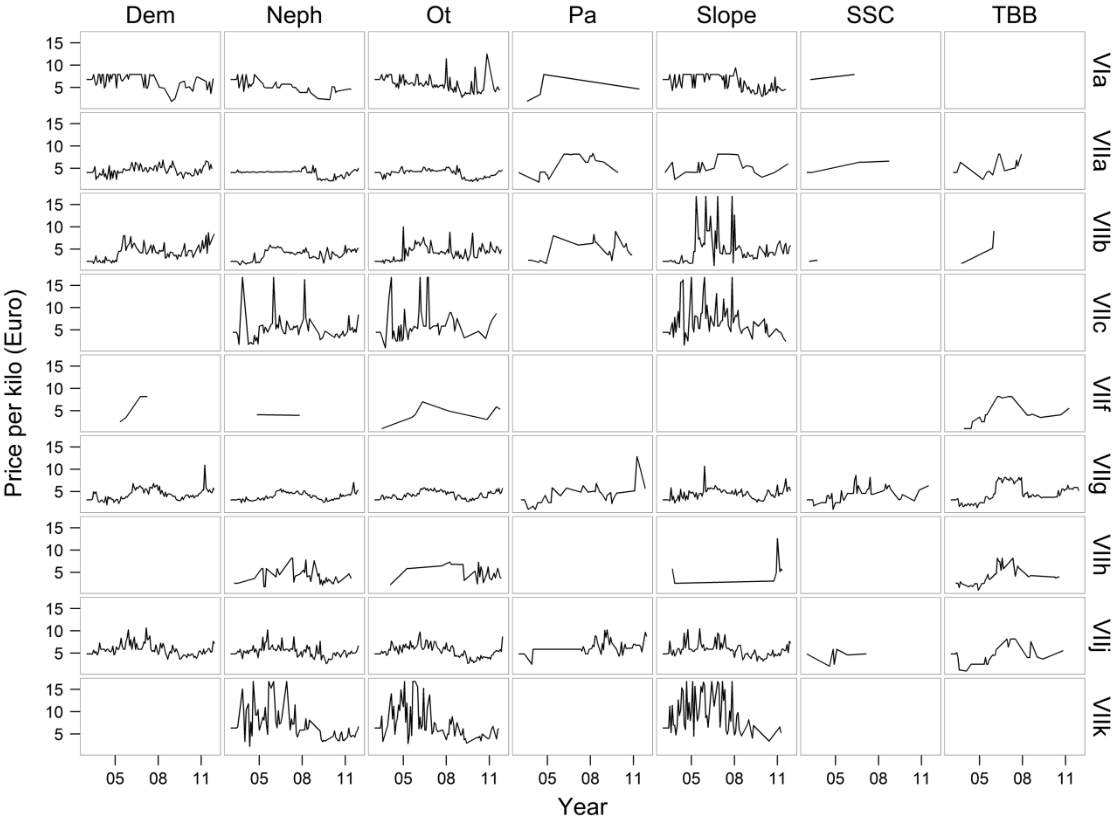


Figure 6.2. Boxplots for each of the 10 métier groups of natural log transformed Euro value per trip. Notches within boxes represent confidence intervals around the mean.

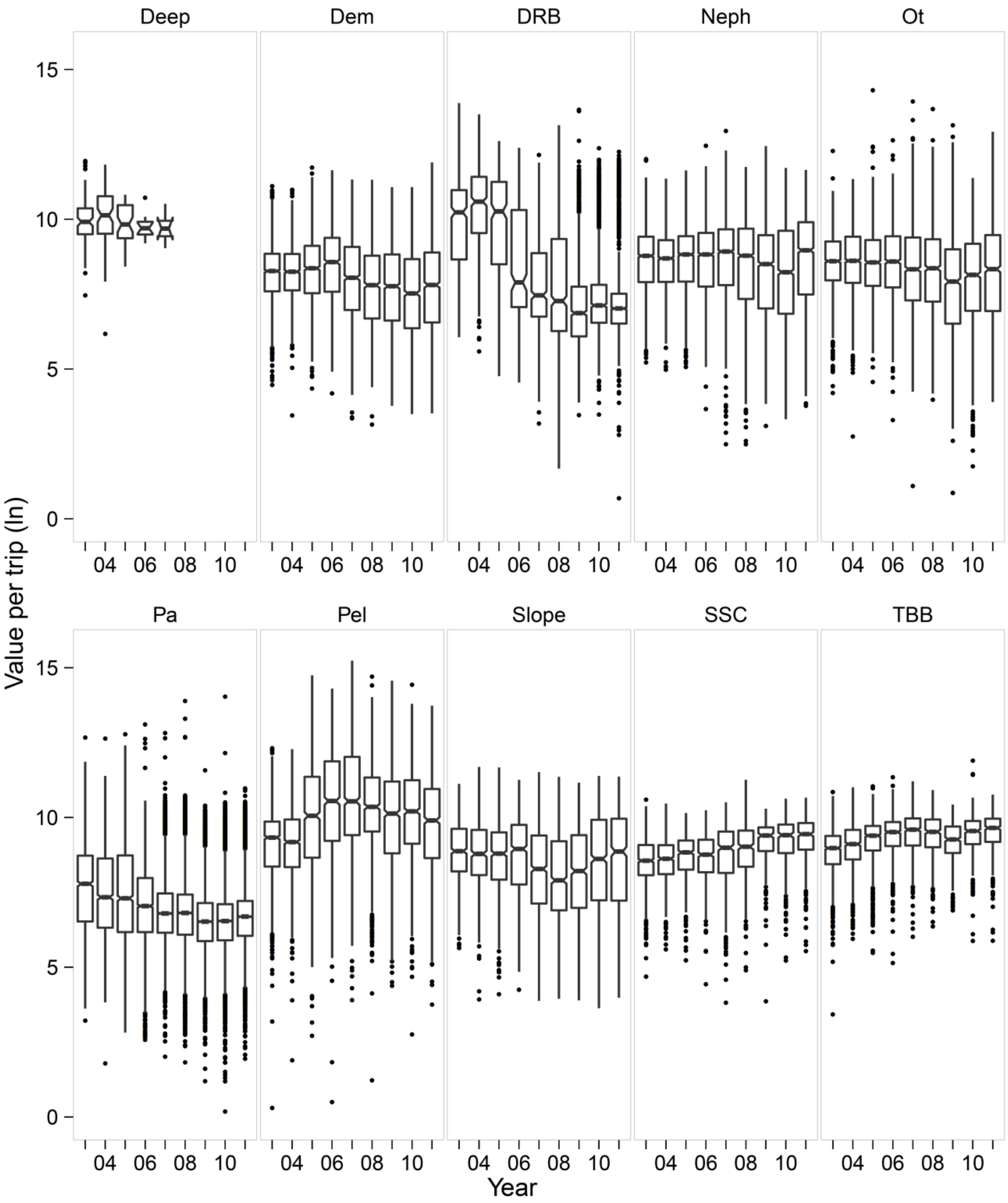


Figure 6.3. Average monthly per fishing trip value (‘000 €) for of the 10 métier groups, 2003-2011.

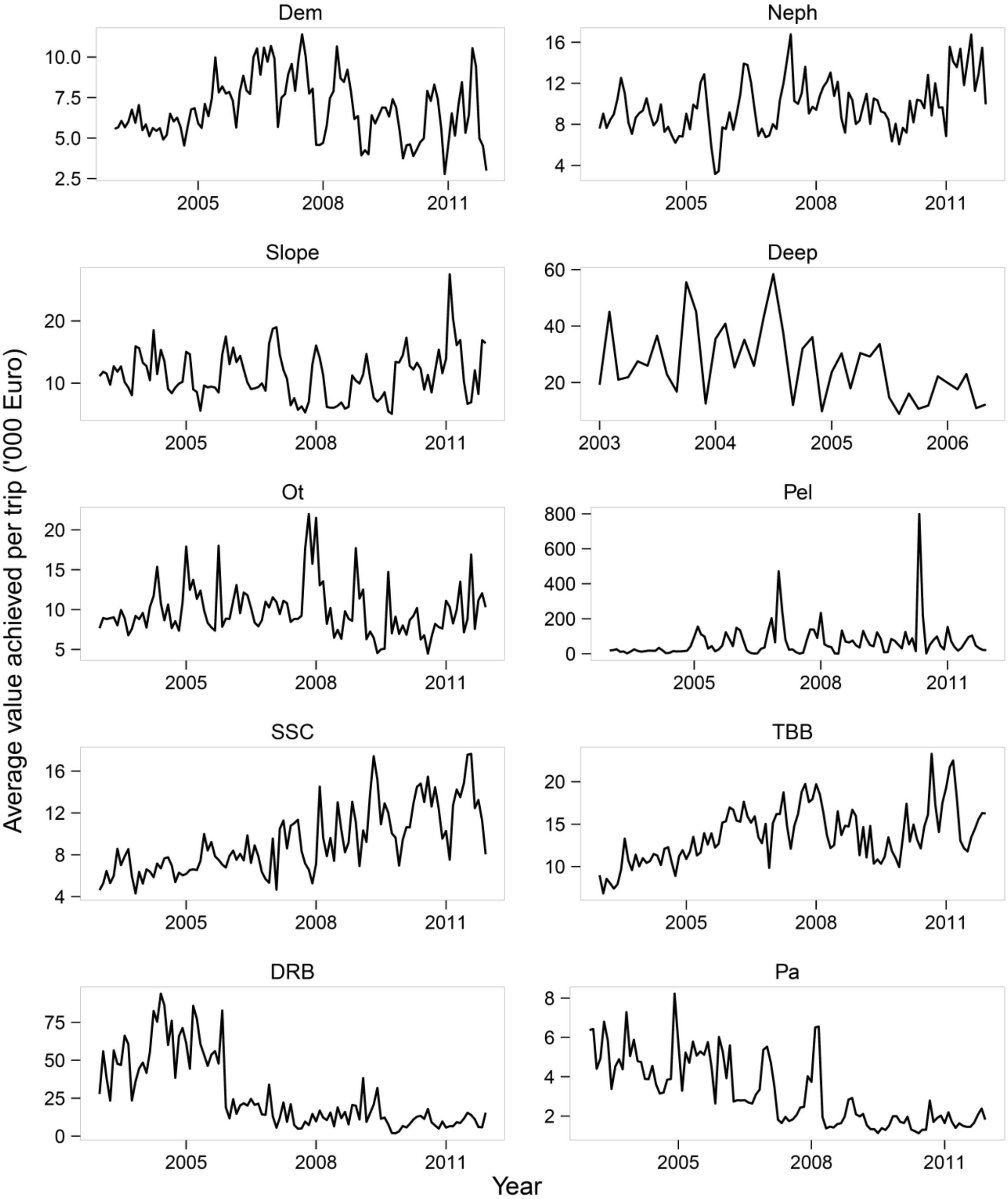
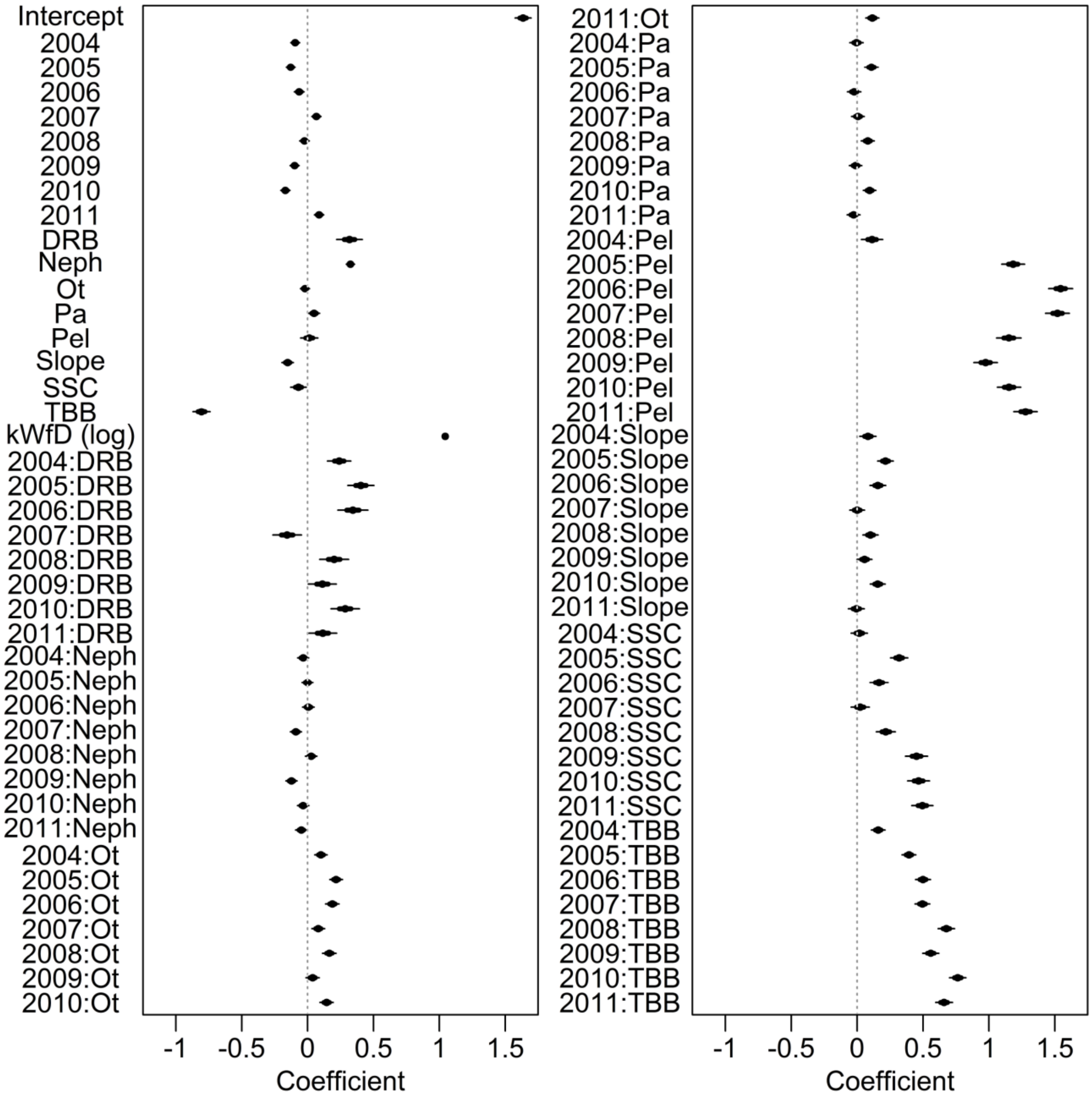


Figure 6.4. Fixed effects coefficients of the final modelled value per trip. The intercept represents a combination of 2003 and the demersal métier group. Boxes represent 50% confidence intervals, whiskers to the 90%.



Tables

Table 6.1. Effort measure coefficients of the four most relevant models. Notation: Res. Dist. is the type of residual distribution applied within the model; Days are fishing days (ln); kWfD are kilowatt fishing days (ln).

Model	Res. Dist.	Days	kWfD
$a_{0,Y_iM_i} + a_1 \log(fD) + a_2 \log(P) + a_3 \log(fD)\log(P) + \varepsilon_i$	$N(0,\sigma^2)$	1.847	
$b_{V_i} + a_{0,Y_iM_i} + a_1 \log(fD) + a_2 \log(P) + a_3 \log(fD)\log(P) + \varepsilon_i$	$N(0,\sigma^2)$	1.692	
$b_{V_i} + a_{1,Y_iM_i} + a_2 \log(kWfD) + \varepsilon_i$	$N(0,\sigma^2)$		0.987
$b_{V_i} + a_{1,Y_iM_i} + a_2 \log(kWfD) + \varepsilon_i$	$N(0,\sigma^2_{M_i})$		1.045

Appendix

Table 6.A1. Summary of models fitted during development. Final model highlighted in bold. All bar the last model have assumed normally distributed random residuals with zero mean and constant variance. The last has random residuals with zero mean and between métier variance. Table details: degrees of freedom (df), log likelihoods, AIC values and difference in AIC to best fitting model. Notification: Each model has a log intercept, *Y* as year, *M* as métier group, *P* as vessel engine power. Effort measures: *sD* as sea days, *fH* as fishing hours, *fD* as fishing days, *kWsD* as kilowatt sea days, *kWfD* as kilowatt fishing days, *kWfH* as kilowatt fishing hours.

Table 6.A1

Formula	df	Likelihood	AIC	ΔAIC
$a_{Y_iM_i} + \varepsilon_i$	82	-240860	481883	194304.0
$a_{1,Y_iM_i} + a_2\log(sD) + \varepsilon_i$	83	-189128	378422	90843.3
$a_{Y_iM_i} + \log(sD) + \varepsilon_i$	82	-195022	390207	102629.0
$a_{1,Y_iM_i} + a_2\log(fH) + \varepsilon_i$	83	-197916	395997	108419.0
$a_{Y_iM_i} + \log(fH) + \varepsilon_i$	82	-198009	396181	108603.0
$a_{1,Y_iM_i} + a_2\log(fD) + \varepsilon_i$	83	-192578	385323	97744.0
$a_{Y_iM_i} + \log(fD) + \varepsilon_i$	82	-200355	400873	113295.0
$a_{1,Y_iM_i} + a_2\log(kWsD) + \varepsilon_i$	83	-178998	358162	70583.3
$a_{Y_iM_i} + \log(kWsD) + \varepsilon_i$	82	-181051	362267	74688.1
$a_{1,Y_iM_i} + a_2\log(kWfH) + \varepsilon_i$	83	-180408	360982	73403.9
$a_{Y_iM_i} + \log(kWfH) + \varepsilon_i$	82	-190586	381335	93756.5
$a_{1,Y_iM_i} + a_2\log(kWfD) + \varepsilon_i$	83	-178958	358082	70503.6
$a_{Y_iM_i} + \log(kWfD) + \varepsilon_i$	82	-179362	358887	71308.9
$a_{1,Y_iM_i} + a_2\log(sD) + a_3\log(P) + \varepsilon_i$	84	-177717	355601	68022.7
$a_{Y_iM_i} + \log(sD) + \log(P) + \varepsilon_i$	82	-181051	362267	74688.1
$a_{1,Y_iM_i} + \log(sD) + a_2\log(P) + \varepsilon_i$	83	-177794	355755	68176.0
$a_{1,Y_iM_i} + a_2\log(sD) + \log(P) + \varepsilon_i$	83	-180465	361095	73516.9
$a_{1,Y_iM_i} + a_2\log(fD) + a_3\log(P) + \varepsilon_i$	84	-177646	355459	67880.6
$a_{Y_iM_i} + \log(fD) + \log(P) + \varepsilon_i$	82	-179362	358887	71308.9
$a_{1,Y_iM_i} + \log(fD) + a_2\log(P) + \varepsilon_i$	83	-178120	356407	68828.3
$a_{1,Y_iM_i} + a_2\log(fD) + \log(P) + \varepsilon_i$	83	-179361	358888	71309.2
$a_{1,Y_iM_i} + a_2\log(fD) + a_3\log(P) + a_4\log(fD)\log(P) + \varepsilon_i$	85	-177240	354650	67071.8
$b_{V_i} + a_{1,Y_iM_i} + a_2\log(fD) + a_3\log(P) + a_4\log(fD)\log(P) + \varepsilon_i$	86	-150683	301537	13958.5
$b_{V_i} + a_{1,Y_iM_i} + a_2\log(kWfD) + \varepsilon_i$	84	-150945	302058	14479.8
$b_{0,V_i} + a_{1,Y_iM_i} + (a_2 + b_{1,V_i})\log(kWfD) + \varepsilon_i$	86	-148425	297022	9443.5
$b_{V_i} + a_{1,Y_iM_i} + a_2\log(kWfD) + \varepsilon_i$	**92**	**-143697**	**287579**	**0**

Chapter VII: Modelling Fisher Choice and Métier Dynamics using Markov Transitions

Abstract

A métier-based bio-economic model of the Irish fleet is presented. The model uses Markov transition probability to predict fisher métier choice, based on a series of explanatory variables mimicking fishing decisions and drivers. These include economic variables: previous fishing trip landings value, cost of fuel consumption, and quota availability.

Application of this model highlighted variation between métier transition probabilities implying that métiers groups are affected by, and respond differently, to drivers and external pressures. The high level of fidelity observed within métiers indicates vessels usually maintain the status quo. When change does occur, the interaction of vessel length was an important descriptor of transition probability, as was fuel cost interaction. Season and value interaction were less important drivers of métier transitions. Thus, management within mixed fisheries should be targeted at a fine scale and include consideration of the economic influences behind fisher behaviour (such as fuel costs). Not only would this increase the likelihood of achieving management goals, it would also facilitate improved management focus on those métiers associated with issues of particular concern, and avoid penalising other fishers.

Key words:

Fisher behaviour; Markov process; bio-economic modelling; Fisheries management

Introduction

European fisheries management has attempted to maintain sustainable stocks through the application of single species considerations like total allowable catches (TACs), minimum landing sizes, and technical measures (e.g. minimum mesh sizes). Such measures are focused on managing discrete stocks. This approach is considered to be inefficient in mixed fisheries in which multiple species and fleets operate within the same fishing areas (Kraak *et al.*, 2012). In a mixed fisheries context, fisheries managers should focus more on managing the fishers to achieve sustainability of the resource. Investigation into fisher responses to management initiatives is a crucial element to determining the likely impact of management strategies of comparable importance to biological and ecological factors (Wilen *et al.*, 2002; Hilborn, 2007).

Concern has been expressed over the focus on biological of resource management (Andersen *et al.*, 2012), while discounting important influences on fishers' adaptability to respond to system pressures (Wilen *et al.*, 2002; Hilborn, 2007) such as management regimes, increasing fuel prices, and changing consumer tastes. Gaining insight into factors influencing the fishing decision processes is necessary to understand observed individual and group behaviour. The interdisciplinary nature of fisheries demands consideration of social, economic, and biological aspects when modelling behaviour. Such investigations into fisheries behaviour have become more prevalent in recent years such as those by Tidd *et al.* (2012), Andersen *et al.* (2012), Edwards *et al.* (2011), and Bastardie *et al.* (2013).

van Putten *et al.* (2012) identified a number of behavioural types: location choice, strategic, compliance, discards, or entry/exit. These categories can examine behaviour at short-, medium-, and long-term scales. Short-term dynamics and decisions are those which affect the way fishing occurs, for example the month to month, or trip to trip, spatial, temporal, and species targeting choices. Longer-term dynamics relate, for example, to vessels entering and exiting fisheries (capacity dynamics) or technical creep (vessels improving in efficiency over time). Differing imperatives at each scale result in different strategies from both fishers and managers.

To examine these various aspects of behaviour, a number of different methodologies have been applied including: ideal free distribution, agent-based, and random utility models (see reviews by Branch *et al.* (2006), Hilborn (2007), and more recently van Putten *et al.* (2012)). These approaches attempt to simplify the complexity of dynamics, whilst balancing against corresponding associated uncertainty (Bence *et al.*, 2008). The majority of methods can be employed as bio-economic models. Specific model choice can be attributed to several reasons, including the underlying model theories and assumptions, data type (distributions and assumptions), application and objectives, as well as data availability. One such emerging methodology is the application of neural networks. A novel model of Markov transition probabilities was applied to simplified conditional logit models to determine effort allocation dynamics within Australia’s Northern Prawn fishery (Venables *et al.*, 2009).

The current investigation builds on the approach applied by Venables *et al.* (2009) to apply a novel method of examining strategy choice behaviour within the Irish fleet in the context of movement between métier groups (homogeneous groups of fishing trips described by a combination of fleet and fishery characteristics; ICES, 2003) to examine mixed fisheries dynamics and responses to management. The analysis assesses the capacity of this novel modelling approach at predicting transition probabilities between métiers for a given set of conditions mimicking fisher choice behaviour. Specifically, the analyses aim to:

- Determine explanatory variables that best describe transitions within and between métiers;
- Formulate a Markov chain multinomial model with main effects and interactions between main effects and the previous métier; and
- Evaluate the model's capacity to predict responses to a series of changing pressures.

Materials and Methods

Data

Irish logbook data for vessels ≥10m total length from 2003 to 2011 were made available from the Department of Agriculture, Food and the Marine. For each fishing trip, fishing operations (dates; time fishing; location; gear; estimated catches), landings declarations (date; location; landed volumes; per kg first sale value) and vessel characteristics (overall length; engine power) were available. Incomplete records were excluded (~1.5% of available data). Unrealistic trip landing values were removed (i.e. 3 trips with values <€1).

Data from vessels with <5 fishing tips per quarter were excluded from the analysis (~3% removed). This satisfies a stipulation from the data providers to ensure the activities and privacy of individual operators were protected. It also reduces the likelihood of erroneous data obscuring the representation of recurring patterns. Venables *et al.* (2009) made a similar, although more extensive, exclusion of less active vessels to ensure that retained data produced vessel movement parameter values of most relevance to the fishery.

The final dataset consisted of 139,587 fishing trip records from 704 vessels across the years 2003 to 2011. Initial trials assessed the explanatory capacity of combinations of variables describing engine power, vessel length, fishing effort, métier, fuel price, fuel consumption, value, quota availability, season, and profit.

Engine power and vessel length

Engine power and overall vessel length for each vessel were obtained from the Irish fleet register, and given in kilowatts (kW) and meters (m) respectively.

Effort

Effort is calculated as kilowatt fishing days; days where fishing operations were reported within a trip multiplied by engine power. This was identified as the most appropriate effort measure for value per unit effort calculations, as detailed in Chapter VI.

Métiers

Fishing trips were assigned to métier classifications according to Chapter II (Davie & Lordan, 2011a) for otter trawls and Chapter III classifications for remaining gears.

The complex transition matrix resulting from the 67 métiers (Figure 7.1) was considered excessively high dimensional (67x67 transitions for the simplest transition model). This complexity was reduced by combining métiers into the following "métier groups":

Nephrops directed (Neph), demersal directed (Dem; targeting various whitefish, flatfish and rays), slope directed (Slope; targets including: megrim, monkfish, hake and ling), deep sea directed (Deep), pelagic directed (Pel), and other trawl (OT; trips with unclear or highly mixed targets). Non otter trawl métiers were grouped to gear type as: Scottish seiner (SSC), beam trawl (TBB), dredges (DRB) and passive gears (Pa; including gillnets, pots, longlines). These métier groupings result in a much simpler transition matrix (Figure 7.2). It was considered important to retain the OT group to account for the polyvalent nature of the Irish fleet in which vessels are able to target multiple species (groups) or areas during a trip. Deep sea trips (234) were excluded due to the decline and cessation of deepwater fishing within the time period (as outlined by Davie and Lordan, 2011a).

Fuel price and consumption

Average overall annual fuel prices per litre, 2004 to 2011 (Table 7.1), were provided by Bord Iascaigh Mhara (BIM). Average fuel price per litre was not available for 2003 and assumed to be the same as that from 2004.

Values of fuel consumption per day (litres) were estimated applying Equation 1 (reproduced from Equation 3 Chapter V) for each fishing trip based on annual dominant fleet segment (determined according to DCF definition and methodology[10]). Fuel consumption estimates were not available for 'polyvalent mobile' or polyvalent passive' fleet segments. The small number of instances relating to these gears (28 vessels resulting in 33 year-vessel combinations) were assigned a fleet segmentation on a trip by trip basis.

$$\log(F_i) = a_{0,G[i]} + s_1(\log(SL_i)) + s_2(\log(SE_i)) + \varepsilon_i \qquad \text{Equation 1}$$

Where F is fuel per day, s_1 and s_2 are GAM smoother functions (thin plate regression splines) applied to SL as standardised length and SE as standardised engine power respectively, G is gear, and i is the ith observation. Vessel length and engine power were log standardised by applying the mean (3.085 and 5.810 respectively) and standard deviations (0.379 and 0.793 respectively) obtained from modelled data of Chapter V.

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[10] A vessel is allocated a gear annually based on the gear with the highest number of fishing days within the year (i.e. over 50% of fishing days), if no gear dominates the vessel is allocated to one of 3 polyvalent segments (all mobile gears, all passive gears, mixed mobile and passive gears), from http://datacollection.jrc.ec.europa.eu/dcf-fish/eco/dsgr visited 12/03/2013

Application of Equation 1 was deemed appropriate given the overlap between the sampled vessel characteristics and those of the wider Irish fleet (Figure 7.3a and 7.3b). One vessel (120m and 6600kW) greatly exceeded the modelled range. Records for this pelagic vessel were removed (18 trips) as the accuracy of its fuel consumption predictions could not be determined.

Fuel consumption estimates generated four potential test variables: fuel per day (litres); fuel cost per day (litres x average fuel price); fuel per trip (litres x days at sea given as days absent from port); and fuel cost per trip (trip fuel x average fuel price).

Value

Landed weight and price at first sale per kilo were available from the logbooks. The reported landed weights were raised to estimated live weight using conversion factors if fish were not landed whole. Validated first sale prices per kilo scaled to live weight (the methodology of which is given in Chapter VI) were used to calculate the total value of each species landed (weight x price), and then summed across species to give a total Euro value per trip (VPT).

Quota

For most demersal TAC species/stocks the Irish quota management system is not individualised to vessels (Note: different quota management arrangements are used for pelagic stocks). Quota limits are set according to vessel length (above and below 55ft), gear type (e.g. higher limits of haddock (*Melanogrammus aeglefinus*) and whiting (*Merlangius merlangus*) for Scottish seine gears) and special licence categories (e.g. monkfish scheme). The Irish demersal species quota allocations assigned to vessels by DAFM and published within fisheries management notices[11] were available from 2006 to 2011. Demersal quota is allocated to vessels on a monthly, or occasionally bi-monthly, basis as detailed within fisheries management notices. Where bi-monthly allocations were stipulated this investigation divided the quota equally between the two months.

Based on primary target species, it was possible to generate a monthly available quota (tonnes) for each métier group. For example, monthly megrim (*Lepidorhombus spp.*),

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[11] Available online at www.agriculture.gov.ie/fisheries/fisheriesmanagementnotices

monkfish (*Lophius spp.*), hake (*Merluccius merluccius*), ling (*Molva molva*), and tusk (*Brosme brosme*) quotas were used to generate quota available to the slope métier. Closed fisheries were assigned a zero allocation, while open fisheries were assigned a value above the maximum observed monthly vessel landings over the period 2003-2011, simulating an "unlimited" quota. A number of species with small national quotas, (e.g. sole; *Solea solea*) are restricted to non-targeted landings through the use of by-catch percentages. As trip landings vary, a nominal weight of 0.02t per percentage point was assigned to by-catch percentages to ensure low, yet realistic monthly volumes. For example, a monthly limit of 1t per vessel was assigned to a 50% by-catch limit (0.02x50). A number of vessels partook in the annual "monkfish scheme" to obtain additional monkfish allocations in exchange for by-catch limits of cod (*Gadus morhua*), haddock, *Nephrops*, plaice (*Pleuronectes platessa*) and sole. Monthly quota allocations were adjusted for these vessels to account for variations (applying 0.02t per by-catch percentage as above).

It was not possible to simplify quota management arrangements for pelagic species in this study, so instead quotas were reduced to a single, large monthly vessel limit of 3,000t (few vessels landed volumes above this between 2003 and 2011). Within the passive gear métier grouping 300t was allowed to account for landings of species caught in pots (crabs, lobsters, and whelks (*Buccinum undatum*) which are not currently managed by quota. Similarly, a combined limit of 500t was specified for dredge gears. These primarily target scallops (*Pecten spp.*), clams (*Spisula spp.*), mussels (*Mytilus edulis*), and razor shells (*Solenidae*) for which quota is only set for scallops.

Monthly allocations were also translated into a monetary value (Euro) by applying a monthly average validated live weight first sale price (as described in Chapter VI) per quota species summed across primary target species. An average of the dominant species landed by each pelagic fishers, dredgers and potters were used to estimate values for the quota assigned weights of the pelagic, dredge and passive métier groups.

Season

Year and seasonal proxies were derived from reported trip landing dates. Based on preliminary analyses, seasonal proxies were considered at the level of day of the year (DOY) following a poor performance of month and quarter which appeared to artificially segment seasons. A number of different trend types were trialled including linear, quadratic, cubic, and half sin wave. From these application of a half sin wave and a cubic polynomial trend gave the best fits to the averaged seasonal trends observed. These were therefore retained as possible seasonal proxies within subsequent analyses.

Model

A time inhomogeneous Markov process was used to describe vessel movements between métiers on a trip by trip basis, with transition probabilities based on perceived key drivers (detailed below). Analysis was carried out within R (R Core Team, 2012), based on the *multinom* function via neural networks within the *nnet* package (described in Venables and Ripley, 2002). Data were available from 2003 to 2011 for all variables except quota allocations which were limited to 2006-2011. Therefore, model construction and conditioning was limited to 2006-2011 (103,711 fishing trips).

The transitions considered here represent the movements of vessels between métier groups on a fishing trip basis, in which fidelity to the same métier group was permitted. There are no restrictions on the movement between specific métiers so vessels can transition freely. Let Y_t denote the métier state at time *t*, we are focused on $P(Y_t = j|Y_{t-1} = i) = p_{j|i}(t), t > 1$ that is, the probability of being in state *j* at time *t* given that it was in state *i* at time *t-1*, which is given by the time-inhomogeneous transition probability $p_{j|i}(t)$. Time-inhomogeneity enters through the influence of explanatory variable on the transition probabilities. The influence of explanatory variables is included, as in Venables *et al.* (2009), as:

$$p_{j|i}(t) = \frac{\exp(\boldsymbol{X_t}'\boldsymbol{\beta}^{(ij)})}{\sum_{i,j} \exp(\boldsymbol{X_t}'\boldsymbol{\beta}^{(ij)})}$$

Where $\boldsymbol{X_t}$ is a vector of explanatory variables.

The transition matrix is conditioned on perceived drivers as explanatory variables. A number of single variable model runs were carried out to determine variables which best described observed transitions. Results from these preliminary runs given in Appendix D. AIC values were used to compare these single variable models and to select the following variables for inclusion within the full model:

- Year as a categorical variable, representing between year variability in behaviour and tradition.
- Achieved value of the previous trip as a proxy for gross revenue representing economic attractiveness of the previous time step. If the value achieved was poor, a fisher is more likely to enter a different métier in the next time step.
- Estimated per day fuel cost as a proxy of operational costs
- Season described by a cubic day of year relationship as a proxy for temporal within-year variability between métiers
- Monthly available quota represents both a management regulation occurring at a monthly time step but also a proxy for stock health where quotas (total allowable catches) are set annually according to perceived stock health.
- Vessel length conditioning the model to vessel capability limitations

The full model was limited to two way interactions with the métier group of the previous time step ($state_{t-1}$) to specifically explain transitioning between métiers. To test the relevance of all terms and interactions within the full model, ensuring signals and not noise were captured, the Akaike's Information Criterion (AIC; Akaike, 1974) value of all possible permutations (792 models) were tested against the full model. The influence of explanatory variables was subsequently investigated by modelling the model AIC values as a function of presence or absence of given explanatory variables using regression trees (De'ath and Fabricius, 2000).

It should be noted that quota availability and abundance could affect the species mixture achieved by a trip without a change in practice or target, but would however influence the métier assignment. The current model looks only at the last trip and current trip, time spent at the quay side or vessels exiting the fleet were considered irrelevant to métier choice. This varies from effort allocation models including, Venables *et al.* (2009), where a dummy region or group were often stipulated to represent inactive fishers.

Results

Model selection

From all permutations of the full model (792) a single instance of lower AIC occurred (interaction between métier grouping at $state_{t-1}$ and available quota omitted). This indicates model terms included are justified, representing signals within the data rather than noise. Using AIC values of these models, the strongest (and most marked) influence determining $state_t$ métier choice was identified as the métier grouping of the previous time step (Figure 7.4 and Figure 7.5). Further to this, the interactions between grouping at $state_{t-1}$ and i) vessel length, ii) per day fuel cost in $state_{t-1}$, and iii) season were the of greatest importance in determining transition into $state_t$ métier grouping (Figure 7.6).

Model application

Due to the complexity of the model (117 parameters estimated in the final model), visualisation and description of variation in transition probabilities resulting from all model terms is not practicable. Visualisation was limited to varying the three main transition effects against static values for remaining variables chosen based on importance. A high and low fuel cost per day at $state_{t-1}$ estimate were tested on July 1st (to represent summer) and December 15th (representing winter) over the range of vessel lengths occurring within métier groups at $state_{t-1}$. Year was restricted to 2011, being the most recent year modelled from which average estimates within métier group at $state_{t-1}$ for value at $state_{t-1}$ and available quota at $state_t$ were generated. Even at this level the resulting matrix demonstrates a huge degree of detail and variation of interest between métiers and how they transition (Figure 7.7). Some of the example outcomes for each métier are highlighted here.

In 2011 fuel and season had greater effect on Neph to Neph transitions for smaller vessels, with lower fidelity probability when fuel prices were high, more so in winter. For these vessels, transitions to alternative metier groups occurred mostly into Slope or Pa métiers. Small vessels are unlikely to be Slope fishers, which is identified within the original métiers which have been grouped here (Davie & Lordan, 2011a). However, beyond ~15m there is little variability in the proportion continuing to fish within the

Slope métier under the two scenarios tested. Within the Dem métier fidelity declines with vessel length influenced by fuel cost while changing season shows little impact on the transition probability. The Ot métier shows a great deal of transition diversity, migrating into Neph, Slope, Dem as well as continuing within Ot. "Humps" occurred at low fuel costs for smaller vessels in each of these three alternative métiers, while at high fuel costs transition levels are more constant across the range of vessel lengths. The Pa métier is attractive with low fuel costs. Season can only really be observed as slightly elevated transitions into the Slope métier in summer. Transitions from the Pel métier are highly influenced by both fuel cost variation and season. At high fuel costs almost 100% maintain fidelity to the Pel métier. At low fuel cost in winter, transition fidelity is high for smaller vessels but declines with increased length, preferring instead the Slope métier. While in summer there is a lower probability of remaining within the Pel métier even for smaller vessels, again fidelity decreases with increasing vessel length. The smaller vessels have greater preference for the Neph métier while larger vessels have an affinity to the Slope.

Across most of the SSC length range, vessels continue the status quo exhibiting little variation between fuel costs or season. The same is true within the Pa métier group for most lengths. A switching point occurs for larger vessels resulting in movement to DBR however this is caused by very few data examples. Within TBB over the observed length range at high fuel costs 100% of transitions result in fidelity to the TBB métier. At low fuel cost, transition is reported as switching to the DRB métier although this is likely to result from few data examples. Finally, DRB tend to maintain fidelity to the métier at high fuel costs, but switch to Pa at lower fuel costs. Although lower fuel costs are unrealistic for DRB vessels given their high fuel consumption (Chapter V), thus generating an artificial transition probability.

An example of inter-annual transition predictions was run varying fuel cost and value (Figure 7.8) for a 50m vessel according to 2011 transition probabilities having begun the year in the Pel métier group. This showed the consequence of high fuel cost and decreased value, as well as the influence of the time of year. For the first several months transitions maintained the status quo then began what appeared to be a cyclic pattern of transition across a variety of métiers without consistency. When fuel price increased transition became constant within the SSC métier, switching back to Pel toward winter months when value dropped significantly.

Discussion

The overall goal of this work was to examine strategic behaviour, in the context of métier groups, within the Irish fleet. A Markov multinomial model was applied to generate a series of transition probabilities developed from a similar concept to that applied by Venables *et al.* (2009) for effort allocation. The model developed here incorporated seven explanatory variables covering vessel characteristics (vessel length), fishery preferences (métier group at state_{t-1}), annual and seasonal variation, economic considerations (value at first sale at state_{t-1} and fuel cost per day at state_{t-1}), stock health and management regulations (available quota). The inclusion of these variables attempts to mimic complex relationships whilst avoiding over parameterisation of the model, an issue identified in other investigations of fisher behaviour (Venables *et al.*, 2009; Andersen *et al.*, 2010). Previous investigations into fisher behaviour have often been limited by the restricted availability of detailed economic data. They have thus applied proxies for fuel costs such as distance travelled to fishing regions (Andersen *et al.*, 2012) or fuel price (Abernethy *et al.*, 2010). Here, attempts were made to replace this type of proxy with more detailed economic data an effort to increase the ability of the model to map data variability. A model was used to estimate fuel consumption (Chapter V) and a detailed validation of underlying first sale prices used to generate value (Chapter VI).

The greatest influence on métier group choice at state_t was the métier group of the previous trip representing recent knowledge. Ulrich *et al.* (2007) and Andersen *et al.* (2010) also found the proxy recent knowledge (i.e. fishing pattern in the previous time step) influenced choice. The high level of fidelity observed to the previous métier indicates a high level of inertia in fishing behaviour. This finding is not new. Similar studies have found this high degree of inertia representing a general conservativeness in fisheries behaviour (Suuronen *et al.*, 2012; Bastardie *et al.*, 2013). Other studies have shown or suggested that switching behaviours indicated "switching thresholds" being points at which a métier becomes unattractive and fishers must move to a more attractive alternative (Figure 7.7) (e.g. Andersen *et al.*, 2010). Whilst switching thresholds are likely to be individual to the skipper and based on their personal circumstances, here we have generalised and visualised the transition probability matrices in a way that allows us to explore future scenarios through management simulations.

Transition between métiers is complex, and a number of drivers aid in explaining that complexity. Within the current investigation vessel length was the most important influence on métier transition probability. Here small vessels tended to have different transition probabilities to those of larger vessels. This is a variable which has previously received little attention in behaviour studies, however such differentiation has been highlighted within studies defining métiers (Davie & Lordan, 2011a). The finding is a logical result within fisher behaviour given the different operating limitations related to vessel size, such as gear configuration possibilities, maximum travelling distance, weather dependence, and capacity of both hold and crew.

Fuel cost per day of the previous trip was also an important driver of métier transitions. Fuel usage proxies were previously identified as an important driver of fishing behaviours within Danish fisheries (Bastardie *et al.*, 2013) and within the UK's southwest fishing fleet (Abernethy *et al.*, 2010). However, Andersen *et al.*'s (2012) use of distance travelled to fishing ground as a proxy for fuel cost was only identified as a descriptive term of lesser importance.

These findings highlight the importance of including appropriately detailed proxy variables when analysing choices. They also affirm the economic nature of fisher choices and the major impact fuel costs have within the decision making process. This is unsurprising given that fishing is an economic operation, where fishers are assumed to act in a profit (or utility) maximising, rational manner using the information available to them to choose the most profitable fishing options (Wilen *et al.*, 2002; van Putten *et al.*, 2012). Within such a system fuel costs can represent one of the largest costs associated with fishing at the operational level, although the proportions are known to vary between fisheries (Sumaila *et al.*, 2008).

Season was also found to be important, reflecting the underlying seasonal dynamics of various target species, for example, emergence behaviour of *Nephrops* or timing of mackerel migration with the movement of fishers mirroring resource availability. Seasonal knowledge or experience was an important driver of fishing decisions in several previous studies (e.g. Marchal *et al.*, 2009; Andersen *et al.*, 2012).

Surprisingly the value obtained on the previous trip was of lesser importance. Although surprising, this finding agrees with Andersen *et al.* (2012) where fish price was identified as a lesser variable. Furthermore, Marchal *et al.* (2007) considered that fish prices (and trip values) provide only partial information on the economic incentives driving fishermen’s decisions, this concurs with the results presented here.

A proxy of "profit" was trialled as an explanatory variable having been identified as an important explanatory term in other behavioural studies (e.g. Andersen *et al.*, 2010). However of the series of preliminary runs expanding the model to choose variables "profit" was not defined within the best fitting runs. Such a result indicates the proxy was not well estimated and hence unable to accurately reflect the true profit obtained from the previous fishing trip. Per litre price of fuel used was an annual average and may have resulted in artificial negative "profits". Furthermore, the individual financial situation of the fisher is not accounted for within this proxy. For example some may have larger overheads than others.

Available quota was shown to be of lesser importance within the model. This indicates the method used here to include quota allocations is not as effective at describing fisher behaviour as other included terms. This, at some level may hint that quotas are unrestrictive, and thus not controlling mortality on the resource, at least in a mixed fisheries context. This finding concurs with the general acknowledgement of the failure of single species quotas to control removals unless combined with other tools (e.g. effort restrictions). For quotas to be effective, there must be a tangible limiting or moderating effect on fishing behaviours. During the data formulation stage of this investigation, the maximum monthly landing of any vessel was tested as a proxy for quota availability to enable use of the full dataset (no quota allocations available for 2003-2005) applying the assumption fishers fish to the quota allowance available. However, maximum monthly landings tended to be lower than the total monthly allowances assigned here. This would indicate that in the majority of situations the total quota available to fishers was not a limiting factor, and explains the low importance of this term within the full model. The current setup of quota management regime allows for mixed fisheries to continue even when quotas for "choke species", i.e. those of the poorest biological status, are very restrictive or closed, incentivising high-grading and/or discarding, as has occurred within the past for Celtic Sea cod for example (ICES, 2010b). Such choke species may result in some total quota allocations being restrictive, explaining the retention of available quota within the final model.

The transition probabilities formulated here indicate that métiers respond differently to the ranges of the different variables examined. This highlights the presence of differing incentives, drivers, and range of fishing options available between the various métier groups. Andersen *et al.* (2010) identified similar differentiation within the North Sea in relation to flatfish targeting fleets. Improving management outcomes within mixed fisheries contexts will require improved incorporation of métier interactions when an overlap of stocks and fishing grounds exists between métier groups. This finding adds weight to the conclusions of a growing number of studies (e.g. Reeves *et al.*, 2008; Andersen *et al.*, 2010) that fisheries management should encompass métier (or some form of mixed fisheries) interactions in addition to single stock considerations.

Some unusual probabilities were generated by the model, particularly probabilities of moving into the dredging métier group from a number of the otter trawl métiers (Figure 7.7). This is an unlikely switch in practice given the degree of gear refit required to change to or from dredge fishing making regular switches unlikely. The probabilities were based on few instances of switching into or out of dredging. Where little other between métier switches occur, the model may over emphasise these rare occurrences. The occurrence of rare switches was reduced following the removal of trips from the least active vessels. However, the presence of switches including dredges implies that an amount of uncertain data remains. To further investigate this it would be possible to model the misspecification in the original dataset using a hidden Markov model which assumes there an underlying true métier states which are recorded with error (e.g. Rabiner and Juang, 1986). A series of penalties could also be added to restrict, for example, capacity, effort, or the number of vessels so the model works only within what is physically possible.

The model presently uses "recent knowledge" and "season" to aid métier choice. If the conditions within the current métier become less favourable a vessel will switch, dependent on the formulated transition matrix, to another more favourable métier. However, if conditions within the original métier improve the vessel will only revert back if the attractiveness of new métier decreases. In going forward to the next state, there is no "memory" within the system other than that of the present state. Although the Irish fleet is highly polyvalent, its polyvalence is likely to be more opportunistic and include an underlying preference toward tradition (or memory), enhancing the likelihood of reverting to preferred fishing targets when conditions are favourable. For use within management strategy evaluation it may be preferable to incorporate a form of "memory" into the model. Ulrich *et al.* (2007) and Andersen *et al.* (2010) for example use the same time in the previous year as a tradition proxy which may be able to act as such a memory. An alternative could be to include a "home métier" which could be defined as the dominant métier of the previous year, in a similar way to DCF annual fleet segment allocation. The attractiveness of the current métier may then be compared to that of the home metier; when equal to or better, preference is given to the home métier.

The transition model described here is not spatially explicit beyond the different variation in location of métier group target species, e.g. slope fisheries occurring on the edge of the continental shelf, demersal fisheries on the shelf, and *Nephrops* fisheries within discreet "muddy" patches. The resolution of métier groupings could be increased to account for specific spatial métiers or changed to model métiers congruent with the spatial similarities observed between analytically identified métiers (Davie & Lordan, 2011a), and those identified using vessel monitoring systems (Gerritsen *et al.*, 2012). One could imagine future applications such as examining and simulating transitions within *Nephrops* métiers or Celtic Sea mixed fisheries to inform species specific or regional management plans.

The model could also be improved by considering quota as a wider variable, using the future quota availability of all different métier groups to determine the most attractive métier for a given set of conditions. An additional explanatory variable or layer of interaction relating to discards could be developed within the model to allow for investigations to inform the discard reduction policies outlined in the CFP reform.

Although within the data range examined the discarding would represent the current practices, this could then be used to alter the importance and penalty of discards within a simulation process.

In addition to the possible improvements in the structure of the model presented here, there are several areas where extension of this current work is to be considered. Development and inclusion of further behavioural drivers should be explored and translated into explanatory variables. A primary imperative when increasing model complexity through such developments is to avoid over parameterisation. Incorporation of international data through altering the métier groups to those defined within the Data Collection Framework (EC, 2008e) could also be explored. As could the further disaggregation of the métier groups applied here, for example into specific *Nephrops* fisheries to identify the variability of movement and the causes. The current transition model could be reversed and developed into an optimisation tool for industry. For example, if a desire existed to maximise the value of a particular entity the model could identify the best métier grouping to target, given known constraints of other parameters such as fuel cost and season.

The primary avenue of interest however, is to develop the model's predictive capability within a management strategy evaluation (MSE) framework which are increasingly utilised to analyse management initiatives (e.g. Kraak *et al.*, 2008; Andersen *et al.*, 2010). Within such MSEs fisher behaviour (fleet module), resource dynamics (operating module), and regulation implementation (management module) are run in concurrent simulations to determine possible outcomes of changing drivers and management pressures. Incorporation of fleet dynamics models, such as the one developed, here could improve the predictive capability of pre-existing simulation frameworks such as ISIS-Fish (Mahévas & Pelletier, 2004; Pelletier & Mahevas, 2005; Drouineau *et al.,* 2006), FLR (Kell *et al.*, 2007; Vermard *et al.*, 2008), or TEMAS (Ulrich *et al.*, 2007; Andersen *et al.*, 2010). The outputs of such evaluations could subsequently better identify potential effects on effort distribution and mixed fisheries implications of prospective management strategies.

Conclusions

Detecting changes in fishing behaviour in response to external drivers and pressures is an important and expanding research area. Greater understanding of fisher behaviour can be used to improve the design and implementation of management initiatives. Increasing understanding of fisher, and aggregated fleet, behaviour can help to harmonise incentives with management objectives, and thus reduce likely implementation errors and unintended incentives through greater understanding of human factors (Fulton *et al.*, 2011). The bio-economic model presented here adds a new angle of examining fisher behaviour. A first attempt to integrate a métier strategy approach through the modelling of transition probabilities conditioned by detailed economic (fuel and value) explanatory variables within a lesser utilised framework of Markov transition probability. The model highlights the importance of recent knowledge, and interactions with vessel length and fuel costs in explaining transitions. Most importantly, the analyses indicate management should be focused on mixed fisheries, targeted at a fine scale, and include consideration of the economic influences behind fisher behaviour. Not only would this increase the likelihood of achieving management goals, it would facilitate focusing management on those métiers associated with issues of particular concern, and avoid penalising other fishers.

Figures

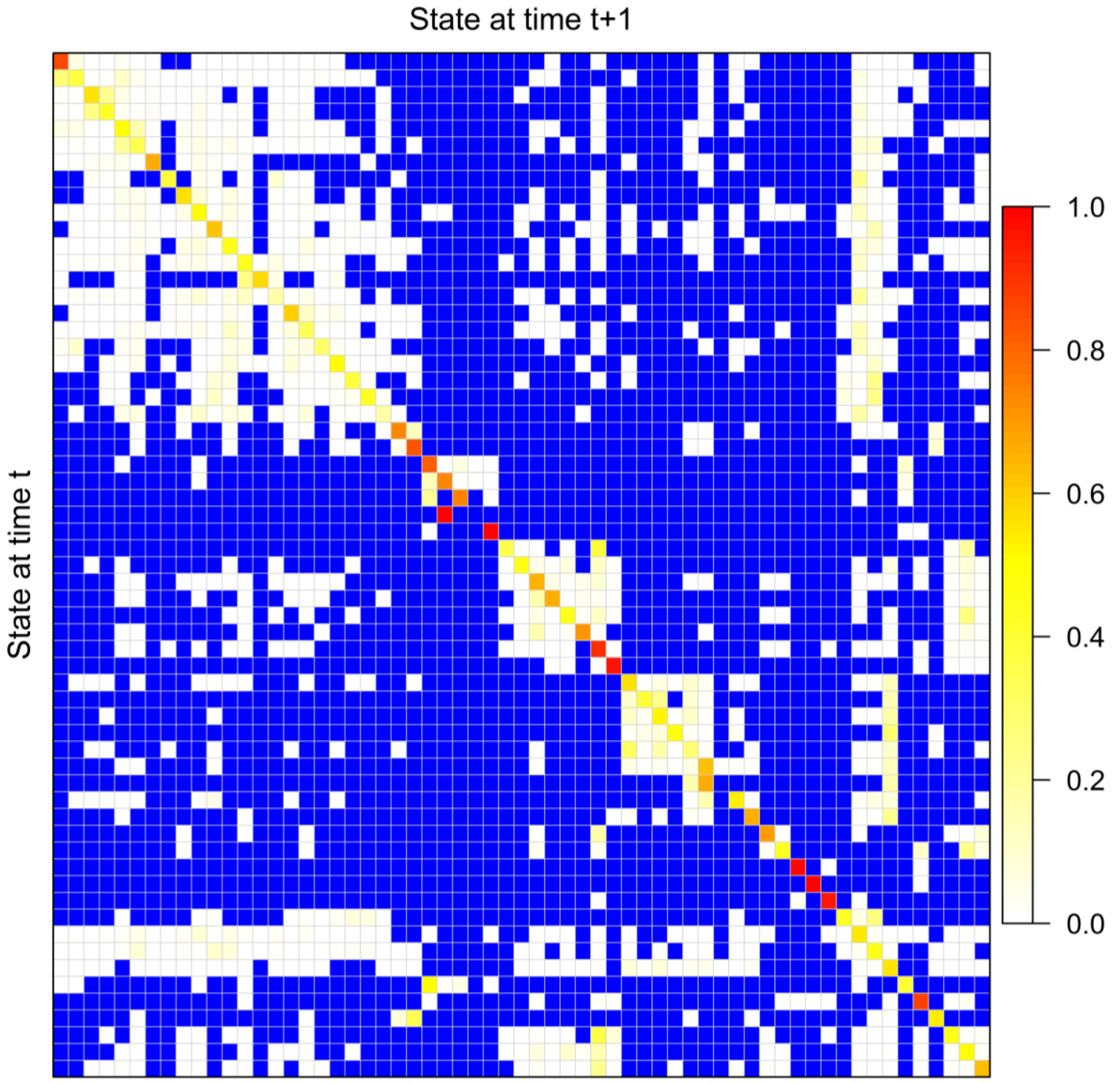


Figure 7.1. Transition matrix of the 67 Irish métiers (states), 2006-2011. Each square represents the likelihood of transitioning from one state (t) to another (t+1). Blue squares indicate zero likelihood.

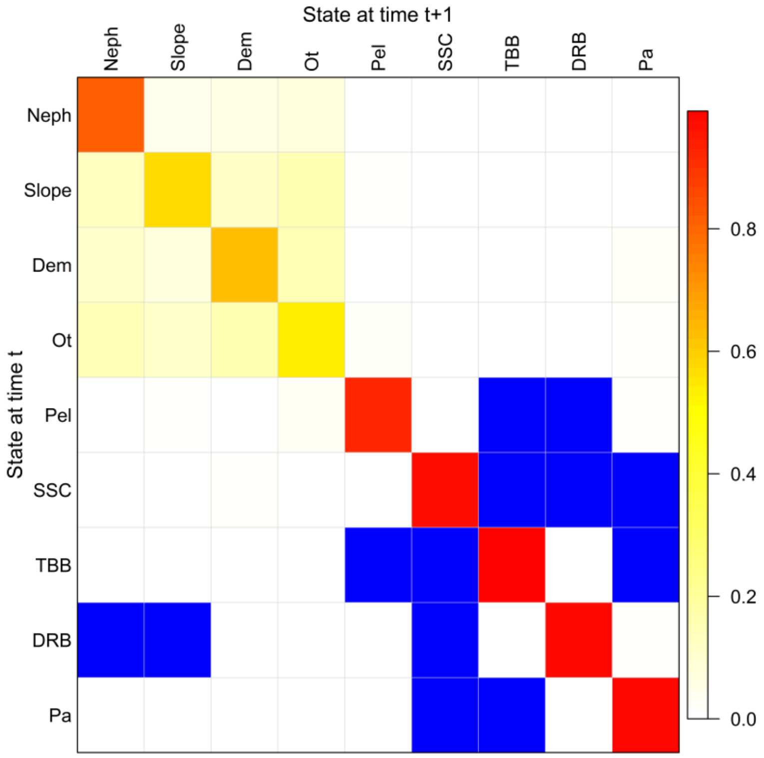


Figure 7.2. Transition matrix of condensed Irish métier groups (states), 2006-2011. Each square represents the likelihood of transitioning from one state (t) to another (t+1). Blue squares indicate zero likelihood.

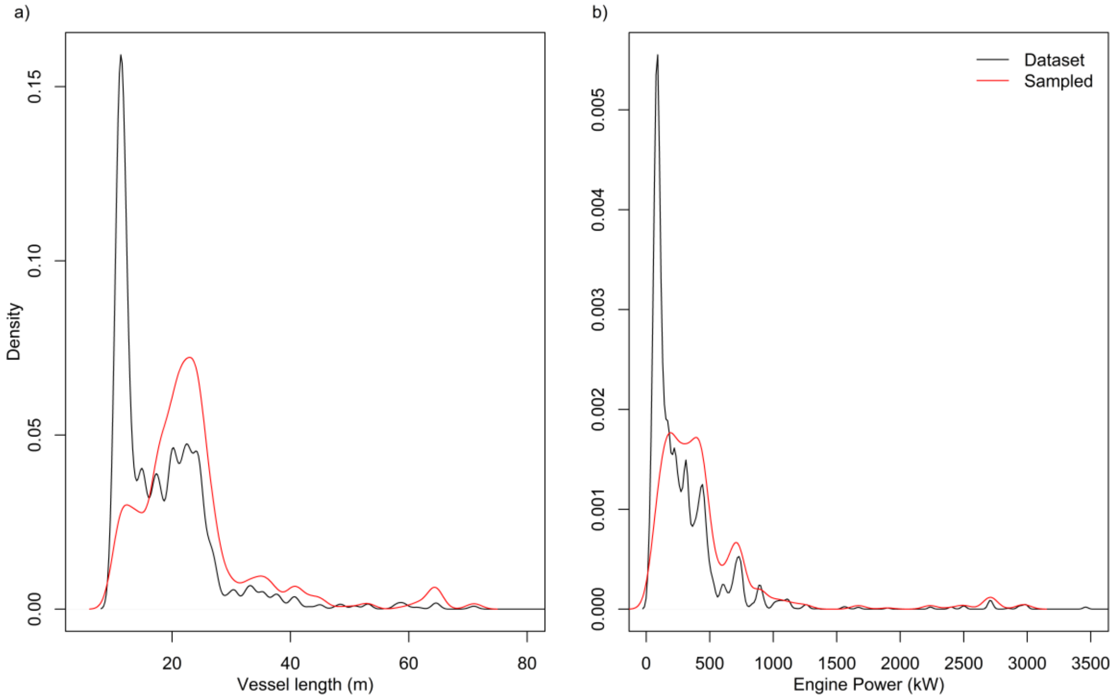


Figure 7.3. Density plots of sampled and main dataset ranges for a) overall vessel length (m) and b) engine power (kW).

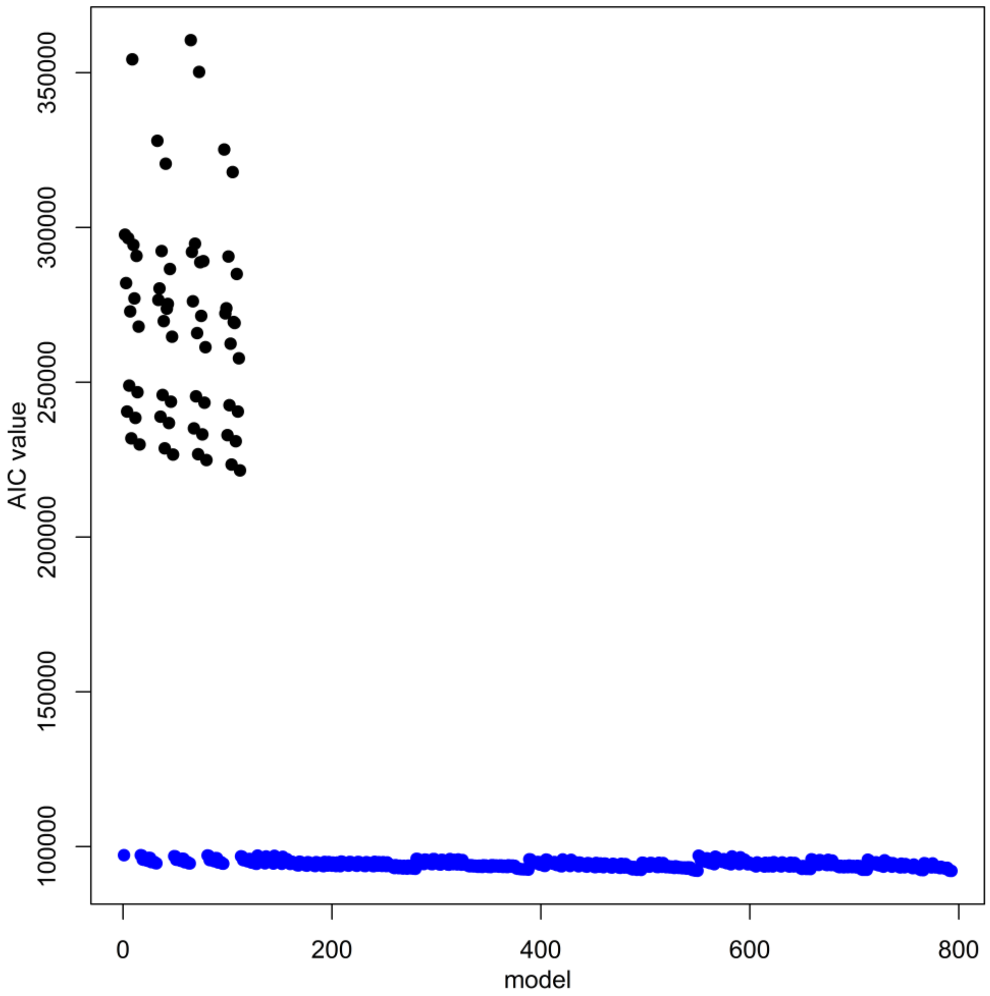


Figure 7.4. Representation of AIC values of all full model permutations. Black dots in the upper left represent models without $state_{t-1}$ term, blue dots across the bottom contain the $state_{t-1}$ term.

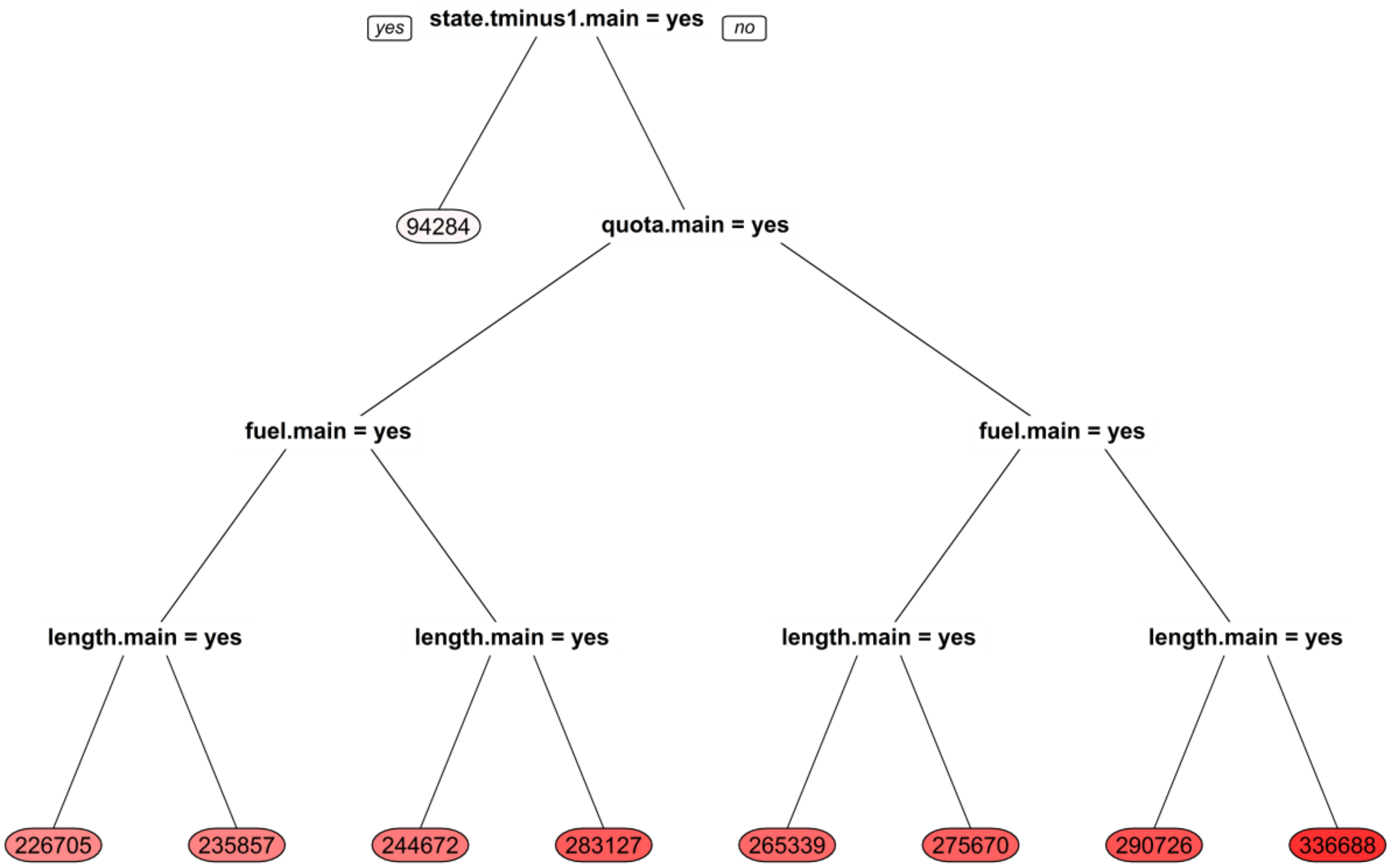


Figure 7.5. Regression tree of all full model permutations where response values are the resulting AIC values and model terms are the explanatory variables. Greatest explanatory terms affecting reductions in AIC values begin at the top. Subsequent splitting explains progressively less differentiation between AIC values. Most important terms are tracked down the left side of the plot.

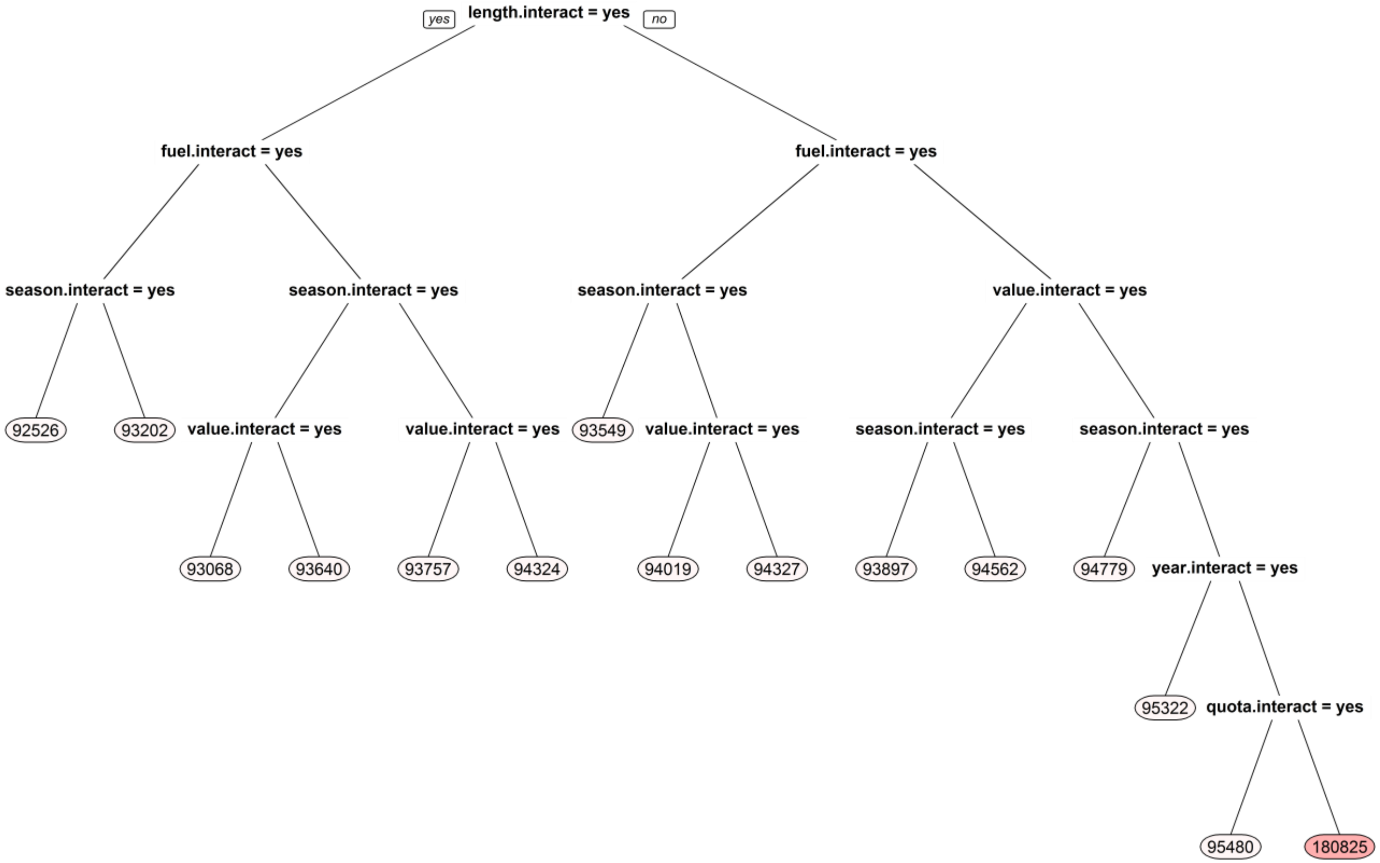


Figure 7.6. Regression tree of full model permutations containing one or more interaction terms. Where response values are the resulting AIC values and model terms are the explanatory variables. Greatest explanatory terms affecting reductions in AIC values begin at the top. Subsequent splitting explains progressively less differentiation between AIC values. Most important terms are tracked down the left side of the plot.

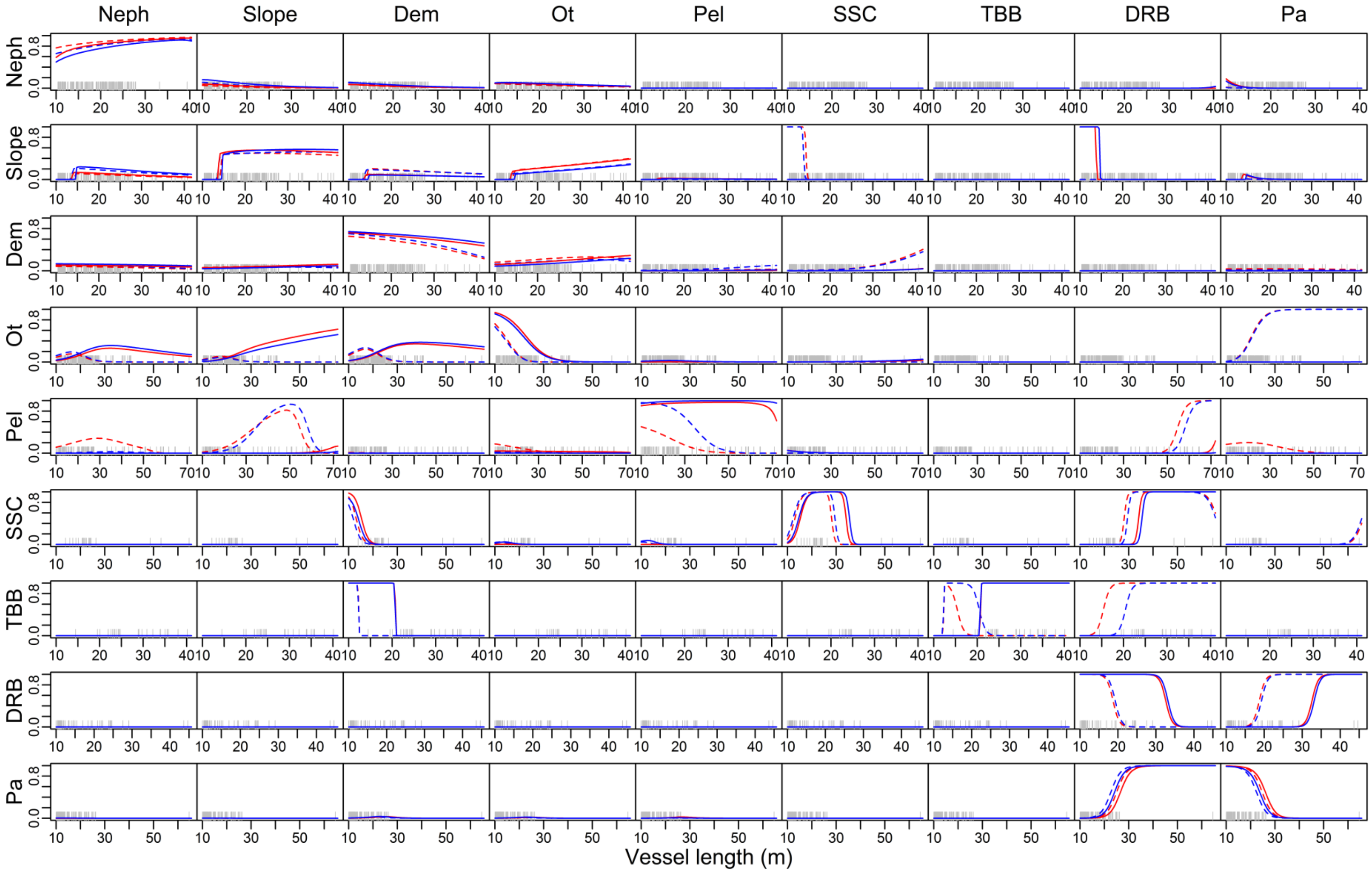


Figure 7.7. Matrix of transition probabilities from métier group at state$_{t-1}$ (left) to state$_t$ métier group (top) over the main interaction effect, vessel length (m) over the x-axis when varying fuel per day cost of the previous trip (low = dashed line , high = solid line) in summer (July 1st = red) and winter (December 15th = blue).

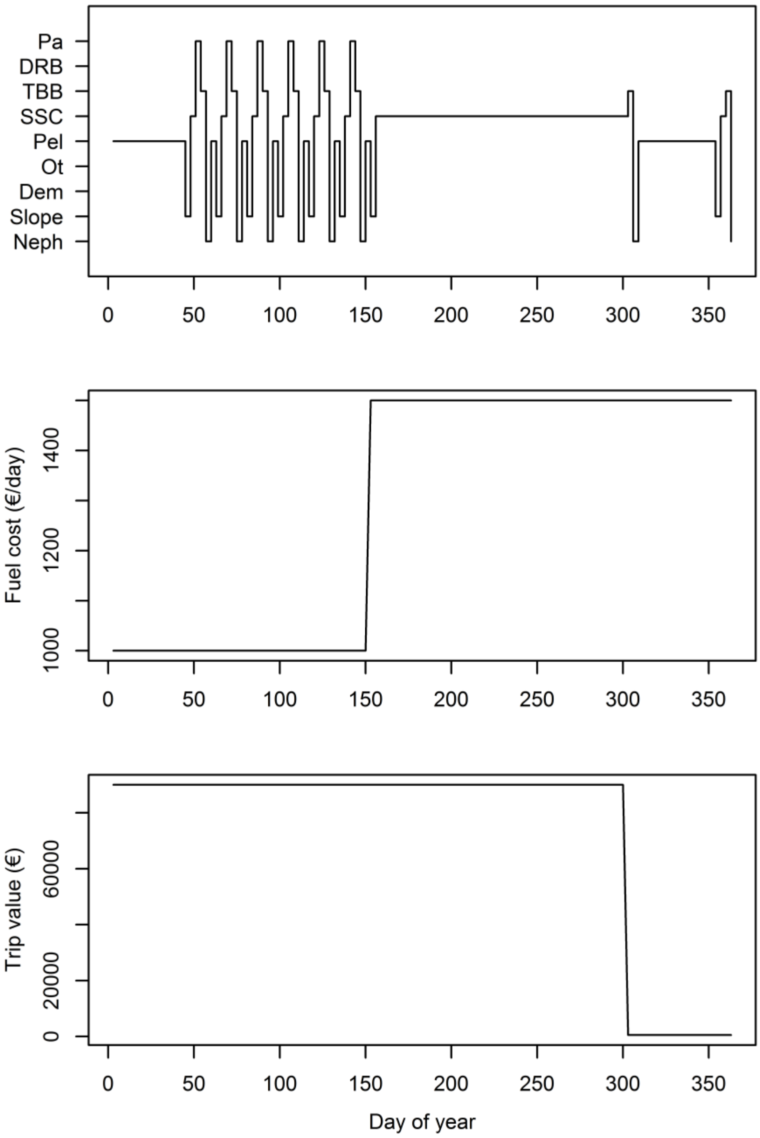


Figure 7.8. Panel plot depicting métier transitions resulting from the combined probability of varying the explanatory variables for a 50m length vessel in 2011 shown in the lower plots.

Tables

Table 7.1. Average annual fuel price per litre 2003-2011 applied in analyses, provided by BIM. N.B. 2003 price was not available at time of analysis and was assumed to be the same as 2004.

Year	fuel Euro/l
2003	0.329
2004	0.329
2005	0.420
2006	0.490
2007	0.490
2008	0.636
2009	0.418
2010	0.534
2011	0.660

Chapter VIII: General Discussion

Fish stocks in European Community waters have traditionally been assessed and managed under the common fisheries policy (CFP) under a single-species framework. The main management tools have been limited to single species output (e.g. Minimum Landings Sizes and Total Allowable Catch (TAC) quotas) and input controls (mainly technical gear regulations, closed areas, and more recently effort limitation). In the early to mid 2000's there was concern over the effectiveness of this traditional management system where several key stocks, including North Sea cod, demonstrated continued declines. This lead to changing policy perspectives in subsequent years, shifting emphasis towards more integrated, holistic approaches to account for mixed fisheries considerations and those of the ecosystem. The emerging ecosystem approach to fisheries management (EAFM) takes into account the multi-fleet, mixed fisheries nature of many European fisheries (by considering the biological status of multiple species together) as well as important economic and social considerations (Hilborn, 2007). The evolution and provision of advice and management tools in accordance with these approaches require a detailed knowledge of the underlying multi-species interactions and the multi-fleet nature of fisheries (ICES, 2012d). An understanding of the complexity, dynamics and adaptability within operational fisheries is also required (Holley & Marchal, 2004), particularly in relation to predicting the impacts of changing management strategies (Soulié & Thébaud, 2006).

The recently passed Common Fisheries Policy reform (EC, 2013) represents the commitment of European policy makers toward mixed fisheries and ecosystem based management. Understanding the feedback processes between human and biological aspects of the fisheries system is an important requirement in adaptive ecosystem-based management (van Putten *et al.*, 2013). Heretofore fisheries research has focused efforts on understanding the biological systems, but the responses of fishers to changing circumstances has received less attention (Hilborn, 2007). There is an imperative to improve our understanding of the motivations and incentives behind fishing and how these change with shifting pressures and incentives.

The potential inclusion of fisheries-fleet dynamics within the framework of management strategy evaluations (MSEs; e.g. Kraak *et al.*, 2008, Andersen *et al.*, 2010) has stimulated much of the current interest in fisher behaviour. Modelling of fisher behaviour itself is not a new concept, with early works going back to the 1950's, and reviewed most recently, by van Putten *et al.* (2012). This is an extremely complex, multifaceted subject, encompassing a vast quantity of possible drivers, incentives and pressures. Research literature on this topic continues to expand and at present specific focus is in relation to changing dynamics under economic and/or social drivers.

The main purpose of many investigations has been to develop more realistic behavioural responses to management in MSEs. Models have been developed to examine fisher location choice and effort allocation aimed at identifying fisher adaptation and displacement in response to management imposed effort restrictions and closed areas (e.g. North Sea flatfish, Bay of Biscay Anchovy). However, little direct investigation has been carried out relating to métier choice particularly around Ireland. Vermard *et al.* (2008) is an exception, having examined "trip choices", based on métiers, to identify switching responses within the Bay of Biscay pelagic fleet to a fishery closure. More recently Andersen *et al.* (2012) carried out a métier based choice model on short term effort allocation. However, identifying and understanding the drivers influencing the choice to switch or continue within particular métiers remains a very challenging research area.

Many fisher behavioural studies are limited to specific fisheries and/or areas within which specific management responses were expected to occur, for example English North Sea beam trawlers (Hutton *et al.*, 2004), Dutch North Sea beam trawl fleet in relation to plaice box closures (Poos & Rijnsdorp, 2007) or the French Bay of Biscay hake and *Nephrops* mixed fishery (Drouineau *et al.*, 2006). However, a small number of general investigations have been carried out, for example individual trip planning in Danish fisheries (Bastardie *et al.*, 2013). Although management is proposed at a regional level, vessels are capable of moving between fishing tactics and grounds influencing a wider area. This is particularly true within the Irish fleet where a large number of polyvalent vessels exist targeting a wide range of species across a diversity of regional areas (Davie & Lordan, 2011a; 2011b). To date, little modelling has been carried out in the diverse waters surrounding Ireland. Interest has been stimulated within the area following a request from the North Western Waters Regional Advisory Council (NWWRAC) to develop a mixed demersal fisheries management plan in the Celtic Sea (NWWRAC, 2011).

At present a variety of statistical methodologies have been utilised to analyse fisher behaviour, some examine individuals or a group of individuals assumed to act as a single entity, including ideal free distribution, agent-based, and random utility. Other methods are founded on a different approach, examining the behaviour of individuals within a group situation, e.g. game theory and network theory. Ideal free distribution and dynamic state models are founded on foraging theory (e.g. Powers & Abeare, 2009; Poos et al., 2010). The underlying rational asserts that individuals (in this context the fisher) will optimise gain rates, such as profit. Agent-based models are built upon a rule-based concept where behaviour can be described by a discontinuous rule set (e.g. Little *et al.*, 2009 and Bastardie et al., 2010). However, there have been relatively few empirical studies applying such models as they are data intensive and computationally demanding (van Putten *et al.*, 2012).

Random utility models (RUMs) follow utility maximisation through discrete choice (e.g. Hutton *et al.*, 2004; Vermard et al., 2008; Andersen et al., 2010). This type of model can be fairly versatile, allowing for a variety of choice attributes (van Putten *et al.*, 2012). Within game theory fishers are bound by not only their own decisions but also by the decisions of others within the group (see review by Bailey et al., 2010). Network theory "aims to explain the characteristics of a connected system and the behaviour of connected individuals within that system" (van Putten *et al.*, 2012), for example, the sharing of information, or lack thereof, and it’s resulting effect on fishers. More recently, Bayesian techniques have been developed and applied to fisheries applications, such as to model fisheries behaviour (Vermard *et al.*, 2010) and effort allocation (Venables et al., 2009).

Further details on a number of these models can be found in the review by van Putten *et al.* (2012). The majority of these models can be employed as bio-economic models. Specific model choice can be based on several reasons including the underlying model theories and assumptions, data type (distributions and assumptions), application and objectives, as well as data availability. One of the most widely applied in fisheries applications over recent years has been the RUM, this could primarily be due to its more economic-theoretic mathematical basis. Yet, in a comparison between RUM and Markov modelling of household brand choice, the two models were shown to be "remarkably similar" in their ability to predict observed brand choices (Seetharaman, 2003). The main difference is that a RUM is a discreet choice model where you model the utility of the state, while the Markov approach is a stochastic choice model in which you model the state itself and the transition probabilities. Given that a Markov chain is a natural discrete variable time series method and computationally straightforward to implement, it is a valid alternative choice to the popular RUM, especially when economic variables are included.

Many of the current approaches simplify various aspects of the dynamics, attempting to balance the complexity of dynamics and levels of uncertainty (Bence et al., 2008). The model review carried out by van Putten *et al.* (2012) also includes a detailed discussion of the variables selected to account for drivers of modelled behaviour. In addition to vessel and fisher based descriptors many investigations attempt to include economic drivers. Improvements are still considered necessary as few studies effectively incorporated direct measures of "profits per choice" but rather utilised proxies to represent profit, cost and or revenue (see Table 2 in van Putten *et al.* (2012) for a list of proxies). For example, marginal revenue has been represented by value per unit of effort (even instances of catch rates were identified) while distance between port and fishing area has been applied as a cost variable. Such proxies indicate the limited availability of economic data, especially at the level which modelling occurs (often the trip level). Furthermore, these authors state that inclusion of other drivers had been fairly limited, primarily occurring at the group level, such as regulatory constraints. The complexity of drivers combined with insufficiently detailed data, creates a level of limitation in the ability of models to accurately predict behaviour. This is compounded further by differing responses across fleets, fisheries and métiers where the impact of drivers and external pressures are inconsistent (Andersen *et al.*, 2010; Ulrich *et al.*, 2011)

Defining métiers

The segmentation of fishing activities into métiers has been conducted for a wide variety of fleets and fisheries over the last 50 years, with initial identification methods based on *a priori* knowledge. Thereafter statistical methods were developed. Early examples include Biseau (1998), Pelletier & Ferraris (2000), and Ulrich and Andersen (2004). Since 2004 the general approach of applying a cluster analysis with or without prior PCA, similar to that applied within Chapters II and III, has been used in several studies although the specific clustering methods vary. The combination applied within Chapters II and III (PCA and HAC) were deemed the best combination by Deporte *et al.* (2012), who reviewed a number of these methods, although commenting that no method was perfect.

The identification of over 50 métiers and the high level of participation within multiple métiers (vessel polyvalence) illustrates the complex multi-species, multi-fleet interactions within the Irish fleet. These could not be separated by gear or species definitions alone. The range and complexity of métiers identified gives rise to an immense amount of detail. Monitoring the fine scale dynamics can be used to identify behavioural changes such as those described within Chapters II and III. This division of fishing activities within the Irish fleet was fundamental to all subsequent progress to ensure considerations were made at the appropriate level of mixed fisheries in line with European policy and advisory requirements.

Fine scale segmentation of fleets and/or fisheries allows the identified variability of responses between fisheries segments (such as those noted by Andersen *et al.*, 2010; Ulrich *et al.*, 2011) to be accounted for within subsequent driver and behaviour modelling, increasing the descriptive capability of such analyses. It allows separate handling rather than assessment of larger scale combined fleets or fisheries. The latter can result in high variability and poor descriptive capability through attempted fit over multiple signals. In addition to the multiple and often incompatible statistically defined national métiers (for example those identified in Chapters II and III), a number of segmentation levels are currently being used within European management. This includes the combination of gear and mesh size range, such as those implemented within effort management in the Irish Sea (e.g. TR1 demersal trawl gear with mesh sizes ≥100mm and TR2 using the same gear with a mesh range of 70-99mm; EC, 2008a).

The DCF currently stipulates collection of biological information under DCF level 6 combining gear, a broad species target group, mesh size range, and selectivity device (EC, 2008c). However, information on the latter is often unavailable to fisheries scientists. This métier scale has also been incorporated into the recent advances in mixed fisheries advice within the Fcube framework (Ulrich *et al.*, 2011) currently applied by ICES for North Sea mixed fisheries advice (ICES, 2012b). While other segments are targeted at DCF level 5 combining gear and target species such as that used by the ICES cephalopod working group (ICES, 2012e). Meanwhile economic data is still collected at the less detailed level of fleet segments (EC, 2008c).

The multitude of methods for segmentation results in inconsistencies between management, assessment, and advice (in addition to data formulation for international reporting). Discrepancies between raised discard estimates with segmentation level is a particularly contentious issue, often stimulating debate within such international groups.

Uses of métiers include the conditioning of biological and discard sampling within the current métier based approach stipulated within the DCF. However, this utility may be reduced in the future given current DCF developments away from the métier level 6 strategy towards statistically based approaches using random sampling within predefined sampling frames. Métiers will continue to be a useful method of identifying fine scale changes in behaviour, mixed species considerations, and the impacts of external drivers as has been demonstrated. Identification of fine scale métier dynamics could be developed into environmental status indicators, a requirement within the ecosystem approach under the direction of the MSFD. The MEFEPO project (Nolan *et al.*, 2011) has provided initial discussion of the required indicators and possible options.

A further option is development of métiers to redefine and optimise national demersal quota allocations as discussed within Chapter II. This type of métier based quota allocation could also be expanded into regional management as part of multi-annual plans or developed as a method of allocating RTIs as proposed by Kraak *et al.* (2012).

When the Irish métier definitions are reviewed (recommended to ensure continued representation of the main activities), value data which were not available at the time of initial analysis will be used as the base as opposed to the weights originally applied. Broadly speaking, it is expected that the métiers defined using volume (landed weight) would also be identified if applying first sale values, although subtle differences are likely to occur for low volume high value species such as sole. In addition, integration with VMS could be used to improve clarity of métier characterisation by examining the fine spatial aspect to métiers, further harmonising the métiers identified here and those identified by Gerritsen *et al.* (2012).

Identifying responses

Before moving to the developmental focus of the project, the ability to detect changing métier dynamics in response to shifting circumstances was tested. Although it can be reasonably easy to detect the patterns and trends within the Irish fleet, or any fleet for that matter, it can be difficult to distinguish the behaviour and drivers which result in such patterns. This was carried out by examining changes within the Irish fleet in response to a new method of effort limitation allocation introduced in 2009 under the cod long term management plan (EC, 2008a), in addition to technical measure revisions within the West of Scotland. The analysis confirmed the métier unit as an appropriate scale on which to base further analyses, having been able to identify changes in dynamics with the implementation of management.

A detectable response from fishers to a series of pilot effort allocation schemes was identified. These pilot schemes gave rise to uncertainty among fishers, leading to "saving up" and conservation of effort early in the year. This change in fishing behaviour was a "knee jerk" response not observed in subsequent years. This resulted in periods of low and high fishing pressure in combination with effort displacement. Displacement was identified in the areas surrounding those affected by the management plan rather than reductions, as observed on smaller scales in relation to closed areas and management protection areas (Dinmore *et al.*, 2003; Hutton *et al.*, 2004; Powers & Abeare, 2009; Sen, 2010). Such effort displacement can adversely affect resources outside the management remit through increased fishing pressure with possible habitat degradation consequences.

The identification of unintended consequences, such as fishers "saving up" effort, affects the ability to predict responses to management measures. The retrospective exploration of fine-scale changes of behaviour in response to management actions can illustrate its effectiveness, and identify potential unwanted consequences which can subsequently be considered within future planning. Further complication can come from the adaptation of fishers to applications of new gear types (e.g. the Swedish grid) which result in alterations in species profile, selectivity and efficiency. Such changes are difficult to predict within models which have not been previously conditioned by such changes. One of the major issues of retrospective models is that they can only predict from behaviour which has previously been observed. This is a limitation to consider when applying behavioural models where rapid changes occur or new management introduces incentives beyond those previously observed. One such example is the upcoming discard ban to be implemented from 2015.

Development of economic drivers

Having defined métiers and described their dynamics, the next step was to develop appropriate economic data variables for inclusion in bio-economic behavioural modelling. As fishing is a business, it is economically driven with the aim of generating profit by ensuring greater revenues than costs. Decisions made by fishers are based on economic considerations, and are assumed to try to maximise profit. Good management creates economic incentives that are in alignment with fisher objectives. Conflicts arise when management actions fail to account for the fisher's necessity to generate a certain level of profit. Such mismatch results in reduced management efficiency with reduced compliance and occurrence of perverse responses. A topical example of the latter is the high-grading of fish under restrictive TACs and discarding of undersize fish where minimum landing sizes are stipulated.

Integrating economic drivers into fisheries management has previously been hampered by data limitations (van Putten *et al.*, 2012). A number of alternative proxies (e.g. distance travelled to fishing ground or fuel price per litre) have been trialled as substitutes for accurate information. Improvement of economic descriptor variables should lead to increased ability to identify signals associated with economic drivers, subsequently improving bio-economic model accuracy.

Fishing operating costs and revenue were identified as two important drivers behind economic behaviour for which improved representation would be beneficial. Variation in landings prices at first sale have been shown to influence fisher behaviour (Marchal *et al.*, 2007; Sumaila *et al.*, 2007), as has the cost of fuel (e.g. Abernethy *et al.*, 2010; Bastardie *et al.*, 2013; Cheilari *et al.*, 2013). For most fishing vessels fuel represents one of the largest variable costs associated with individual fishing trips. Thus fuel cost is likely to be a good descriptor of per trip cost decisions. Other costs such as crew, depreciation, and other fishing costs are likely to remain relatively consistent regardless of the type of fishing trip.

The model developed here to estimate fuel consumption per day for the different fleet segments (as defined by the DCF) is an important development. It provides the ability to incorporate realistic fuel usage estimates either as a litre value, or as fuel cost when appropriate fuel price information is available. The generic nature of this model allows for wider application across international fishing fleets utilising the same types of gears as the Irish fleet, as well as application within the sphere of economic research, calculation of biological efficiency, and for use in estimating greenhouse gas emissions.

There were a large number of explanatory variables which could have been included within the analysis of fuel consumption (Chapter V), such as vessel age and condition, vessel speed and gear configuration, sea state and weather conditions (Driscoll & Tyedmers, 2010; Schau *et al.*, 2009; Tyedmers, 2001). However, in this case only a relatively small sample size was available on which to base the analysis. As such, the number of variables was limited to prevent occurrence of a greater number of variables than data points. Furthermore, details of a number of possible variables, such as those listed above, were not available for inclusion. Variables therefore were limited to those of fleet segment, vessel length and engine power, all of which are easily obtained and applicable across the wider European fleet to enable a wider application. Parente (2004) tested a greater number of variables many of which related to vessel characteristics. Although this was tested against the Portuguese coastal seine fleet, some direction can be taken from the outcome of such an investigation to make an indication of what type of characters may influence fuel consumption.

This work has presented a time series for first sale prices and subsequent total per trip landings values for Irish fisheries not previously analysed. The two time series highlighted heterogeneity in prices and values achieved by the Irish fleet both spatially and temporally, as well as demonstrating variability between métier groupings. The variability in values indicated the need for a standardisation method to allow direct comparison between trips. However little such work has previously been carried out on a value based term. Focus has instead been on standardisation of catches for inclusion in stock assessment.

A standardised method of generating value per unit effort indices was developed in the form of a linear mixed effects model identifying several important terms to reduce possible bias resulting from changing availability. This model highlighted the importance of the type of effort variable applied to generate these indices. A notable outcome of this analysis was that fishing hours, when used as the main effort variable to generate catch per unit effort, performed poorly in comparison to kilowatt fishing days.

The number of explanatory variables is currently a limitation within such analyses. Here, unlike the fuel consumption investigation, sample size is not a limiter on the number of variables which can be included. The greatest of which is a proxy for season, given the variability in species availability. Seasonality should be included as a form of continuous variable as the inclusion of a categorical variable such as month or quarter are too finite to encompass the gradual changes in season and availability.

A second variable worthy of consideration is a form of area differentiation. The inclusion of this variable however, would be more complex. ICES division would be the easiest variable to include, yet a number of fisheries cover multiple divisions, whilst other divisions contain multiple fisheries which may or may not show variation in species prices, and thus trip value. Other options include ICES rectangle, however trips often cover several rectangles within a single trip. The application of vessel monitoring systems (VMS) to identify fishing grounds is another possibility, similar to the spatial identification made in Gerritsen *et al.* (2012). The inclusion of further, useful, explanatory variables would alter the reliance on the random vessel effect which at present absorbs much of the variation unaccounted for as fixed effects and would therefore make the analysis application more versatile.

This analysis was carried out with the intention of its results being incorporated into a behavioural model. The level of species targeting segregation was formulated to reflect this. However, as a standalone study, the number of species targeting groups could have been expanded to the more detailed level of métiers identified within the first two chapters. Inclusion of métiers for species targeting would reduce the need for the inclusion of an area variable mentioned above as métiers include an area aspect.

Here the achieved value per trip is considered a more direct representation of revenue generation than the modelled standardised VPUE, as is also noted by van Putten *et al.* (2012). The former, therefore, should be used for behavioural modelling. Standardised VPUE indices can, however, be applied in a similar fashion to CPUE outside of the assessment framework. These can be used as indicators to monitor and detect changes, provide spatial information identifying areas of high importance "hotspots" for incorporation into applications like marine spatial planning and economic based management. A further suggestion is its application within the RTI (real-time incentives) management system recently suggested by Kraak *et al.* (2012) as a fisher perspective.

As an additional note, inflation was not accounted for within either the fuel consumption or the value per unit effort investigations. Here however it was not considered to be an important issue given the short length of the time series. If the time series was lengthened, inflation may become an important factor when incorporating economic datasets.

Behavioural modelling

The innovative approach developed and applied here uses a Markov state-transition process for fisher métier strategy selection. This modelling technique was suggested by preliminary research into vessel métier movements as part of examining métier dynamics. Variable métier sequences were observed over a number of instances, which lead to investigation of techniques for métier transfer probability modelling, and thus to Markov state-transition processes. It is believed that this project represents their first application to modelling métier selection.

Markov processes have long been used in other areas, such as Systems Dynamics (Howard, 1971) and brand choice (Seetharaman, 2003), but it is believed Venables *et al.* (2009) is one of few, if not the only study to have utilised a Markov process to simulate fisher behaviour, having focused on effort allocation in a "trip choice" methodology. Switching to a métier selection focus was considered to give a more "wholesale" generalist approach through inclusion of many other factors influencing behaviour to mimic information available to fishers, albeit in a simplified form.

This model identified the previous métier state to be the most important influence on transition probability, where a large amount fishers choosing to remain within the same métier. This reluctance to switch was as also found by Suuronen *et al.* (2012) and Bastardie *et al.* (2013). In addition, vessel length was found to greatly influence métier choice, highlighting differences in operational limits between small and large vessels. Fuel cost per day of the previous trip was also an important driver of métier transitions. Fuel usage proxies were previously identified as an important driver of fishing behaviours within Danish fisheries (Bastardie *et al.*, 2013) and within the UK's southwest fishing fleet (Abernethy *et al.*, 2010). However, Andersen *et al.*'s (2012) use of distance travelled to fishing ground as a proxy for fuel cost was identified as a descriptive term of lesser importance.

These findings highlight the importance of including appropriately detailed proxy variables when analysing behaviour choices. They also affirm the economic nature of fisher choices and the major impact that fuel costs have within the decision making process. Seasonal knowledge or experience was an important driver of fishing decisions within this study, congruent with several others (e.g. Marchal *et al.*, 2009; Andersen *et al.*, 2012). Surprisingly however, the value obtained on the previous trip was of lesser importance. This result was also identified by Andersen *et al.* (2012) using fish price.

It is intended that the bio-economic behavioural model developed here be incorporated into an existing MSE simulation framework to enhance the representation of fleet dynamics. Behaviour is a particularly important consideration. It is especially critical when evaluating mixed demersal fisheries management scenarios when examining key management and policy questions, such as the effectiveness of proposed initiatives and the predictability of future fisher responses to such initiatives. It is particularly important in the identification of unintended disincentives which can cause perverse and undesirable responses, such as the previously observed effort displacement around closed areas and the high-grading of marketable fish. Improved understanding will enhance our ability to estimate responses to future regional management measures and changing economic conditions within the fishing industry.

Extra food for thought

Although the primary application of this project is fisheries management, the outcomes also serve a number of other, wider, marine environment management imperatives. There are potential applications of the research presented here within marine spatial planning, of for example, offshore wind farms, oil, gas and aggregate extraction, designation of marine protected areas (MPAs), and marine ecotourism. Standardised value per unit effort could be utilised to address conflicts between marine spatial planning and fishers by producing spatial distribution maps of VPUE to highlight economically important fishing areas (hotspots). Furthermore, the behavioural model after further development of conditioning variables could be applied to determine consequences of removing, or limiting fishing areas.

Limitations and Improvements

The method applied in the identification of métiers successfully identified many of the main differences within the Irish fleet segment utilising otter trawls (Chapter II) and the non-otter trawl segment (Chapter III). However, this method is not entirely appropriate for the classification of all fishing trips. This is especially highlighted by the classification of around a quarter of trips outside of métier definitions within the non-otter trawl segment. This may be related to the inclusion of so many categorical variables within the multiple correspondence analysis method applied over segregating trips, suggested by the occurrence of clusters containing only the categorical month variable.

A more likely cause lies in the generation of future allocation thresholds where the expert-based aggregation occurs. Here decisions were made on the rules for these thresholds based on the species composition levels which occurred in the majority of trips within clusters. Deporte *et al.* (2012) has since recommended the application of discriminant analysis conditioned on the results of clustering to allocate future trips to reduce the influence and input of expert knowledge. Furthermore, in a number of instances the application of a métier may not be appropriate. Such instances would include very mixed landings profiles in which no clear target can be identified. This type of trip would benefit from identifying métiers through a more spatial approach, building on that carried out by Gerritsen *et al.* (2012). Other instances include those in which include mis-specified information such as gear, or in some cases what appears to be mis-specified species (instances of each were observed in the two analyses carried out within this work) in such cases métiers cannot be assigned appropriately.

A limitation of the identification and segregation of fishing trips into métiers, not just applicable here, but with all métier analyses based on landings is the circularity of métiers. Underlying variation in species abundance can influence the outcome of métier classifications even though the same vessels are still going out and using the same gears in the same places at the same times of year. For example, a large haddock or *Nephrops* year-class passing through within an area may influence allocation if the fisher retains additional haddock onboard because it was available and could be worth landing (in terms of generating additional income for the fisher). This is especially true when there are several métiers targeting the same species but in different levels. Such variation could, for example, easily switch vessels from a "clean" *Nephrops* métier to a "mixed" *Nephrops* métier without the fisher changing anything but their choice in what to land. However, the choice of what they land is actually the important consideration within the subsequent analyses.

Furthermore, instead of two separate analyses, trips could have been broken down further into different fleet segments. These may have then identified more subtle differences in species composition and fishing characteristics. However, such pre-analysis segmentation would require greater expert-based input in the beginning stages compared to the applied method. This suggested alternative method is complicated by the movement of Irish vessels between fleet segments, for example between pelagic, demersal, and *Nephrops* fishing. The applied method allowed for such movements by anglicising otter trawls as a combined fleet segment.

Within this analysis métiers were grouped to reduce overall complexity and restrict the number of parameters within the transition matrix within the Markov modelling, an alternative would have been to consider a nested approach of fleets. This would create a transition matrix of detailed métiers within each fleet segment. Although this approach may have been easier to interpret, Ireland has a number of polyvalent vessels which switch between different fleet segments throughout the year, transitional information which would have been lost. Furthermore, as identified within the limitations of métier definitions, such a detailed approach would include trips where métier allocation is the result of changing resource availability rather than actual changes in targeting choice. The method applied here minimises the occurrence of such instances through the use of broader targeting groups.

A number of further developments to the transition model, requiring investigation, were listed within Chapter VIII. This includes both the improvement of the internal probability calculations incorporating constraints, and limits to more accurately represent reality. Furthermore, investigation into the inclusion of additional descriptor terms is necessary, in particular a concept of tradition, and discarding. However, increasing model complexity directly affects the degrees of freedom, and one must actively avoid model over parameterisation. Such developments could also incorporate adaptation of métier groupings to consider DCF métiers allowing expansion to an international dataset.

Discarding is an important, complex, and topical subject within its own right, primarily caused by a mismatch between management objectives and economically driven fisher incentives. This project has not explicitly examined discarding but this is an important area for future work, with large impacts possible on future dynamics. A substantial development in relation to availability of discard information has been made in the form of the Irish *Atlas of Demersal Discarding* (Marine Institute & Bord Iascaigh Mhara 2011). The atlas would be an immense aid to incorporating such discard information into the transition model design. Integration of discards may not alter métier definition substantially which are based on landings compositions, but management measures to tackle discards are likely to have varying impacts on the different métiers.

Analyses are only as good as the data on which they are based, and these data can introduce a deal of uncertainty. Here, with the exception of the development of fuel consumption predictions, analyses are based on logbook information. This data source, it is acknowledged, is not always complete or accurate. Logbook data contain an amount of uncertainty from a number of sources. Here, logbook information was made available on an annual "snapshot" basis in which a subset of the full logbook data running from 2003 to the last full year (i.e. 2012 in 2013). Updates and improvements are made to the logbook records held by the Irish government on an ongoing basis which affects the data available within the annual "snapshot". One such example is the availability and perceived accuracy of first sale price information, which hindered the use of value within initial métier definition, but subsequently later permitted the generation of trip values and value per unit effort information.

The two main issues occurring within the logbooks are: misreporting of fishing trip details (particularly species and area) often the result of management restrictions, and recording errors at the fisher and transcription level. A certain amount of this error can be highlighted through the application of métiers where identification acts as a broad quality control tool for species and gear oddities. The first sale price valuation method developed within Chapter VI is useful for identifying and replacing outlier prices and filling in missing data. Also of particular interest is the availability (quantity and quality) of economic data to further develop descriptors of economic behaviour drivers and generation of accurate and meaningful "profit" terms. Within the DCF, the collection and availability of such data is improving, although at present the time series is short and variables are often incomplete due to limited data availability.

This study identified a need for a more integrated approach to data collection, storage, and management as integrated data often results in better insights. At present there is a multitude of data being collected in various formats, for example biological sampling, vessel monitoring system positional information. Unfortunately internal links are often missing, thereby complicating integration. Furthermore, various technological developments over recent decades and their increasingly wide spread use (satellite internet, smart phones, CCTV) are making it possible to collect fine scale data (VMS, Automatic Identification Systems (AIS), e-logs) and considerably improve the accuracy of collected data.

Further Work

Examining the drivers and dynamics of fisher behaviour is a highly complex and still developing field of research. Such analyses represent an important step in the larger task of integrating mixed fisheries and ecosystem approaches into successful sustainable management, in which there are almost endless possibilities for development. There are a number of areas in which the research here can be developed, whilst these opportunities are discussed within the individual sections, an overview of potential developments considered most important or interesting follows.

1) Having demonstrated the importance of improving explanatory variables to better describe drivers of behaviour within this project, further exploration and development of behaviour drivers is a necessity. Their translation and application within behaviour prediction models is of great importance. Economic drivers and the better description of "profit" are particularly needed. The oversimplified profit representation trialled here was not an adequate descriptor. Further incorporation of costs should be considered, such as crew and vessel costs (ownership). It is hoped that economic data collected under the remit of the DCF will continue to improve the variety and quality of such useful data.
2) The current transition model could be reversed and developed into an optimisation tool for industry whereby, given a desire for a catch value of *x*, the model could identify the best métier grouping to target given the knowledge of *y* and *z*, for example: fuel cost and season. Such an optimisation tool could be incorporated into the proposed RTI approach, as developed by Kraak *et al.* (2012), advising fishers how best to optimise the credits available to them.
3) Discarding is an important and topical subject, but one which this project has not explicitly examined. Incorporating discards should prove an important area of future work, providing a large impact on future dynamics and, potentially, MSEs.
4) However, the primary avenue of interest, following the improvements of the transition model discussed above, is to incorporate it within the framework of management strategy evaluation, through inclusion into a pre-existing simulation framework as a fleet dynamics sub-model. The outputs from such an implementation can then be translated into consequences on effort distribution and the subsequent mixed fisheries implications. This would enhance assessment and advice of new and emerging management plans, such as the mixed fisheries management plan currently being developed for Celtic Sea by

the GEPETO project in conjunction with members of the NWWRAC. This could utilise existing DCF métier definitions and international transition matrices.

Conclusions

This project vastly improves the understanding of the complex targeting behaviour of Irish commercial fishers in a mixed fisheries context. Identification of métiers has improved understanding of the complexity of interactions within and between fleets and fisheries. These métiers have enabled detailed examination of fine scale dynamics, identification of responses to management implementation, and aided the development of biological and discard sampling strategies when reporting at DCF level 6.

The fuel consumption estimator developed has a wide range of uses within fisheries science; as an economic driver to explain behaviour, as a method of calculating efficiency as energy used, as well as within the broader fields of economics and atmospheric research.

Kilowatt fishing days proved the most appropriate effort metric to use when generating standardised VPUE indices. The VPUE can be applied as an indicator to monitor and detect changes, or provide spatial information to identify areas of high importance, and for incorporation into marine spatial planning and economic based management applications.

It proved possible to develop a novel and informative bio-economic model of Markov transition probabilities incorporating fuel cost, trip first sale value, quota allocation, season, vessel length, and year to explain movement between métier groups. This model is designed to be integrated within management strategy evaluation simulation frameworks to aid assessment of future management proposals and their likely impacts on the Irish fleet and commercial stocks around Ireland. In conclusion this work significantly advances the inclusion of mixed fisheries and fisher’s behaviour into long-term management plans.

References

Abernethy, K. E., Trebilcock, P., Kebede, B., Allison, E. H., and Dulvy, N. K. 2010. Fuelling the decline in UK fishing communities? ICES Journal of Marine Science, 67: 1076–1085.

Akaike, H. 1974. A new look at the statistical model identification. IEEE Transactions on Automatic Control, 19: 716–723.

Allain, V., Biseau, A., and Kergoat, B. 2003. Preliminary estimates of French deepwater fishery discards in the Northeast Atlantic Ocean. Fisheries Research, 60: 185–192.

Andersen, B. S., Vermard, Y., Ulrich, C., Hutton, T., and Poos, J. J. 2010. Challenges in integrating short-term behaviour in a mixed fishery management strategy evaluation framework: a case study of the North Sea flatfish fishery. Fisheries Research, 102: 26–40.

Andersen, K. H., and Rice, J. C. 2010. Direct and indirect community effects of rebuilding plans. ICES Journal of Marine Science, 67: 1980–1988.

Andersen, B. S., Ulrich, C., Eigaard, O. R., and Christensen, A-S. 2012. Short-term choice behaviour in a mixed fishery: investigating métier selection in the Danish gillnet fishery. ICES Journal of Marine Science, 69: 131–143.

Anon. 2005a. Report of the EU Data Collection Regulation (EC) No. 1581/2004 Regional Co-ordination Meeting North East Atlantic (RCM NEA). Gijón, Spain.

Anon. 2005b. Commission Staff Working Paper: Report of the Ad Hoc Meeting of Independent Experts on Fleet-Fishery Based Sampling. Nantes, France.

Anon. 2006. The Stockbook: Annual Review of Fish Stocks in 2006 with Management Advice for 2007. Report to the Minister for Communications, Marine and Natural Resources by the Marine Institute's Fisheries Science Services pp. 425. (available at www.marine.ie)

Anon. 2008. Co-management: managing Australia's fisheries through partnership and delegation. Report of the Fisheries Research and Development Corporation's National Working Group on the Fisheries Co-management Initiative – Project 2006/068. Fisheries Research and Development Corporation, Deakin West. 50 pp.

Anon. 2009. Atlas of the Commercial Fisheries Around Ireland. Marine Institute, December 2009. ISBN 978 1 902895 46 8. 58 pp. (Available at: www.marine.ie).

Arnason, R. 2007. The Economics of Rising Fuel Costs and European Fisheries. Euro Choices, 6: 22–29.

Atema, J. 1988. Distribution of chemical stimuli. In: *Sensory biology of aquatic animals* (Ed. by Atema, J., Fay, R. R., Popper, A. N. & Tavolga, W. N.). Springer-Verlag 29–56pp.

Bailey, M., Rashid Sumaila, U. and Lindroos, M. 2010. Application of game theory to fisheries over three decades. Fisheries Research, 102: 1–8.

Barton, K. 2013. MuMIn: Multi-model inference. R package version 1.9.5. http://CRAN.R-project.org/package=MuMIn

Bastardie, F., Nielsen, J. R., Andersen, B. S., and Eigaard, O. R. 2010. Effects of fishing effort allocation scenarios on energy efficiency and profitability: an individual-based model applied to Danish fisheries. Fisheries Research, 106: 501–516.

Bastardie, F., Nielsen, J. R., Andersen, B. S., and Eigaard, O. R. 2013. Integrating individual trip planning in energy efficiency – Building decision tree models for Danish fisheries. Fisheries Research, 143: 119–130.

Benaglia, T., Chauveau, D., Hunter, D.R., and Young, D. 2009. mixtools: An R Package for Analyzing Finite Mixture Models. Journal of Statistical Software, 32(6), 1–29.

Bence, J. R., Dorn, M. W., Irwin, B. J., and Punt, A. E. 2008. Recent advances in the evaluation and implementation of harvest policies. Fisheries Research, 94: 207–209.

BIM. 2009. Improving fuel efficiency on fishing vessels. BIM user friendly guides, 7. 24 pp. ISSN 1649-9395. ISBN 978-1-903-412-36-7.

Biseau, A. 1998. Definition of a directed fishing effort in a mixed-species trawl fishery, and its impact on stock assessments. Aquatic Living Resources, 11**:** 119–136.

Bishop, J., Venables, W.N., and Wang, Y.G. 2004. Analysing commercial catch and effort data from a penaeid trawl fishery. A comparison of linear models, mixed models, and generalized estimating equations approaches. Fisheries Research, 70: 179–193.

Borges L.A., Rogana, E., and Officer, R. 2005a. Discarding by the demersal fishery in the waters around Ireland. Fisheries Research, 76: 1–13.

Borges, L., Zuur, A., Rogan, E. and Officer, R. 2005b. Choosing the best sampling unit and auxiliary variable for discards estimations. Fisheries Research, 75: 29–39.

Branch, T.A., Hilborn, R., Haynie, A.C., Fay, G., Flynn, L., Griffiths, J., Marshall, K.N. *et al.* 2006. Fleet dynamics and fishermen behaviour: lessons for fisheries managers. Canadian Journal of Fisheries and Aquatic Sciences, 63: 1647–1668.

Campbell, R. A. 2004. CPUE standardisation and the construction of indices of stock abundance in a spatially varying fishery using general linear models. Fisheries Research, 70: 209–227.

Campos, A., Fonseca, P., Fonseca, T., Parente, J. 2007. Definition of fleet components in the Portuguese bottom trawl fishery. Fisheries Research, 83: 185–191.

Castro, J., Punzón, A., Pierce, G.J., Marín, M., Abad, E. 2010. Identification of métiers of the Northern Spanish coastal bottom pair trawl fleet by using the partitioning method CLARA. Fisheries Research, 102: 184–190.

Castro, J., Marín, M., Pierce, G.J., Punzón, A. 2011. Identification of métiers of the Spanish set-longline fleet operating in non-Spanish European waters. Fisheries Research, 107: 100–111.

Cheilari, A., Guillen, J., Damalas, D., and Barbas, T. 2013. Effects of the fuel price crisis on the energy efficiency and the economic performance of the European Union fishing fleets. Marine Policy, 40: 18–24.

Chenhall, S. and Magnet, E. 2008. Fuel for thought. AFMA update, 5(20). ISSN 1449-7697 ABN 8109-849-7517 www.afma.gov.au/afma_update/docs/update_0520/update_0520.htm (last accessed 17 May 2013)

Davie, S., Lordan, C. 2009. Using a multivariate approach to define Irish métiers in the Irish Sea. Irish Fish. Invest. 21, 45.

Davie, S., and Lordan, C. 2011a. Definition, dynamics and stability of métiers in the Irish otter trawl fleet. Fisheries Research, 111: 145–158.

Davie, S., and Lordan, C. 2011b. Examining changes in Irish fishing practices in response to the cod long-term plan. ICES Journal of Marine Science, 68: 1638–1646.

De'ath, G. and Fabricius, K.E. 2000. Classification and regression trees: a powerful yet simple technique for ecological data analysis. Ecology, 81: 3178–3192.

Deporte, N., Ulrich, C., Mahévas, S., Demanéche, S., and Bastardie, F. 2012. Regional métier definition: a comparative investigation of statistical methods using a workflow applied to international otter trawl fisheries in the North Sea. ICES Journal of Marine Science, 69: 331–342.

Dinmore, T. A., Duplisea, D. E., Rackham, B. D., Maxwell, D. L., and Jennings, S. 2003. Impact of a large-scale area closure on patterns of fishing disturbance and the consequences for benthic communities. ICES Journal of Marine Science, 60: 371–380.

Drewery, J., Bova, D., Kynoch, R. J., Edridge, A., Fryer, R. J., and O’Neill, F. G. 2010. The selectivity of the Swedish grid and 120 mm square mesh panels in the Scottish *Nephrops* trawl fishery. Fisheries Research, 106: 454–459.

Driscoll, J. and Tyedmers, P. 2010. Fuel use and greenhouse gas emission implications of fisheries management: the case of the New England Atlantic herring fishery. Marine Policy, 34: 353–359.

Drouineau, H., Mahévas, S., Pelletier, D., Beliaeff, B. 2006. Assessing the impact of different management options using ISIS-Fish: the French *Merluccius merluccius* – *Nephrops norvegicus* mixed fishery of the Bay of Biscay. Aquatic Living Resources, 19: 15–29.

Duarte, R., Azevedo, M., Afonso-Dias, M. 2009. Segmentation and fishery characteristics of the mixed-species multi-gear Portuguese fleet. ICES Journal of Marine Science, 66: 594–606.

EC. 1993. Council Regulation (EEC) No. 2847/93 of 12 October 1993 establishing a control system applicable to the common fisheries policy. Official Journal of the European Communities, L261: 1–16.

EC. 1998. Council Regulation (EC) No. 850/98 of 30 March 1998 for the conservation of fishery resources through technical measures for the protection of juveniles of marine organisms. Official Journal of the European Communities, L125: 1–36.

EC. 2001. Commission Regulation (EC) No. 1639/2001 of July 2001 establishing the minimum and extended Community programmes for the collection of data in the fisheries sector and laying down detailed rules for the application of Council Regulation (EC) No 1543/2000. Official Journal of the European Communities, L222: 53–115.

EC. 2002. Council Regulation (EC) No 2341/2002 of 20 December 2002 fixing for 2003 the fishing opportunities and associated conditions for certain fish stocks and groups of fish stocks, applicable in community waters and, for community vessels, in waters where catch limitations are required. Official Journal of the European Union, L356: 12–120.

EC. 2003. Council Regulation (EC) No 2287/2003 of 19 December 2003 fixing for 2004 the fishing opportunities and associated conditions for certain fish stocks and groups of fish stocks, applicable in community waters and, for community vessels, in waters where catch limitations are required. Official Journal of the European Union, L344: 1–119.

EC. 2004. Council Regulation (EC) No 423/2004 of 26 February 2004 establishing measures for the recovery of cod stocks. Official Journal of the European Union, L70: 8–11.

EC. 2005. Council Regulation (EC) 51/2006 of 22 December 2005 fixing for 2006 the fishing opportunities and associated conditions for certain fish stocks and groups of fish stocks, applicable in Community waters and, for Community vessels, in waters where catch limitations are required. Official Journal of the European Union, L16: 1–183.

EC. 2006. Commission Regulation (EC) No 1077/2008 of 3 November 2008 laying down detailed rules for the implementation of Council Regulation (EC) No 1966/2006 on electronic recording and reporting of fishing activities and on means of remote sensing and repealing Regulation (EC) No 1566/2007. Official Journal of the European Union, L295: 3–23.

EC. 2008a. Council Regulation (EC) No 1342/2008 of 18 December 2008 establishing a long-term plan for cod stocks and the fisheries exploiting those stocks and repealing Regulation (EC) No 423/2004. Official Journal of the European Union, L348: 20–33.

EC. 2008b. Directive 2008/56/EC of the European Parliament and of the Council of 17 June 2008 establishing a framework for community action in the field of marine environmental policy (Marine Strategy Framework Directive). Official Journal of the European Union, L164: 19–40.

EC. 2008c. Council Regulation (EC) No. 199/2008 of 25 February 2008 concerning the establishment of a Community framework for the collection, management and use of data in the fisheries sector and support for scientific advice regarding the Common Fisheries Policy. Official Journal of the European Union, L60: 1–12.

EC. 2008d. Commission Decision of 6 November 2008 adopting a multiannual Community programme pursuant to Council Regulation (EC) No. 199/2008 establishing a Community framework for the collection, management and use of data in the fisheries sector and support for scientific advice regarding the common fisheries policy. Official Journal of the European Union, L346: 36–88.

EC. 2008e. Commission Regulation (EC) No 665/2008 of 14 July 2008 laying down detailed rules for the application of Council Regulation (EC) No 199/2008 concerning the establishment of a Community framework for the collection, management and use of data in the fisheries sector and support for scientific advice regarding the Common Fisheries Policy. Official Journal of the European Communities, L186: 3–5.

EC. 2009a. Council Regulation (EC) No 43/2009 of 16 January 2009 fixing for 2009 the fishing opportunities and associated conditions for certain fish stocks and groups of fish stocks, applicable in community waters and, for community vessels, in waters where catch limitations are required. Official Journal of the European Union, L22: 1–205.

EC. 2009b. Council Regulation (EC) No 1224/2009 of 20 November 2009 establishing a Community control system for ensuring compliance with the rules of the common fisheries policy, amending Regulations (EC) No 847/96, (EC) No 2371/2002, (EC) No 811/2004, (EC) No 768/2005, (EC) No 2115/2005, (EC) No 2166/2005, (EC) No 388/2006, (EC) No 509/2007, (EC) No 676/2007, (EC) No 1098/2007, (EC) No 1300/2008, (EC) No 1342/2008 and repealing Regulations (EEC) No 2847/93, (EC) No 1627/94 and (EC) No 1966/2006. Official Journal of the European Union, L343: 1–50.

EC. 2011. Council Regulation (EU) No. 57/2011 of 18 January 2011 fixing for 2011 the fishing opportunities for certain fish stocks and groups of fish stocks, applicable in EU waters and, for EU vessels, in certain non-EU waters. Official Journal of the European Union, L24: 1–125.

EC. 2013. COMMUNICATION FROM THE COMMISSION TO THE COUNCIL concerning a consultation on Fishing Opportunities for 2014.Brussels, 30.5.2013. COM(2013) 319 final. 17pp.

Edwards, C.T.T., Hillary, R., Hoshino, E., Pearce, J., and Agnewa, D.J. 2011. Bioeconomic evaluation of fisheries enforcement effort using a multifleet simulation model. Fisheries Research, 107: 255–260.

Engås, A. and LØkkeborg, S. 1994. Abundance estimation using bottom gillnet and longline: The role of fish behaviour. In: *Marine fish behaviour in capture and abundance estimation* (Ed. by Fernö, A. & Olsen, S.). Fishing News Books, 134–165pp.

FAO. 2007. The State of World Fisheries and Aquaculture 2006. FAO Fisheries Department, Rome.

FERM. 2004. ITQs, ageing boats, and the price of fish. Profitability and autonomous adjustment in the South East Trawl Fishery. Fisheries economics research and management pty. Ltd.; 2004.

Ferro, R. 2002. Fish conservation and the design of fishing gear. Buckland Occasional Paper, No 9, 20pp.

Fernandes, P.G. and Cook, R.M. 2013. Reversal of fish stock decline in the Northeast Atlantic. Current Biology, 23: 1432–7.

Fowler, J., Cohen, L., Jarvis, P. 2004. Practical Statistics for Field Biologists. John Wiley & Sons, Chichester.

Fulton, E.A, Smith, A.D.M, Smith, D.C., and van Putten, I.E. 2011. Human behaviour: the key source of uncertainty in fisheries management. Fish and Fisheries, 12: 2–17.

Galbraith, R.D., and Rice, A after Strange, E.S. 2004. An introduction to commercial fishing gear and methods used in Scotland. Scottish Fisheries Information Pamphlet, No 25, 43pp.

Gerritsen, H., Lordan, C. 2011. Integrating vessel monitoring systems (VMS) data with daily catch data from logbooks to explore the spatial distribution of catch and effort at high resolution. ICES J. Mar. Sci. 68, 245–252.

Gerritsen, H.D., Lordan, C., Minto, C., and Kraak, S.B.M. 2012. Spatial patterns in the retained catch composition of Irish demersal otter trawlers: High-resolution fisheries data as a management tool. Fisheries Research, 129-130: 127–136.

Gourguet, S., Macher, C., Doyen, L., Thébaud, O., Bertignac, M., and Guyader, O. 2013. Managing mixed fisheries for bio-economic viability. Fisheries Research, 140: 46–62.

Guillen, J., Macher, C., Merzéréaud, M., Bertignac, M., Fifas, S., and Guyader, O. 2013. Estimating MSY and MEY in multi-species and multi-fleet fisheries, consequences and limits: an application to the Bay of Biscay mixed fishery. Marine Policy, 40: 64–74.

Gulland, J.A. 1983. Fish Stock Assessment: A Manual of Basic Methods. Wiley, Chichester, 224pp.

Harley, A.J., Myers, R.A., and Dunn, A. 2001. Is catch-per-unit-effort proportional to abundance. Canadian Journal of Fisheries and Aquatic Science, 58: 1760–1772.

Hastie, T. and Tibshirani, R. 1986. Generalized Additive Models. Statistical Science, 1: 297–310.

Hastie, T. and Tibshirani, R. 1990. Generalized additive models (Vol. 43). Chapman & Hall/CRC, Boca Raton, Florida.

Helser, T.E., Punt, A.E., and Methot, R.D. 2004. A generalized linear mixed model analysis of a multi-vessel fishery resource survey. Fisheries Research, 70: 251–264.

Hilborn, R. 2007. Managing fisheries is managing people: what has been learned? Fish and Fisheries, 8: 285–296.

Howard, R.A. 1971. Dynamic probabilistic systems, Volume I: Markov Models. John Wiley & Sons Inc, New York. 576pp.

Hoff, A., Frost, H., Ulrich, C., Damalas, D., Maravelias, C. D., Goti, L., and Santurtún, M. 2010. Economic effort management in multispecies fisheries: the FcubEcon model. ICES Journal of Marine Science, 67: 1802–1810.

Holley, J.-F. and Marchal, P. 2004. Fishing strategy development under changing conditions: Examples from the French offshore fleet fishing in the North Atlantic. ICES Journal of Marine Science, 61**:** 1410–1431.

Hutton, T., Mardle, S., Pascoe, S., and Clark, R. A. 2004. Modelling fishing location choice within mixed fisheries: English North Sea beam trawlers in 2000 and 2001. ICES Journal of Marine Science, 61: 1443–1452.

ICES. 2003. Report of the Study Group on the Development of Fishery-based Forecasts. Boulogne, France. ICES CM 2003/ACFM:08. 37pp.

ICES. 2006a. Report of the Workshop on Simple Mixed Fisheries Management Models (WKMIXMAN), 9–13 January 2006, Copenhagen, Denmark. ICES CM 2006/ACFM:14. 47pp.

ICES. 2006c. Report of the Working Group on Northern Pelagic and Blue Whiting Fisheries (WGNPBW). ICES CM 2006/ACFM:34. 294pp.

ICES. 2007a. Report Of The Study Group On Mixed Fisheries Management (SGMIXMAN), 15–19 January, Copenhagen, Denmark. ICES CM 2007/ACFM:02. 56pp.

ICES. 2007b. Report of the Working Group on the Assessment of Northern Shelf demersal stocks (WGNSDS), 8–17 May 2007, Galway, Ireland. ICES CM 2007/ACFM:22. 867pp.

ICES. 2009a. *Nephrops* on Porcupine Bank (FU 16). In: ICES, Report of the ICES Advisory Committee 2009. ICES Advice 2009, Book 5, Copenhagen. 228–235pp.

ICES. 2009b. Report of the Working Group on Widely Distributed Stocks (WGWIDE). ICES CM 2009/ACOM:12. 583pp.

ICES. 2009c. Report of the Working Group on the Biology and Assessment of Deep Sea Fisheries Resources (WGDEEP). ICES CM 2009/ACOM:14. 511pp.

ICES. 2010a. Report of the joint ICES – STECF Workshop on methods for merging métiers for fishery based sampling (WKMERGE). ICES CM 2010/ACOM:40. 94pp.

ICES. 2010b. Report of the Working Group on the Celtic Seas Ecoregion (WGCSE), 12–20 May 2010, ICES Headquarters, Copenhagen. ICES CM 2010/ACOM:12. 1435pp.

ICES. 2012a. Report of the Working Group for the Celtic Seas Ecoregion (WGCSE), 9-18 May, Copenhagen, Denmark. ICES CM 2012/ACOM:12. 1727pp.

ICES. 2012b. Report of the Working Group on Mixed Fisheries Advice for the North Sea (WGMIXFISH), 21-25 May, Copenhagen, Denmark. ICES CM 2012/ACOM:22. 94pp.

ICES. 2012c. Report of the Working Group on Mixed Fisheries Advice for the North Sea (WGMIXFISH2): August Meeting, 27–31 August, Copenhagen, Denmark. ICES CM 2012/ACOM:74. 75pp.

ICES. 2012d. ICES Strategy for Mixed Fisheries (Technical Interactions) and Multi-species (Biological Interactions) advice. ACOM Meeting (ICES HQ), December 2012. Doc 6a ii. 6pp.

ICES. 2012e. Report of the Working Group on Cephalopod Fisheries and Life History (WGCEPH), 27–30 March, Cadiz, Spain. ICES CM 2012/SSGEF:04. 241pp.

Jentoft, S., and McCay, B. J. 1995. User participation in fisheries management: lessons drawn from international experience. Marine Policy, 19: 227–246.

Jiménez, M. P., Sobrino, I., and Ramos, F. 2004. Objective methods for defining mixed-species trawl fisheries in Spanish waters of the Gulf of Cádiz. Fisheries Research, 67**:** 195–206.

Johannes, R. E., Freeman, M. M. R., and Hamilton, R. J. 2000. Ignore fishers' knowledge and miss the boat. Fish and Fisheries, 1: 257–271.

Kell, L.T., Mosqueira, I., Grosjean, P., Fromentin, J.M., Garcia, D., Hillary, R., Jardim, E., Mardle, S., Pastoors, M.A., Poos, J.J., Scott, F., Scott, R.D. 2007. FLR: an open-source framework for the evaluation and development of management strategies. ICES Journal of Marine Science, 64: 640–646.

Kelly, C. J., Codling, E. A., and Rogan, E. 2006. The Irish Sea cod recovery plan: some lessons learned. ICES Journal of Marine Science, 63: 600–610.

Kraak, S.B.M., Buisman, F.C., Dickey-Collas, M., Poos, J.J., Pastoors, M.A., Smit, J.G.P., van Oostenbrugge, J.A.E., Daan, N. 2008. The effect of management choices on the sustainability and economic performance of a mixed fishery: a simulation study. ICES Journal of Marine Science, 65: 697–712.

Kraak, S. B. M., Reid, D. G., Gerritsen, H. D., Kelly, C. J., Fitzpatrick, M., Codling, E. A., and Rogan, E. 2012. 21st century fisheries management: a spatio-temporally explicit tariff-based approach combining multiple drivers and incentivising responsible fishing. ICES Journal of Marine Science, 69: 590–601.

Lewy, P., Vinther, M. 1994. Identification of Danish North Sea trawl fisheries. ICES Journal of Marine Science, 51: 263–272.

Little, L. R., Punt, A. E., Mapstone, B. D., Begg, G. A., Goldman, B., and Ellis, N. 2009. Different responses to area closures and effort controls for sedentary and migratory harvested species in a multispecies coral reef line fishery. ICES Journal of Marine Science, 66: 1931–1941.

Løkkeborg, S. & Johannessen, J. T. 1992. The importance of chemical stimuli in bait fishing - fishing trials with pre-soaked bait. Fisheries Research, 14: 21–29.

Løkkeborg, S. & Pina, T. 1997. Effects of setting time, setting direction and soak time on longline catch rates. Fisheries Research, 32: 213–222.

Løkkeborg, S. 1990. Rate of release of potential feeding attractants from natural and artificial bait. Fisheries Research, 8: 253–261.

Mace, P.M. 2001. A new role for MSY in single-species and ecosystem approaches to fisheries stock assessment and management. Fish and Fisheries, 2: 2–32.

Mackinson, S., Deas, B., Beveridge, D., and Casey, J. 2009. Mixed-fishery or ecosystem conundrum? Multispecies considerations inform thinking on long-term management of North Sea demersal stocks. Canadian Journal of Fisheries and Aquatic Sciences, 66: 1107–1129.

Mahévas, S., and Pelletier, D. 2004. ISIS-Fish, a generic and spatially explicit simulation tool for evaluating the impact of management measures on fisheries dynamics. Ecological Modelling, 171: 65–84.

Mahévas, S., Vermard, Y., Hutton, T., Iriondo, A., Jadaud, A., Maravelias, C.D., Punzón, A., *et al.* 2011. An investigation of human vs. technology-induced variation in catchability for a selection of European fishing fleets. ICES Journal of Marine Science, 68: 2252–2263.

Marchal, P., Lallemand, P., and Stokes, K. 2009. The relative weight of traditions, economics, and catch plans in New Zealand fleet dynamics. Canadian Journal of Fisheries and Aquatic Sciences, 66: 291–311.

Marchal, P., Little, L. R., and Thébaud, O. 2011. Quota allocation in mixed fisheries: a bioeconomic modelling approach applied to the Channel flatfish fisheries. ICES Journal of Marine Science, 68: 1580–1591.

Marchal, P., Poos, J.J, and Quirijns, F. 2007. Linkage between fishers' foraging, market and fish stocks density: Examples from some North Sea fisheries. Fisheries Research, 83: 33--43.

Marine Institute and Bord Iascaigh Mhara. 2011. Atlas of Demersal Discarding, Scientific Observations and Potential Solutions. Marine Institute, Bord Iascaigh Mhara, September 2011. 82 pp.

Maunder, M.N., Sibert, J.R., Fonteneau, A., Hampton, J., Kleiber, P., and Harley, S.J. 2006. Interpreting catch per unit effort data to assess the status of individual stocks and communities. ICES Journal of Marine Science, 63: 1373–1385.

McLachlan, G.J. and Peel, D. 2000. Finite mixture models. John Wiley, New York.

Nolan, C., Connolly, P., Le Quesne, W.J.F., Frid, C.L.J., Paramor, O.A.L., Piet, G.J., Rogers, S.I., *et al.* 2011. MEFEPO: Making European Fisheries Ecosystem Plans Operational. Assessing the impact of fishing on the Marine Strategy Framework Directive objectives for Good Environmental Status. Developing and testing the process across selected RAC regions: The North Western Waters. EC FP7 project # 212881.

NWWRAC. 2011. Towards a mixed demersal fisheries management plan In the Celtic Sea (ICES VIIfg): framework and objectives. North Western Waters Regional Advisory Council, Position paper, March 2011. http://www.nwwrac.org/admin/publication/upload/NWWRAC_Position_Framework_Objectives_Celtic%20Sea_LTMP_March2011_EN.pdf

Parente, J. 2004. Predictors of CPUE and standardization of fishing effort for the Portuguese coastal seine fleet. Fisheries Research, 69: 381–387.

Pelletier, D. and Ferraris, J. 2000. A multivariate approach for defining fishing tactics from commercial catch and effort data. Canadian Journal of Fisheries and Aquatic Sciences, 57**:** 51–65.

Pelletier, D., and Mahévas, S. 2005. Spatially explicit fisheries simulation models for policy evaluation Fish and Fisheries, 6: 307–349.

Pinheiro, J.C., and Bates, D.M. 2000. Mixed-Effects Models in S and S-PLUS, Springer.

Pinnegar, J.K., Jennings, S., O’Brien, C.M., and Polunin, V.C. 2002. Long-term changes in the trophic level of the Celtic Sea fish community and fish market price distribution. Journal of Applied Ecology, 39: 377–390.

Poos, J. J., Quirijns, F. J., and Rijnsdorp, A. D. 2010. Spatial segregation among fishing vessels in a multispecies fishery. ICES Journal of Marine Science, 67: 155–164.

Poos, J. J., and Rijnsdorp, A. D. 2007. An "experiment" on effort allocation of fishing vessels: the role of interference competition and area specialization. Canadian Journal of Fisheries and Aquatic Sciences, 64: 304–313.

Poos, J. J., Turenhout, M. N. J., van Oostenbrugge, H., and Rijnsdorp, A. D. 2013. Adaptive response of beam trawl fishers to rising fuel cost. ICES Journal of Marine Science, 70: 675–684.

Powers, J.E., and Abeare, S.M. 2009. Fishing effort redistribution in response to area closures. Fisheries Research, 99: 216–225.

Punzón, A., Hernández, C., Abad, E., Castro, J., Pérez, N., Trujillo, V. 2010. Spanish otter trawl fisheries in the Cantabrian Sea. ICES Journal of Marine Science, 67: 1604–1616.

Quirijns, F.J., Poos, J.J., Rijnsdorp, A.D. 2008. Standardizing commercial CPUE data in monitoring stock dynamics: Accounting for targeting behaviour in mixed fisheries. Fisheries Research, 89: 1–8.

R Development Core Team. 2007. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria. ISBN 3-900051-07-0, URL: http://www.R-project.org.

R Development Core Team. 2008. R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. ISBN 3-900051-07-0, http://www.R-project.org.

R Core Team. 2012. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. ISBN 3-900051-07-0, URL http://www.R-project.org/.

Rabiner, L. and Juang, B. 1986. An introduction to hidden Markov models. ASSP Magazine, IEEE, 3: 4–16.

Reid, D.G., Graham, N., Rihan, D.J., Kelly, E., Gatt, I.R., Griffin, F., Garritsen, H.D. and Kynock, R.J. 2011. Do big boats tow big nets? ICES Journal of Marine Science, 68: 1663–1669.

Reeves, S. A., Marchal, P., Mardle, S., Pascoe, S., Prellezo, R., Thébaud, O., and Travers, M. 2008. From fish to fisheries: the changing focus of management advice. *In* Advances in Fisheries Science. 50 Years on from Beverton and Holt, pp. 135–154. Ed. by A. Payne, J. Cotter, and T. Potter. Blackwell Publishing, Oxford.

Rijnsdorp, A.D., Dol, W., Hooyer, M., and Pastoors, M.A. 2000. Effects of fishing power and competitive interactions among vessels on the effort allocation on the trip level of the Dutch beam trawl fleet. ICES Journal of Marine Science, 57: 927–937.

Rossiter, T., and Stead, S. 2003. Days at sea: from the fishers' mouths. Marine Policy, 27: 281–288.

Sainte-Marie, B. & Hargrave, B. T. 1987. Estimation of scavenger abundance and distance of attraction to bait. Marine Biology, 94: 431–433.

Schau, E.M., Ellingsen, H., Endal, A., and Aanondsen, S.A. 2009. Energy consumption in the Norwegian fisheries. Journal of Cleaner Production, 17: 325–334.

Seetharaman, P.B. 2003. Probabilistic versus random-utility models of state dependence: an empirical comparison. International Journal of Research in Marketing, 20: 87–96.

Sen, S. 2010. Developing a frame work for displaced fishing effort programs in marine protected areas. Marine Policy, 34: 1171–1177.

Sethi, S.A., Branch, T.A., and Watson, R. 2010. Global fishery development patterns are driven by profit but not trophic level. Proceedings of the National Academy of Science, 107: 12163–12167.

Silva, L., Gil, J., Sobrino, I. 2002. Definition of fleet components in the Spanish artisanal fishery of the Gulf of Cadiz (SW Spain ICES division IXa). Fisheries Research, 59: 117–128.

Soulié, J.-C., and Thébaud, O. 2006. Modelling fleet response in regulated fisheries: An agent-based approach. Mathematical and Computer Modelling, 44: 553–564.

STECF. 2009. Scientific, Technical and Economic Committee for Fisheries: Report of the SGMOS-09-05 Working Group on Fishing Effort Regimes in Relation to Annex IIA-C and the Celtic Sea. Ed. by N. Bailey, and H-J. Rátz. Office for Official

Publications of the European Communities, Luxemburg. 356 pp. ISBN 978-92-79-15795-0, JRC24369, https://stecf.jrc.ec.europa.eu/reports/effort.

Sumaila, U. R., Cheung, W.W. L., and Teh, L. 2007. Rebuilding Hong Kong's marine fisheries: an evaluation of management option. Fisheries Centre Research Reports, 15(3). Fisheries Centre, University of British Columbia, Vancouver, Canada. 112pp.

Sumaila, U. R., Teh, L., Watson, R., Tyedmers, P., and Pauly, D. 2008. Fuel price increase, subsidies, overcapacity, and resource sustainability. ICES Journal of Marine Science, 65: 832–840.

Suuronen, P., Jounela, P., and Tschenij, V. 2010. Fishermen responses on marine protected areas in the Baltic cod fishery. Marine Policy, 34: 237–243.

Suuronen, P., Chopin, F., Glass, C., Løkkeborg, S., Matsushita, Y., Queirolo, D., Rihan, D. 2012. Low impact and fuel efficient fishing – looking beyond the horizon. Fisheries Research, 119: 135–146.

Swartz, W., Sumaila, R., and Watson, R. 2012. Global Ex-vessel Fish Price Database Revisited: A New Approach for Estimating 'Missing' Prices. Environmental and Resource Economics, October 2012. Published online October 19, 2012, doi:10.1007/s10640-012-9611-1.

Thorson, J. T., Stewart, I. J., and Punt, A. E. 2012. Development and application of an agent-based model to evaluate methods for estimating relative abundance indices for shoaling fish such as Pacific rockfish (*Sebastes* spp.). ICES Journal of Marine Science, doi:10.1093/icesjms/fss003.

Tidd, A.N., Hutton, T., Kell, L.T, and Blanchard, J.L. 2012. Dynamic prediction of effort reallocation in mixed fisheries. Fisheries Research, 125-126: 243–253.

Tidd, A.N. 2013. Effective fishing effort indicators and their application to spatial management of mixed demersal fisheries. Fisheries Management and Ecology, doi:10.1111/fme.12021.

Tyedmers P. 2001. Energy consumed by North Atlantic fisheries. Fisheries Centre Research Reports. *In* Fisheries impacts on North Atlantic ecosystems: catch, effort and national/regional datasets, 9(3). pp. 12-34. Ed. by D. Zeller, R. Watson, and D. Pauly. Fisheries Centre, University of British Columbia, Vancouver.

Tyedmers, P., H., Watson, R., and Pauly, D. 2005. Fuelling global fishing fleets. Ambio, 34: 635–638.

Ulrich, C. and Andersen, B. S. 2004. Dynamics of fisheries, and the flexibility of vessel activity in Denmark between 1989 and 2001. ICES Journal of Marine Science, 61**:** 308–322.

Ulrich, C., Andersen, B. S., Sparre, P. J., and Nielsen, J. R. 2007. TEMAS: fleet-based bio-economic simulation software to evaluate management strategies accounting for fleet behaviour. ICES Journal of Marine Science, 64: 647–651.

Ulrich, C., Reeves, S. A., Vermard, Y., Holmes, S. J., and Vanhee, W. 2011. Reconciling single-species TACs in the North Sea demersal fisheries using the Fcube mixed-fisheries advice framework. ICES Journal of Marine Science, 68: 1535–1547.

UN. 2002. United Nations Report of the World Summit on Sustainable Development Johannesburg, South Africa, 26 August-4 September 2002. A/CONF.199/20*, pp 173.

Valentinsson, D., and Ulmestrand, M. 2008. Species-selective *Nephrops* trawling: Swedish grid experiments. Fisheries Research, 90: 109–117.

van Oostenbrugge, J.A.E., Poos, J.J., van Densen, W.L.T., and Machiels, M.A.M. 2002. In search of a better unit of effort in the coastal liftnet fishery with lights for small pelagics in Indonesia. Fisheries Research, 59: 43–56.

van Putten, I. E., Gorton, R. J., Fulton, E. A., and Thebaud, O. 2013. The role of behavioural flexibility in a whole of ecosystem model. ICES Journal of Marine Science, 70: 150–163.

van Putten, I.E., Kulmala, S., Thébaud, O., Dowling, N., Hamon, K.G., Hutton, T., and Pascoe, S. 2012. Theories and behavioural drivers underlying fleet dynamics models. Fish and Fisheries, 13: 216–235.

Venables, W.N., Ellis, N., Punt, A.E., Dichmont, C.M., and Deng, R.A. 2009. A simulation strategy for fleet dynamics in Australia's northern prawn fishery: effort allocation at two scales. ICES Journal of Marine Science, 66: 631–645.

Venables, W. N. and Ripley, B. D. 2002. *Modern Applied Statistics with S.* Fourth edition. Springer.

Vermard, Y., Marchal, P., Mahévas, S., Thébaud, O. 2008. A dynamic model of the Bay of Biscay pelagic fleet simulating fishing trip choice: the response to the closure of the European anchovy (*Engraulis encrasicolus*) fishery in 2005. Canadian Journal of Fisheries and Aquatic Sciences, 65: 2444–2453.

Vermard, Y., Rivot, E., Mahévas., S., Marchal, P., and Gascuel, D. 2010. Identifying fishing trip behaviour and estimating fishing effort from VMS data using Bayesian Hidden Markov Models. Ecological Modelling, 221: 1757–1769.

Villasante, S., García-Negro, M.-C., González-Laxe, F., and Rodríguez Rodríguez, G. 2011. Overfishing and the common fisheries policy: (un)successful results from TAC regulation? Fish and Fisheries, 12: 34–50.

Vinther, M., Reeves, S. A., and Patterson, K. R. 2004. From single species advice to mixed-species management: taking the next step. ICES Journal of Marine Science, 61: 1398–1409.

Ward, J.H. 1963. Hierarchical grouping to optimize an objective function. Journal of the American Statistical Association, 58: 236–244.

Wilen, J., Smith, M., Lockwood, D., and Botsford, L. 2002. Avoiding surprises: incorporating fisherman behaviour into management models. Bulletin of Marine Science, 70: 553–575.

Winther, U., Ziegler, F., Skontorp Hognes, E., Emanuelsson, A., Sund, V., and Ellingsen, H. 2009. Carbon footprint and energy use of Norwegian seafood products. SINTEF Report Nr. SHF80 A096068, 91pp. (www.sintef.no).

Wood, S. N. 2006. Generalized additive models: an introduction with R (Vol. 66). Chapman & Hall.

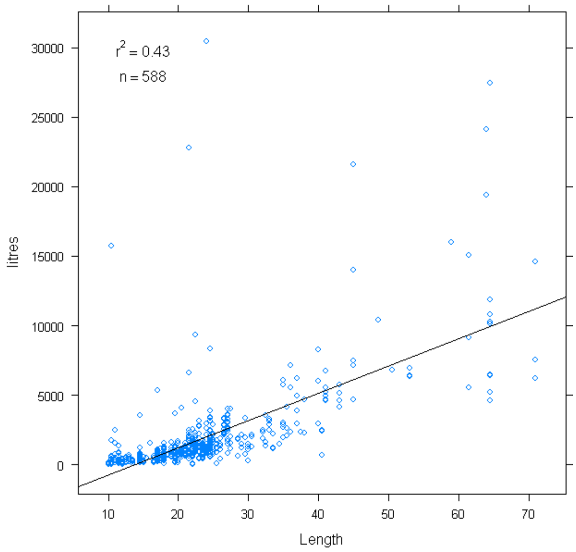
Yergin, D. 1991. The Prize: The Epic Quest for Oil, Money, and Power. Simon & Schuster, New York.

Ziegler, F. and Hansson, P. A. 2003. Emissions from fuel combustion in Swedish cod fishery. Journal of Cleaner Production, 11: 303–314.

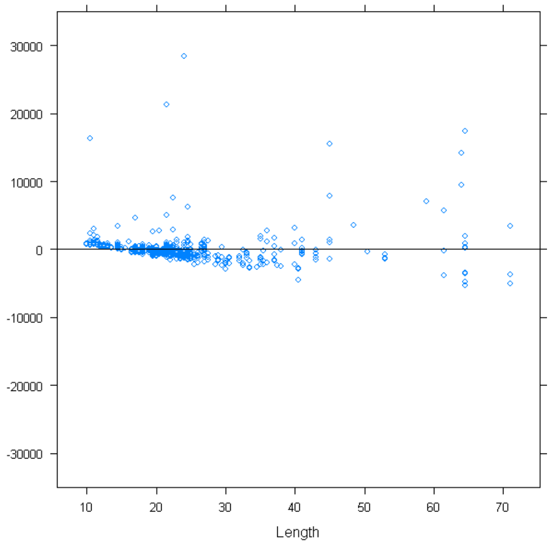
Appendices

Appendix A: Regressions of fuel per day by length, relating to preliminary analyses of Chapter V not included in the published work.

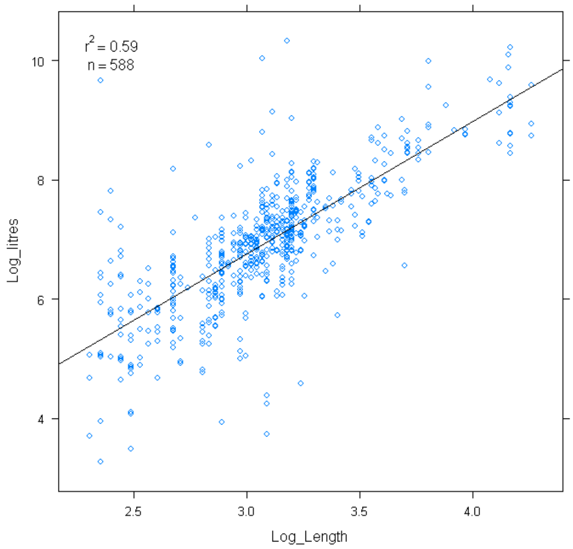
All gears - litres Per Day: linear



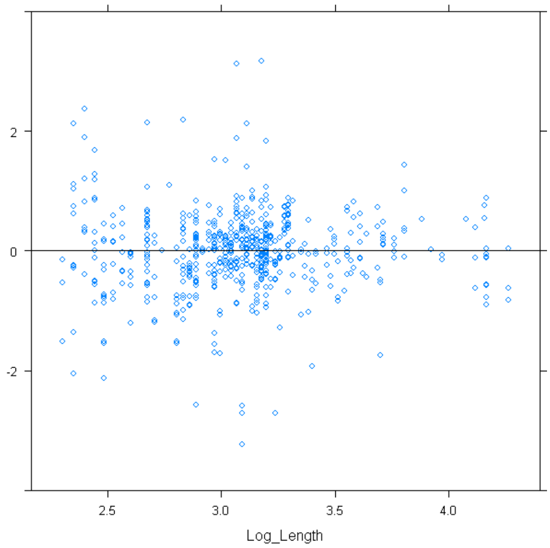
All gears - litres Per Day: linear residuals



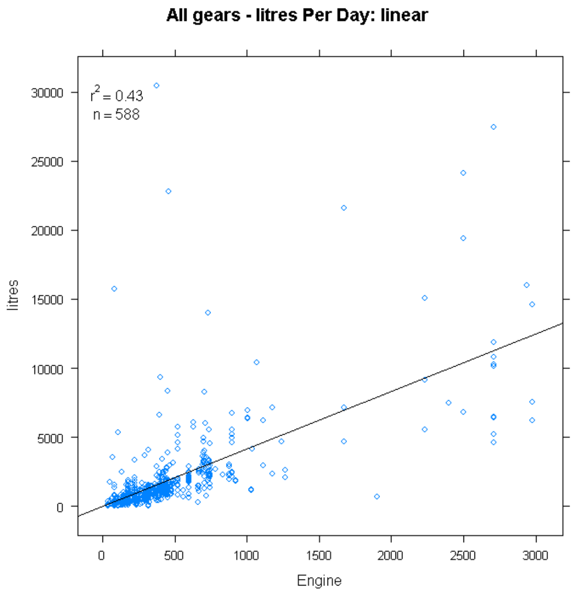
All gears - litres Per Day: Power



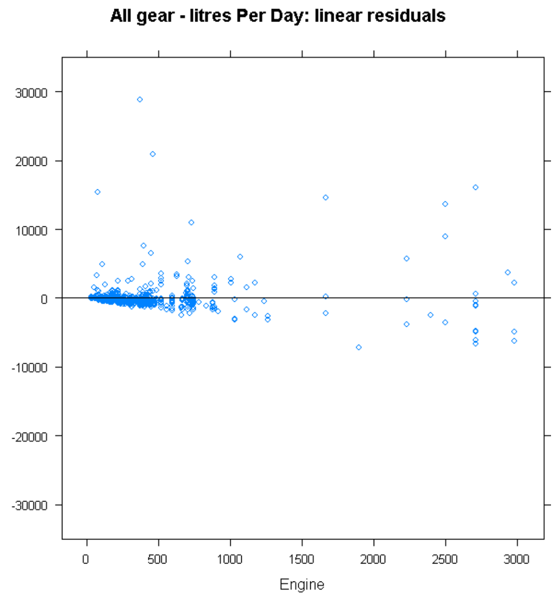
All gears - litres Per Day: Power residuals



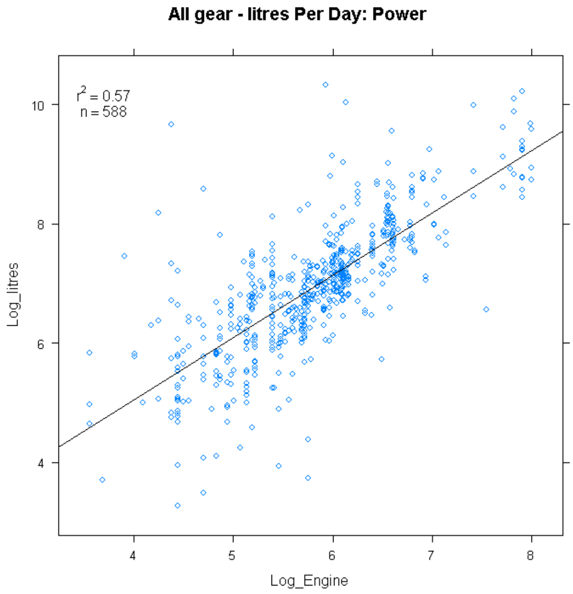
Appendix B: Regressions of fuel per day by engine power, relating to preliminary analyses of Chapter V not included in the published work.



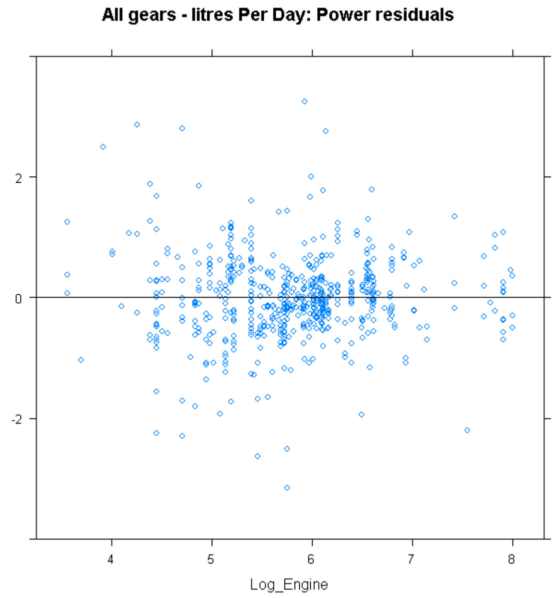
All gears - litres Per Day: linear



All gear - litres Per Day: linear residuals



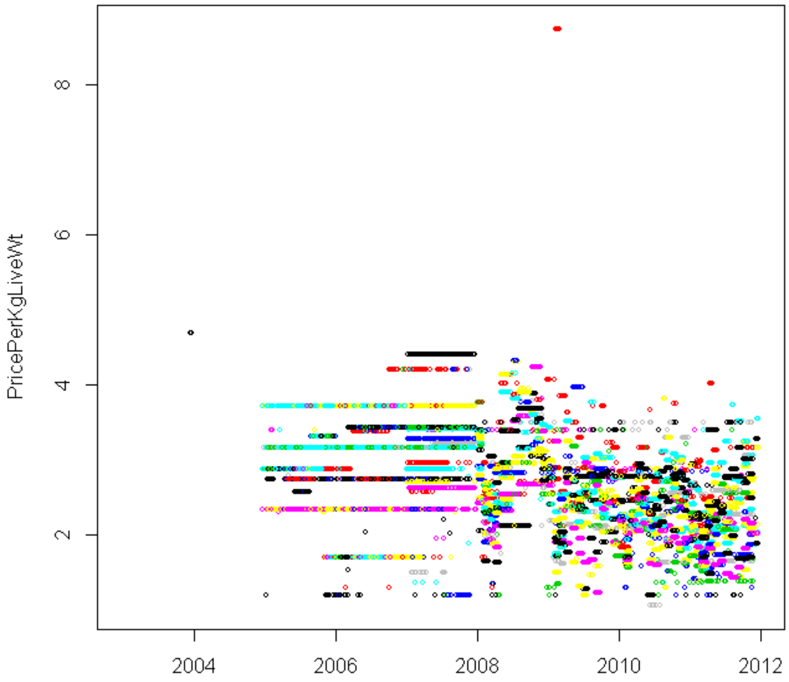
All gear - litres Per Day: Power



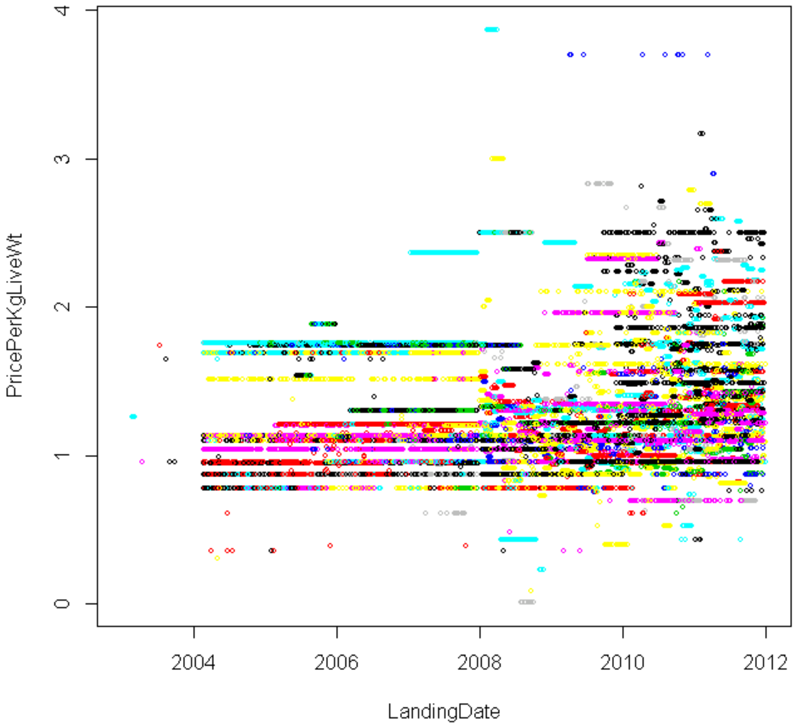
All gears - litres Per Day: Power residuals

Appendix C: Examples of original first sale price plots for species 2003 to 2011, Chapter VI. Examples for cod and ray species in which each dot represents a price per kg live weight and colour variations relate to different landing ports. These plots were used to visualise species (group) price range and variability as well as screen raw data for outliers and data gaps.

Cod



Rays



Appendix D: Chapter VII Markov transition probability model runs including individual available driver descriptors to determine the variables which best describe observed transitions for inclusion within the full model.

Table D1. Results of basic Markov model runs ($state_t$ responding to $state_{t-1}$) with each of the available descriptor terms modelled. Table details degrees of freedom (df), log likelihood, AIC, and AIC change in relation to lowest value.

Variable	df	Likelihood	AIC	ΔAIC
Base model ($state_t$ and $state_{t-1}$ only)	72	-48522.9	97189.88	2594.382
Categorical year	432	-48074.7	97013.49	2417.997
Season cubic day of year	288	-47727	96030.04	1434.542
Season half sine day of year	144	-48139.2	96566.37	1970.876
kilowatt fishing days	144	-47724.3	95736.51	1141.015
kilowatt fishing days at $state_{t-1}$	144	-47662.9	95613.79	1018.299
Engine power	144	-47477.9	95243.78	648.289
Vessel length	144	-47422.5	95132.99	537.4914
Fuel consumption per day	144	-47153.7	94595.5	0
Fuel consumption per day at $state_{t-1}$	144	-47360.5	95008.99	413.4991
Fuel consumption per trip	144	-47686.4	95660.84	1065.345
Fuel consumption per trip at $state_{t-1}$	144	-47621.4	95530.74	935.2425
Fuel price per litre	144	-48414.3	97116.58	2521.089
Fuel cost per day at $state_{t-1}$	144	-47422.9	95133.84	538.3461
Fuel cost per trip at $state_{t-1}$	144	-47638.8	95565.66	970.1651
Profit per day at $state_{t-1}$	144	-47944.9	96177.78	1582.288
Profit per trip at $state_{t-1}$	144	-47919.2	96126.34	1530.842
Value per trip at $state_{t-1}$	144	-47788.3	95864.68	1269.187
Available quota in weight	128	-48416.6	97089.29	2493.794
Available quota in value	144	-52776.5	105841.1	11245.59

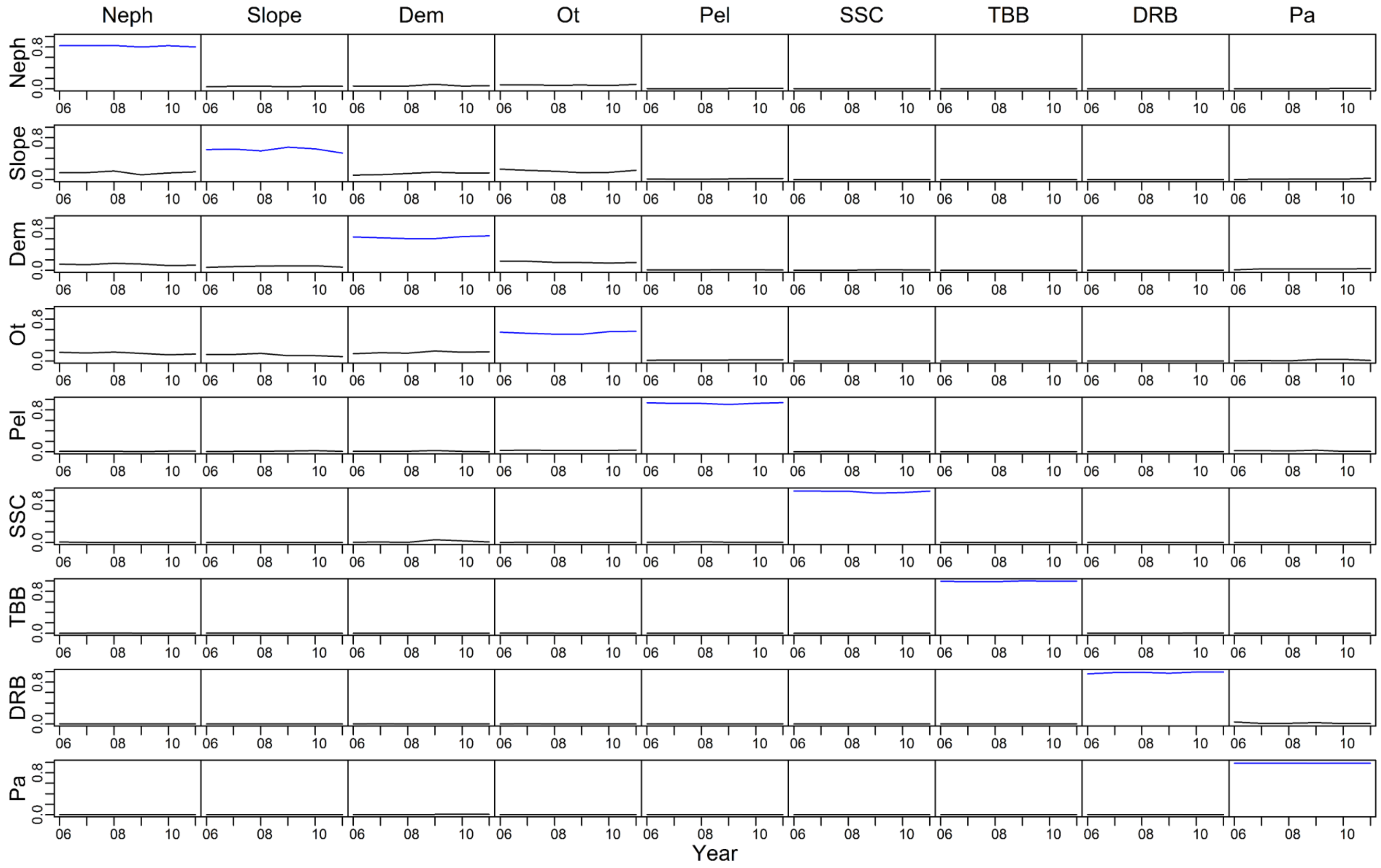


Figure D1. Matrix of transition probabilities for categorical year.

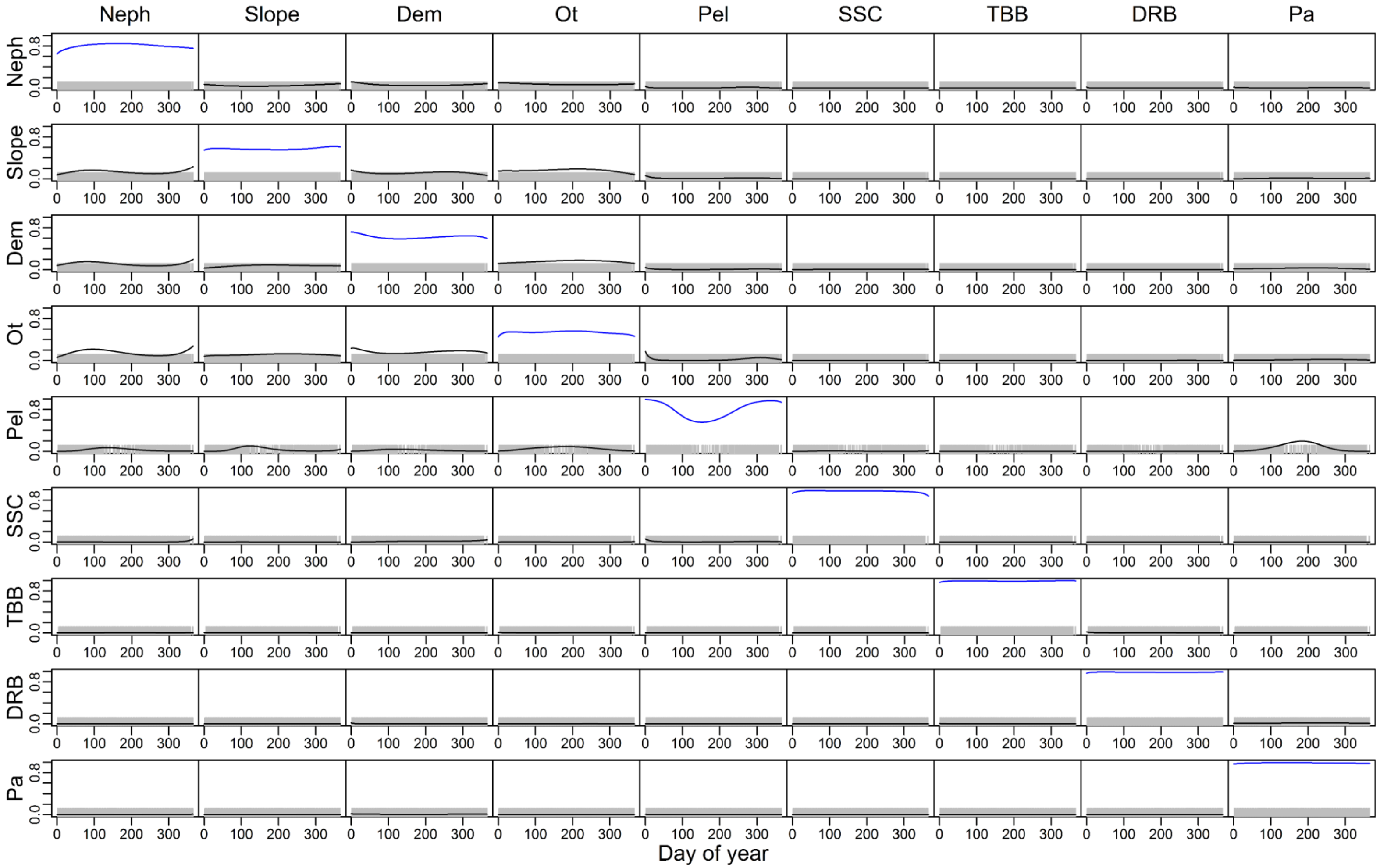


Figure D2. Matrix of transition probabilities for season as a cubic polynomial day of the year.

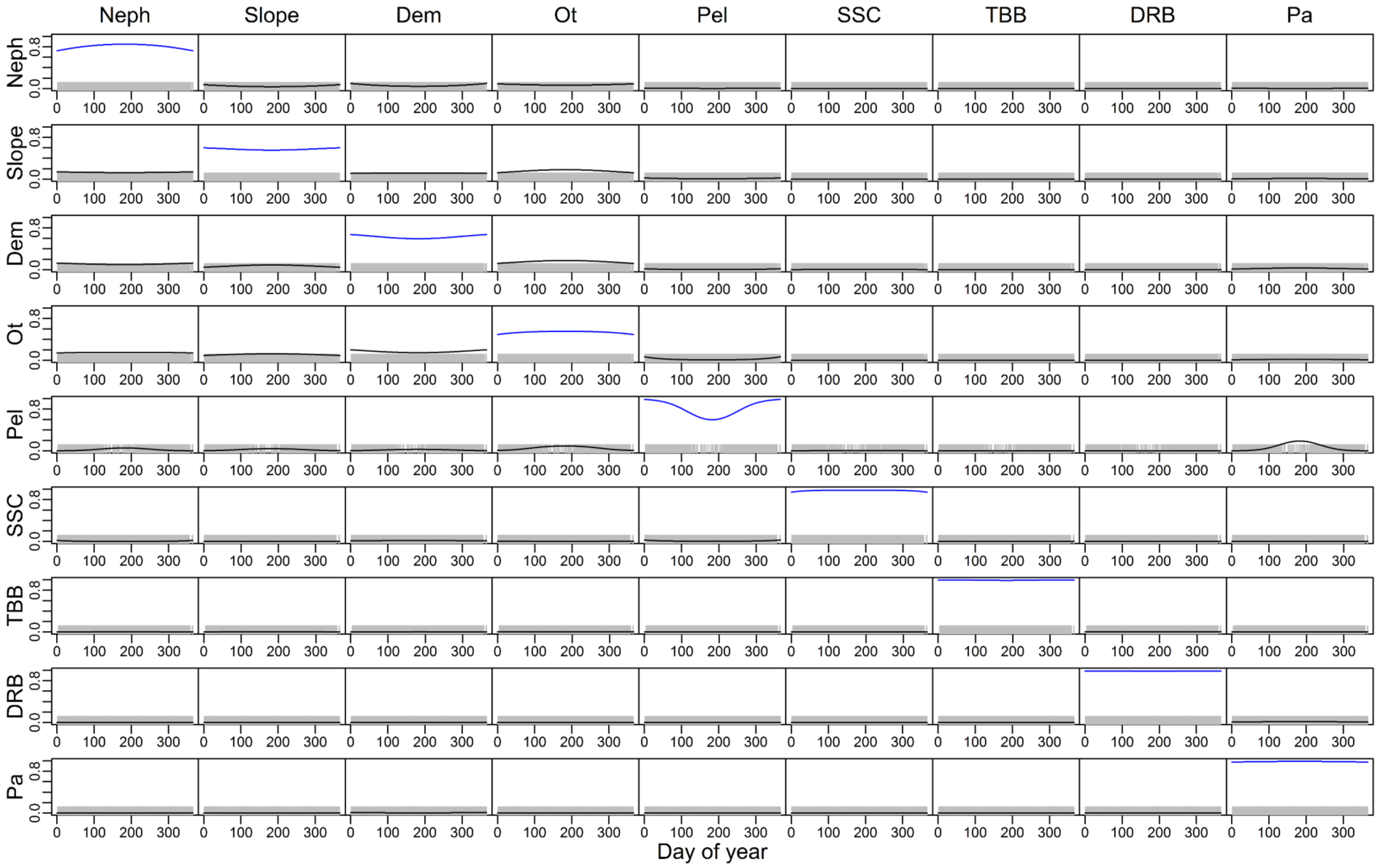


Figure D3. Matrix of transition probabilities for season as a half sine wave day of the year.

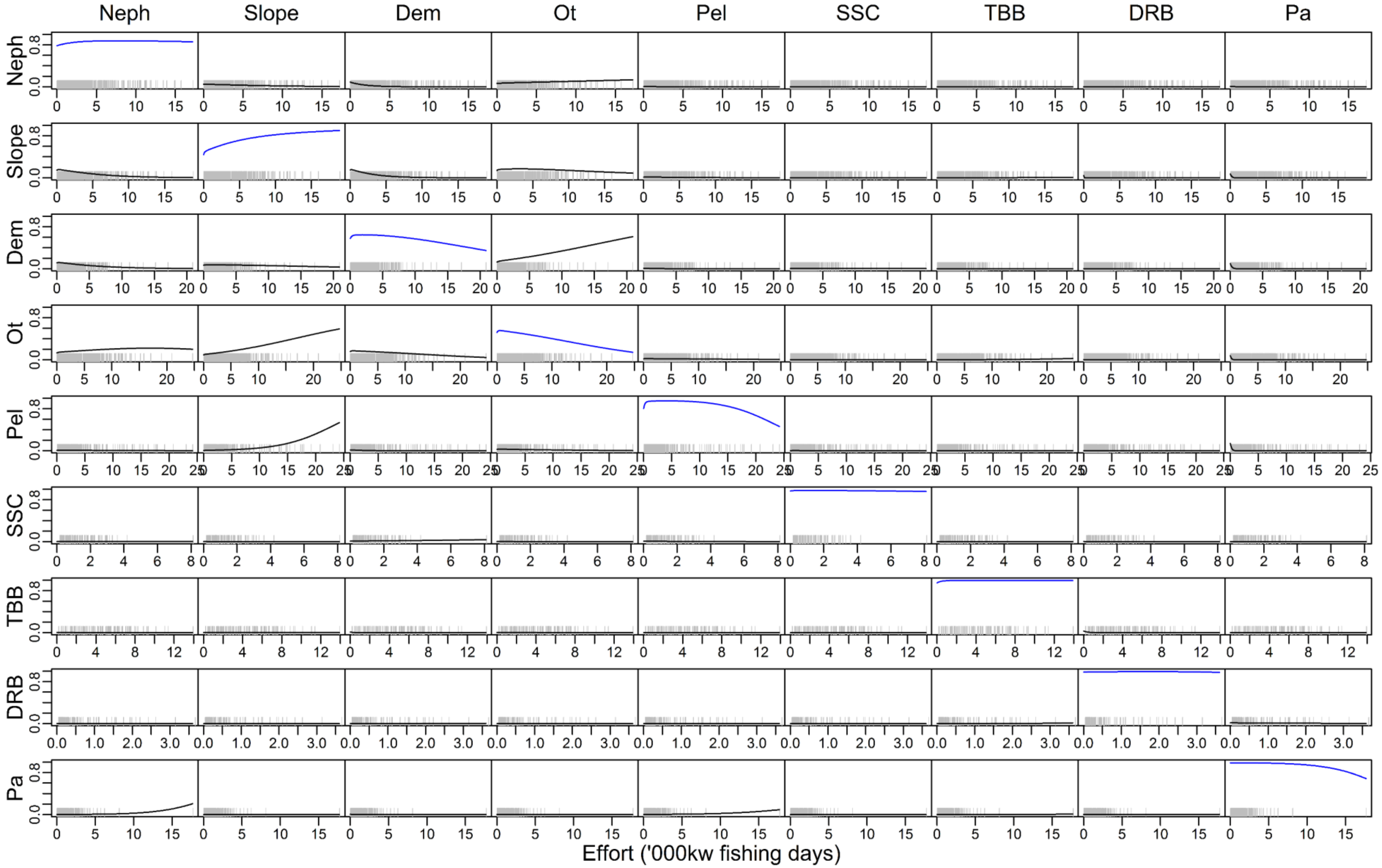


Figure D4. Matrix of transition probabilities for kilowatt fishing days in state$_t$.

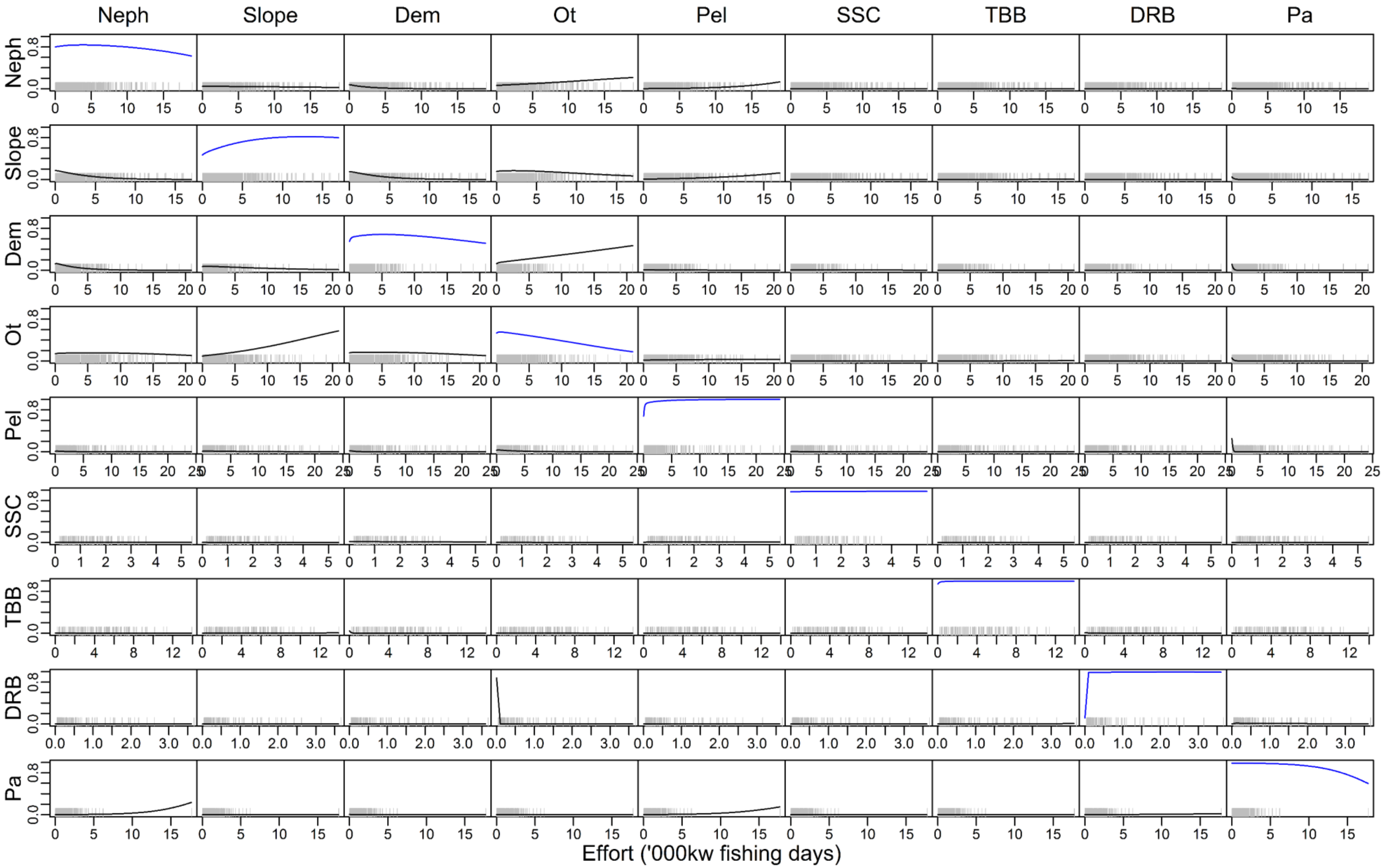


Figure D5. Matrix of transition probabilities for kilowatt fishing days in state$_{t-1}$.

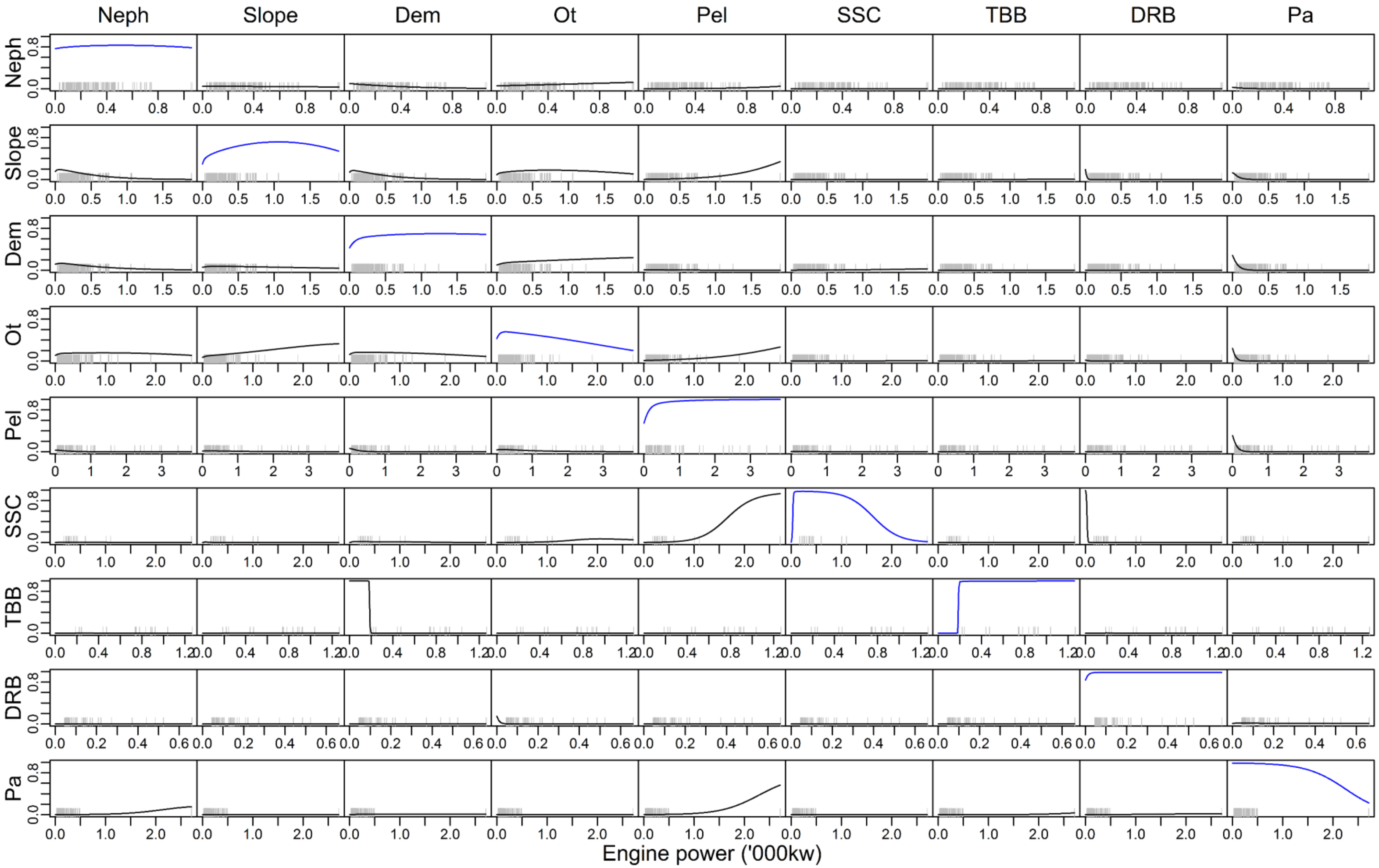


Figure D6. Matrix of transition probabilities for vessel engine power.

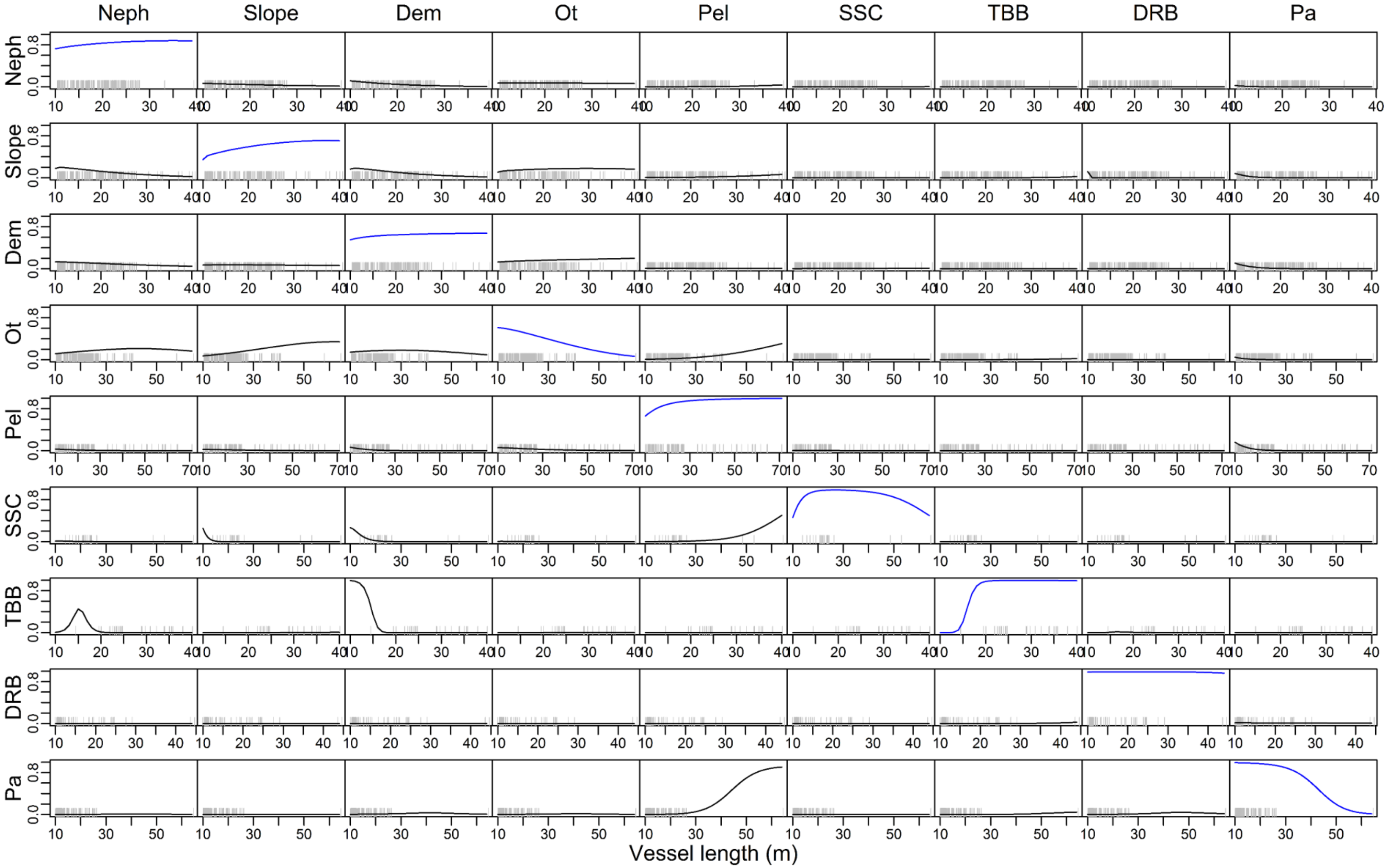


Figure D7. Matrix of transition probabilities for vessel length.

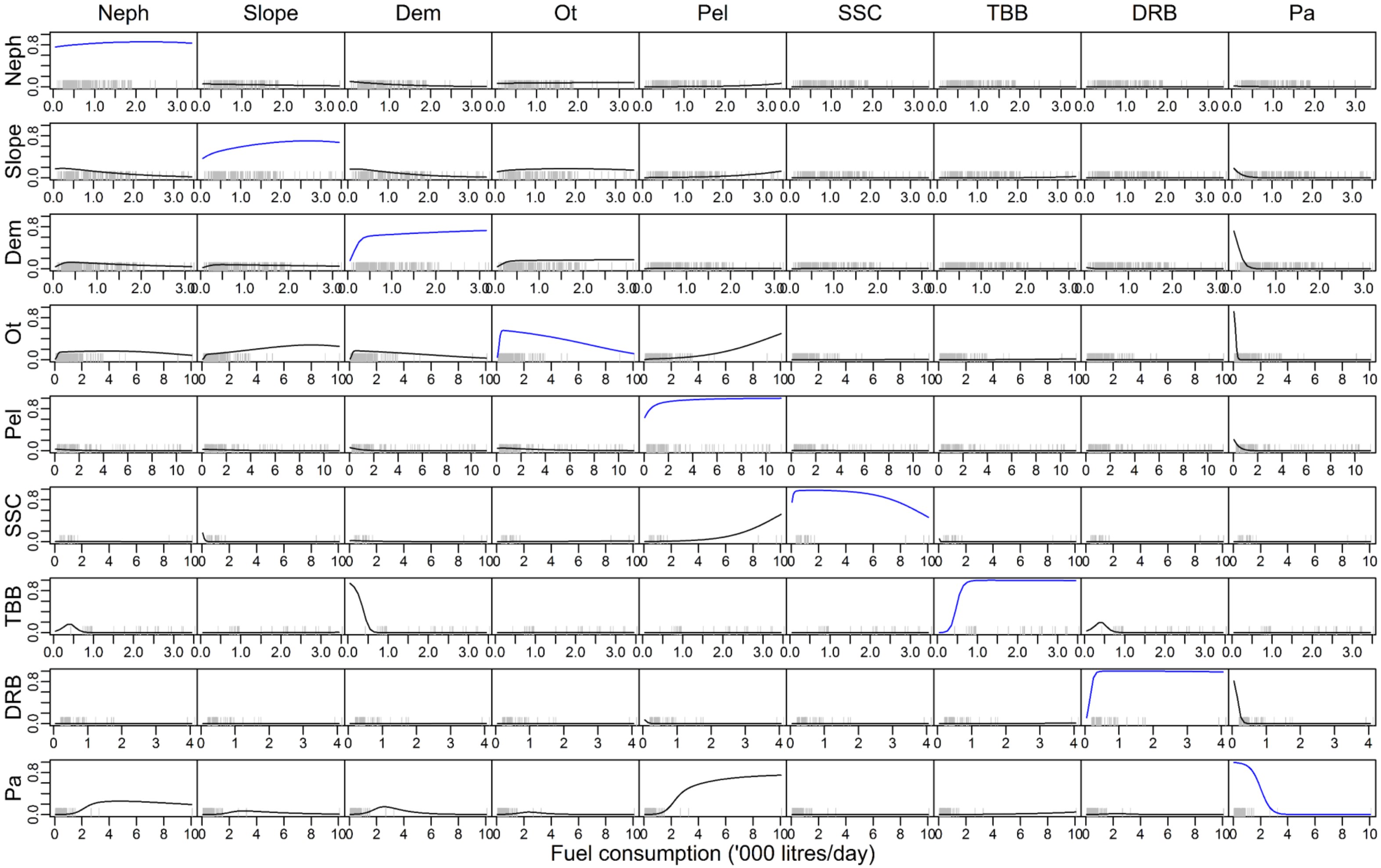


Figure D8. Matrix of transition probabilities for fuel consumption per day at state$_t$.

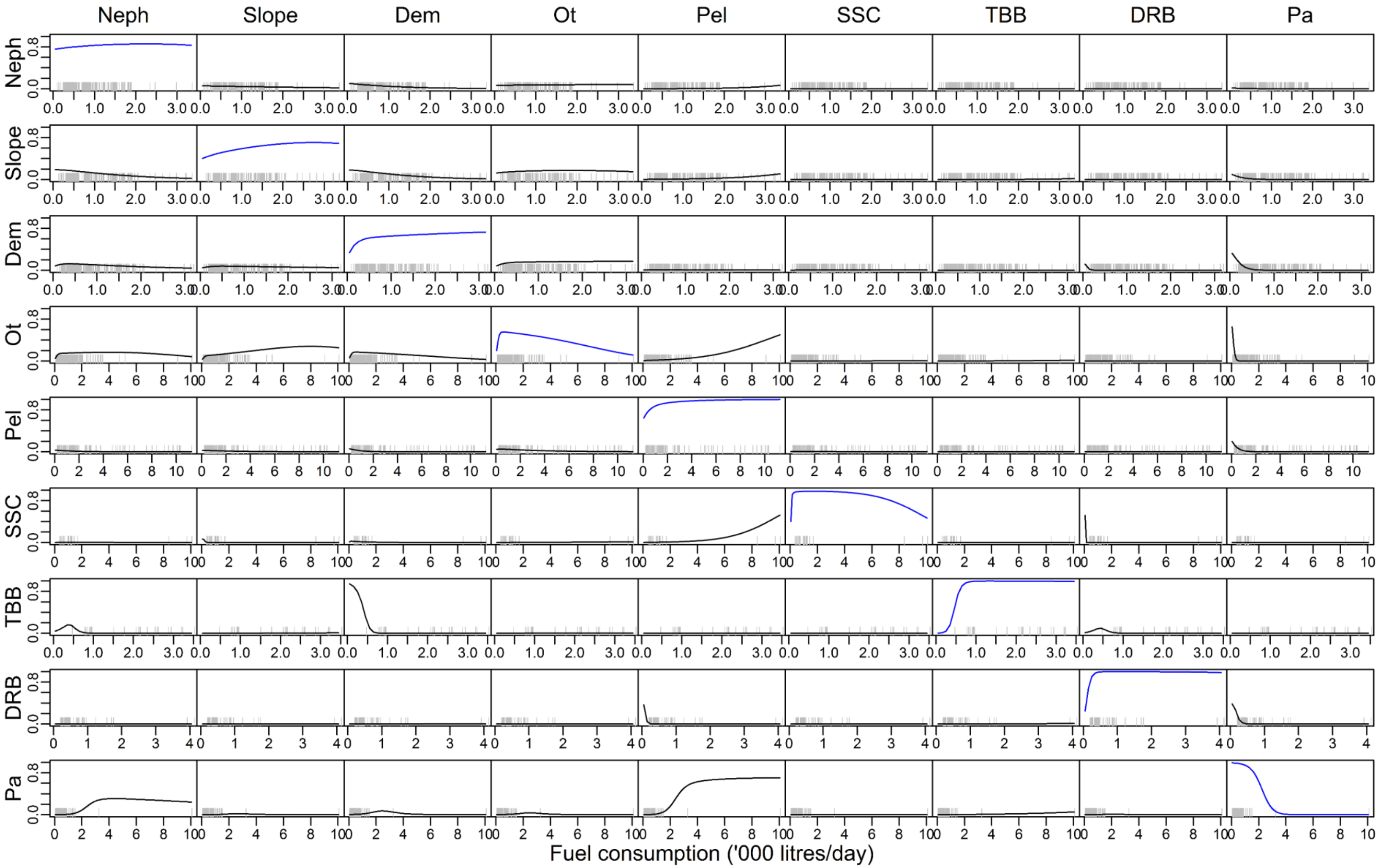


Figure D9. Matrix of transition probabilities for fuel consumption per day at state$_{t-1}$.

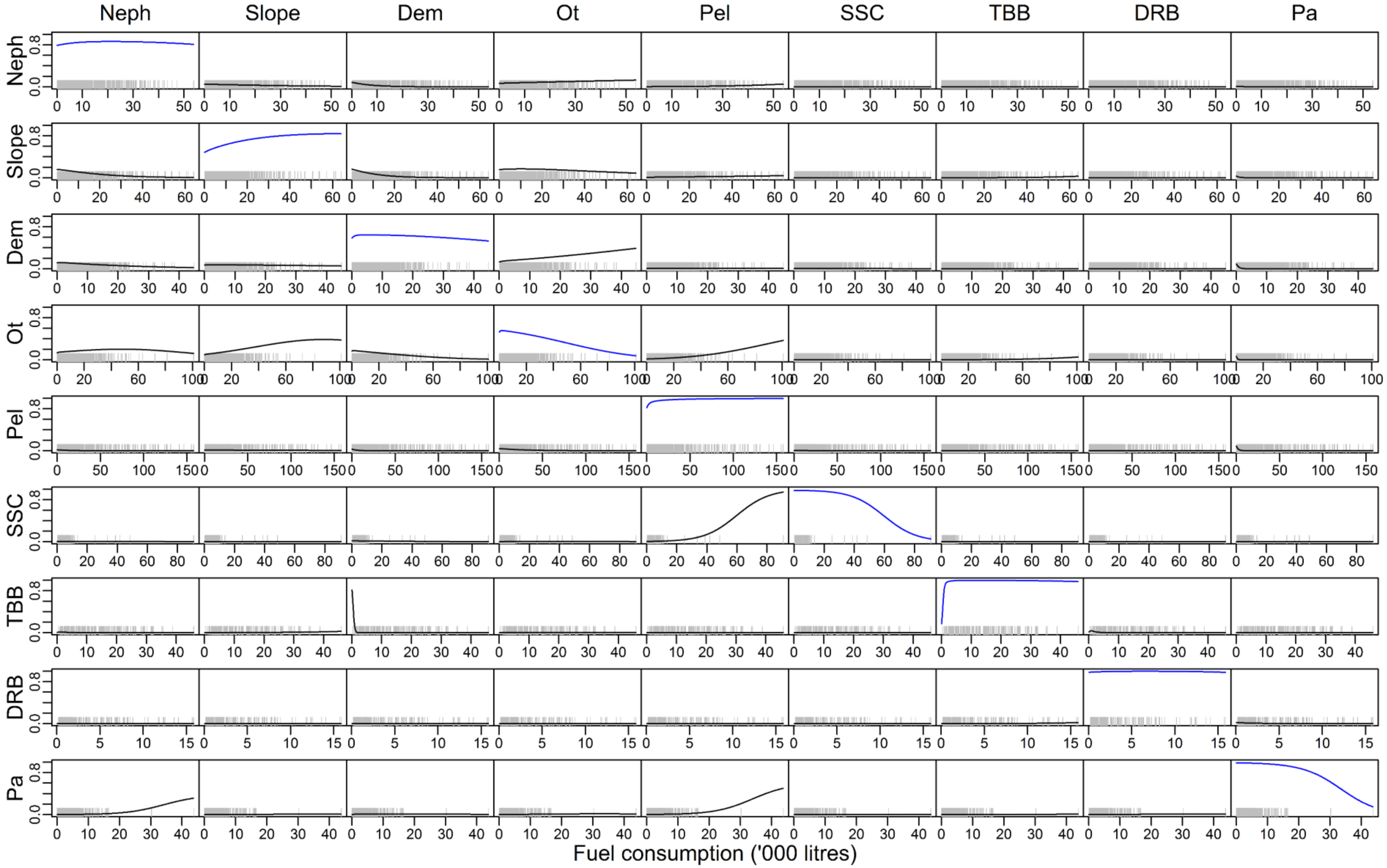


Figure D10. Matrix of transition probabilities for fuel consumption per trip at state$_t$.

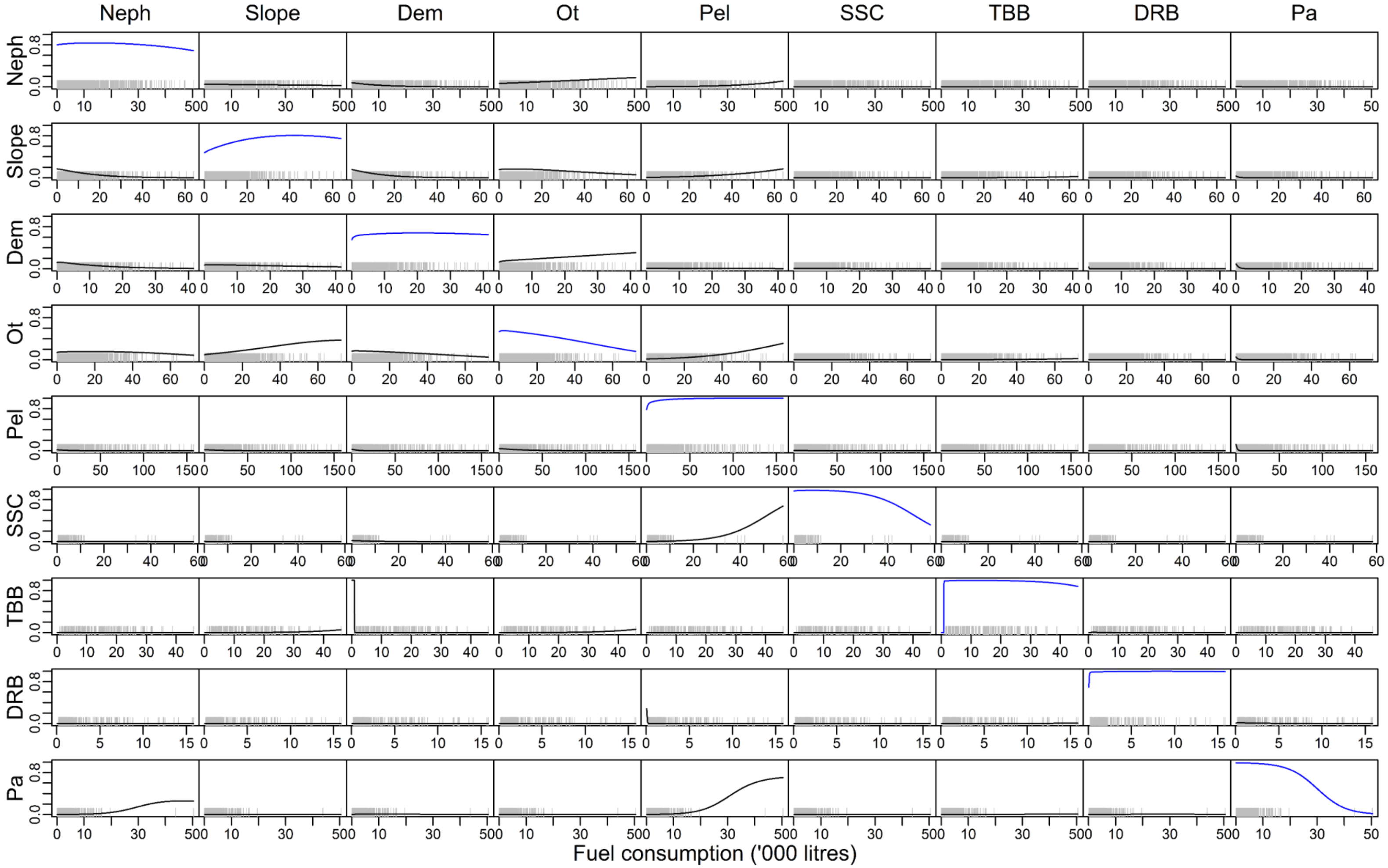


Figure D11. Matrix of transition probabilities for fuel consumption per trip at state$_{t-1}$.

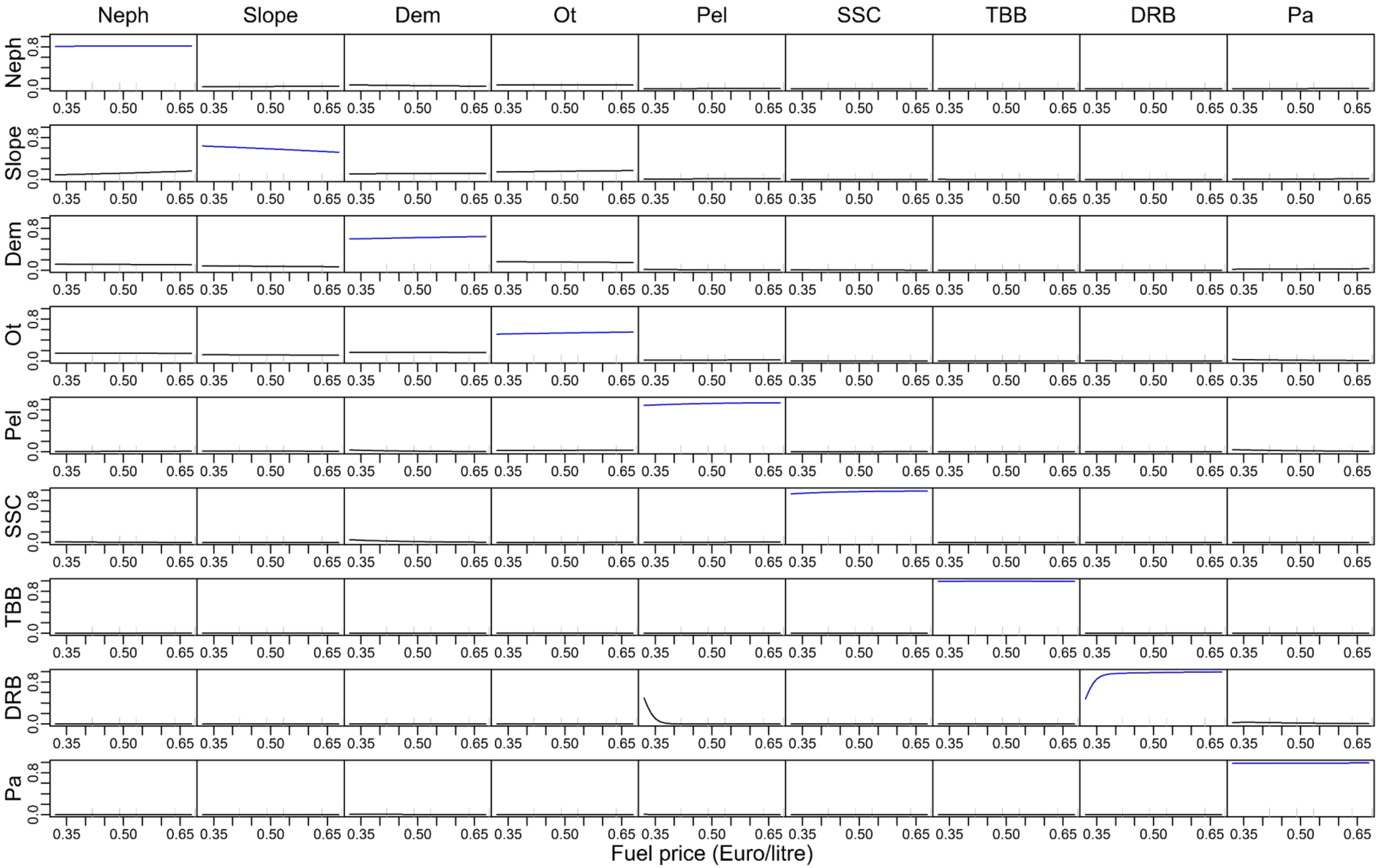


Figure D12. Matrix of transition probabilities for fuel price per litre.

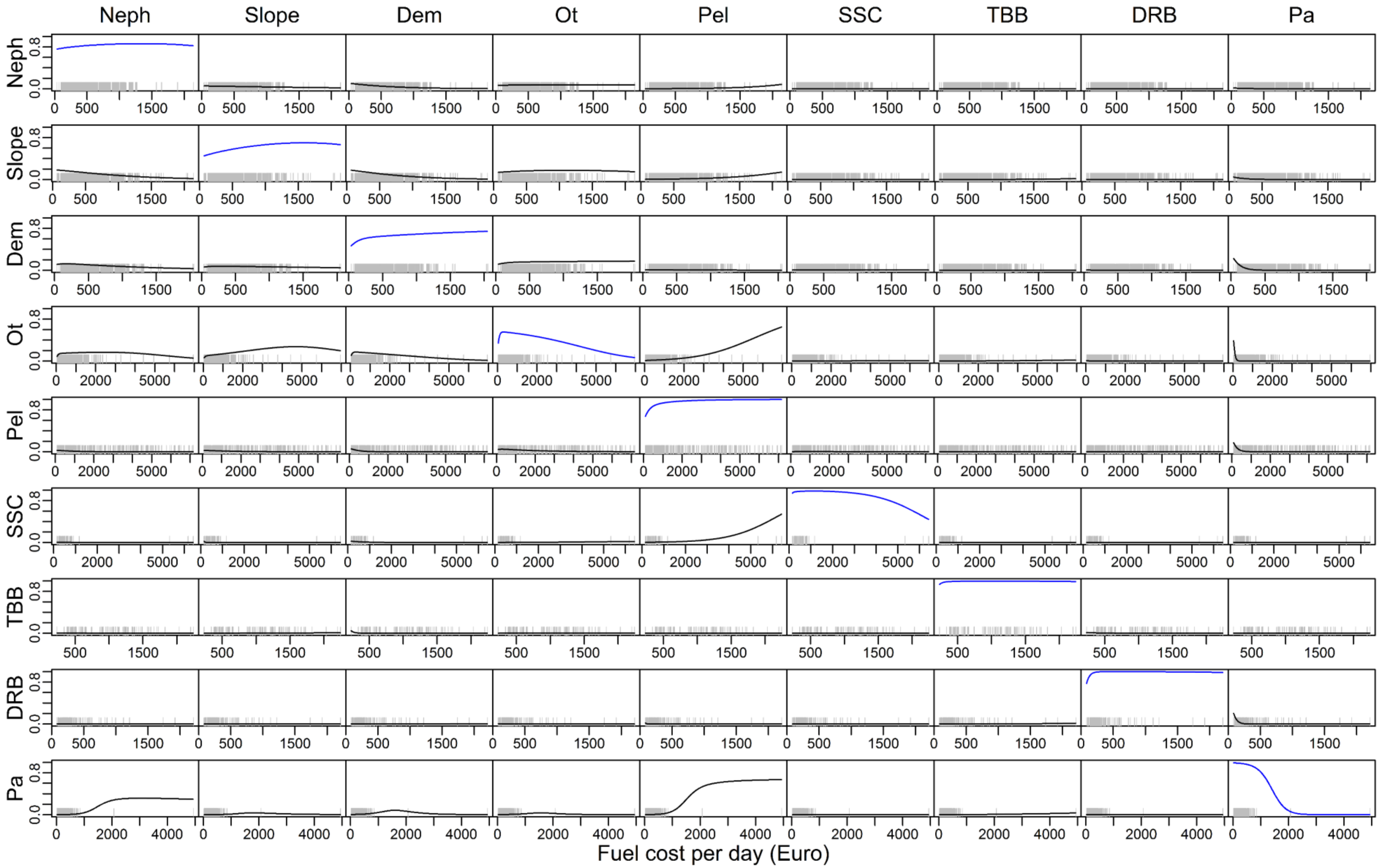


Figure D13. Matrix of transition probabilities for fuel cost per day at state$_{t-1}$.

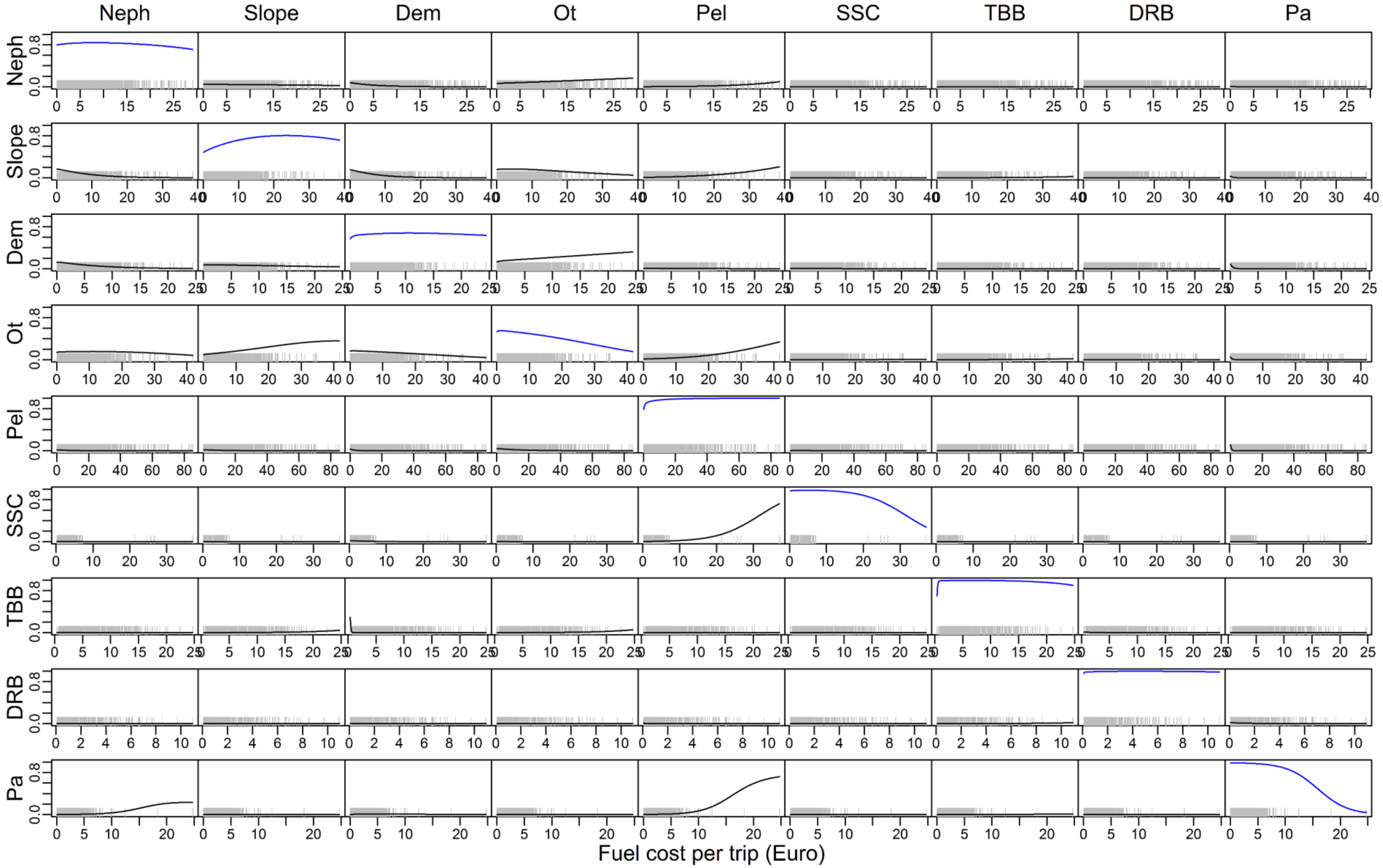


Figure D14. Matrix of transition probabilities for fuel cot per trip at state$_{t-1}$.

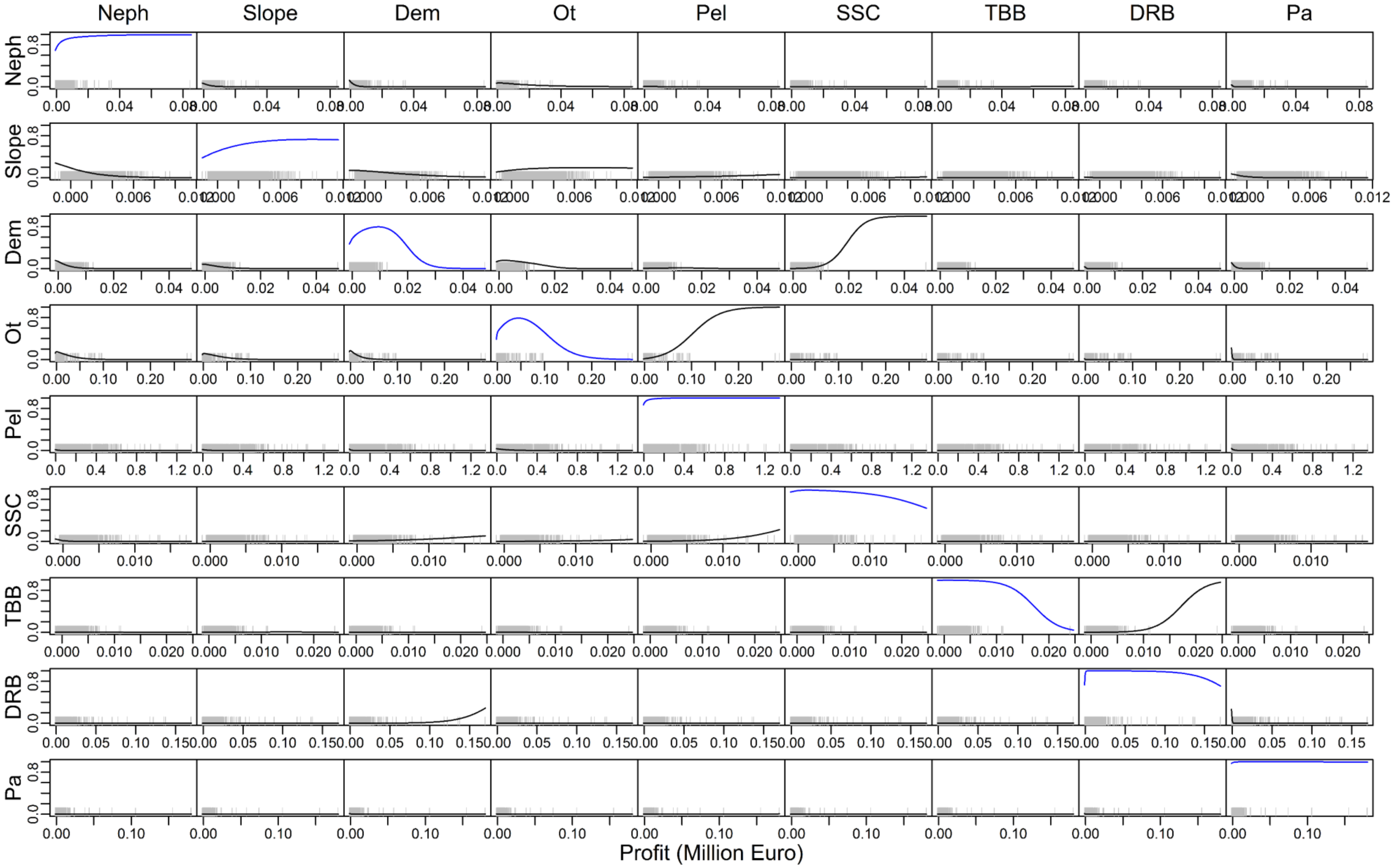


Figure D15. Matrix of transition probabilities for profit per day at state$_{t-1}$.

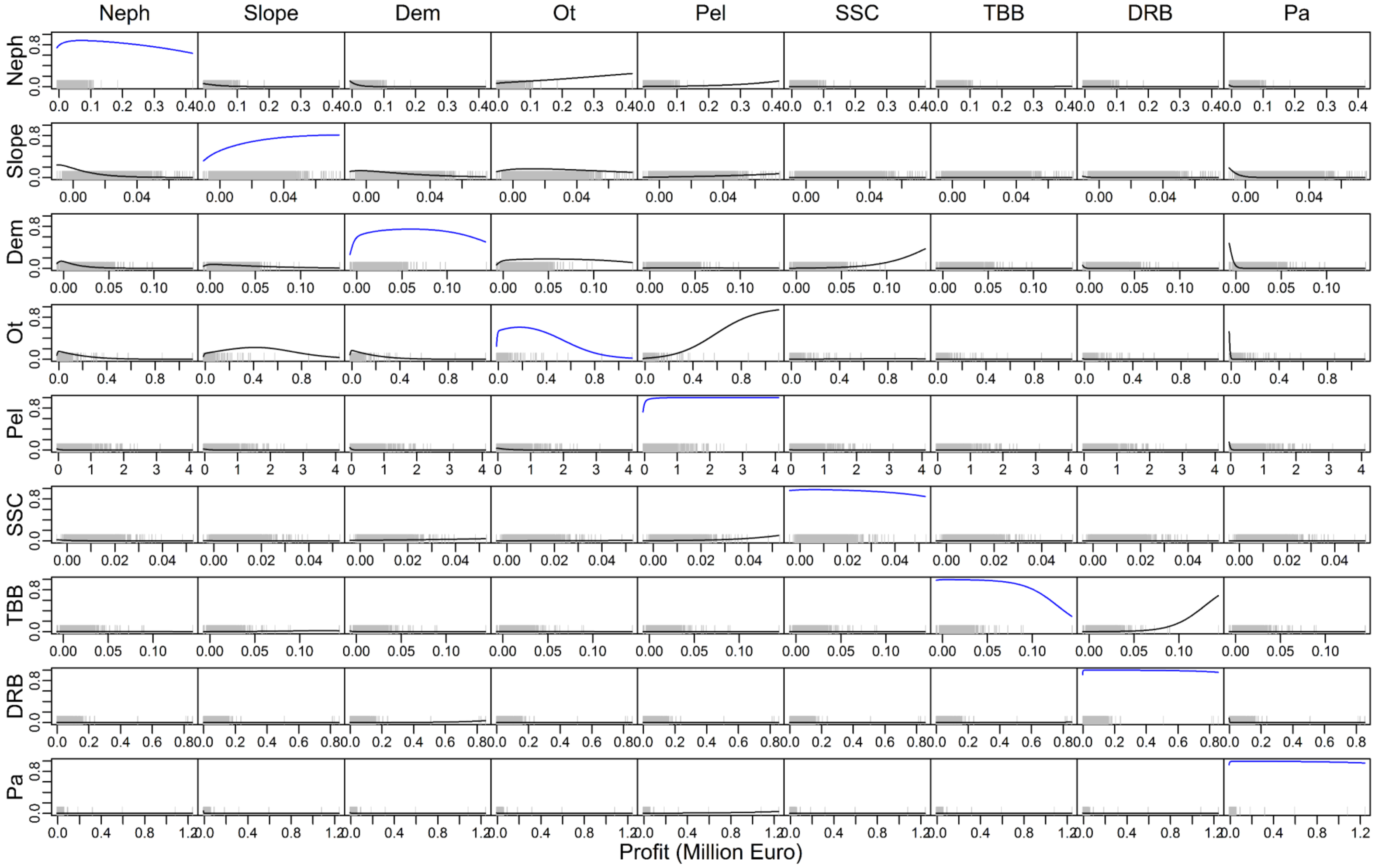


Figure D16. Matrix of transition probabilities for profit per trip at state$_{t-1}$.

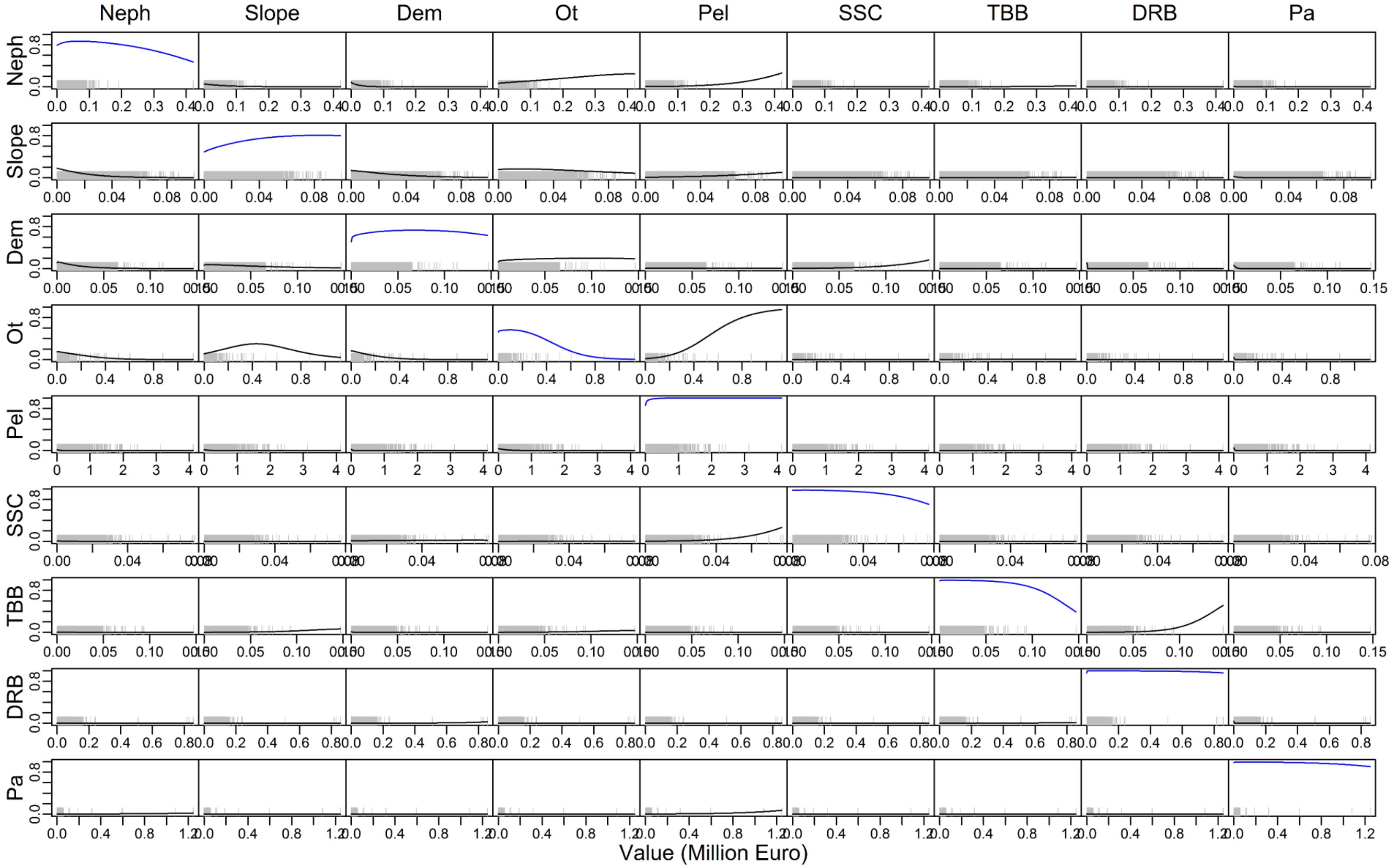


Figure D17. Matrix of transition probabilities for value per trip at state$_{t-1}$.

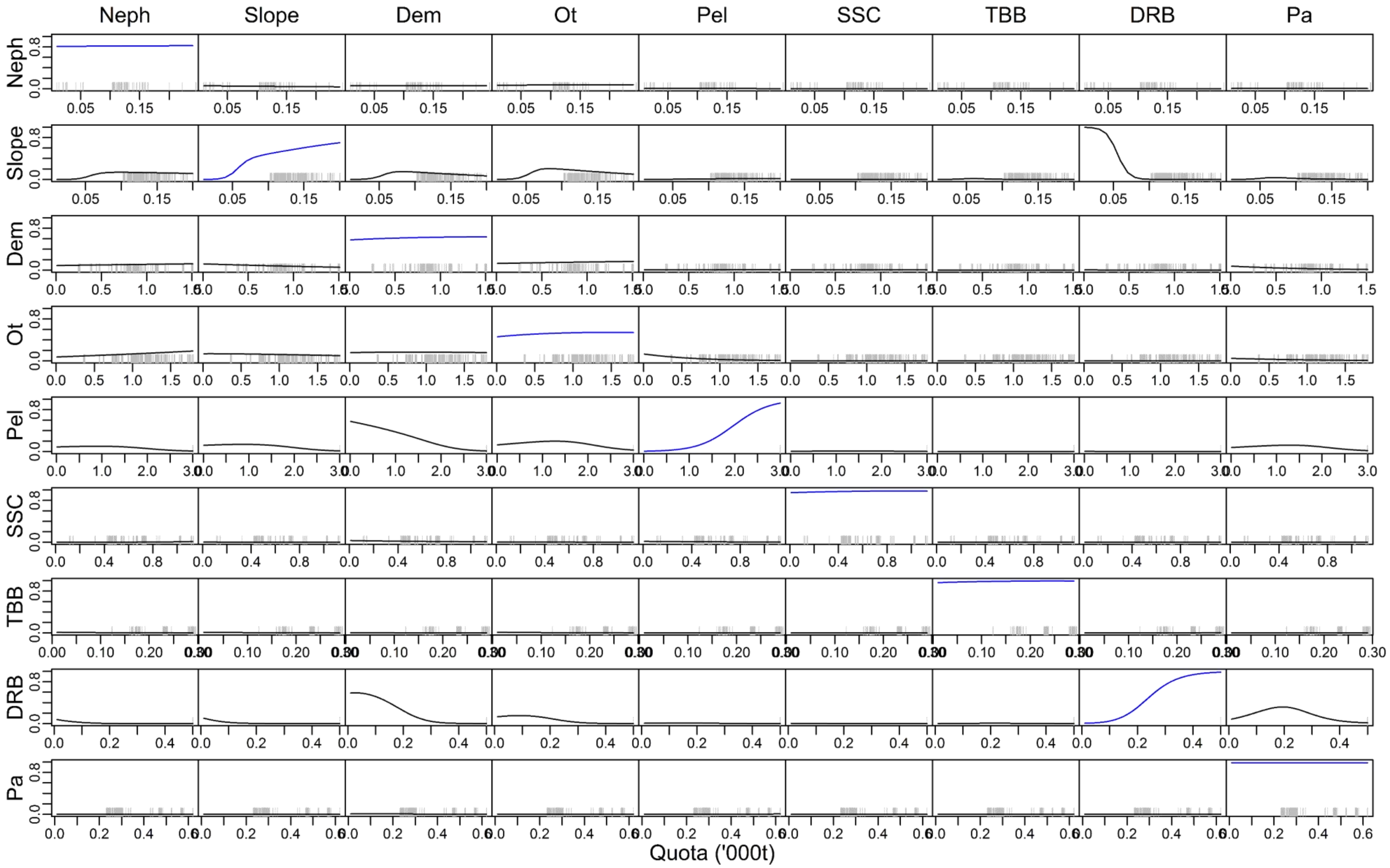


Figure D18. Matrix of transition probabilities for available quota in weight.

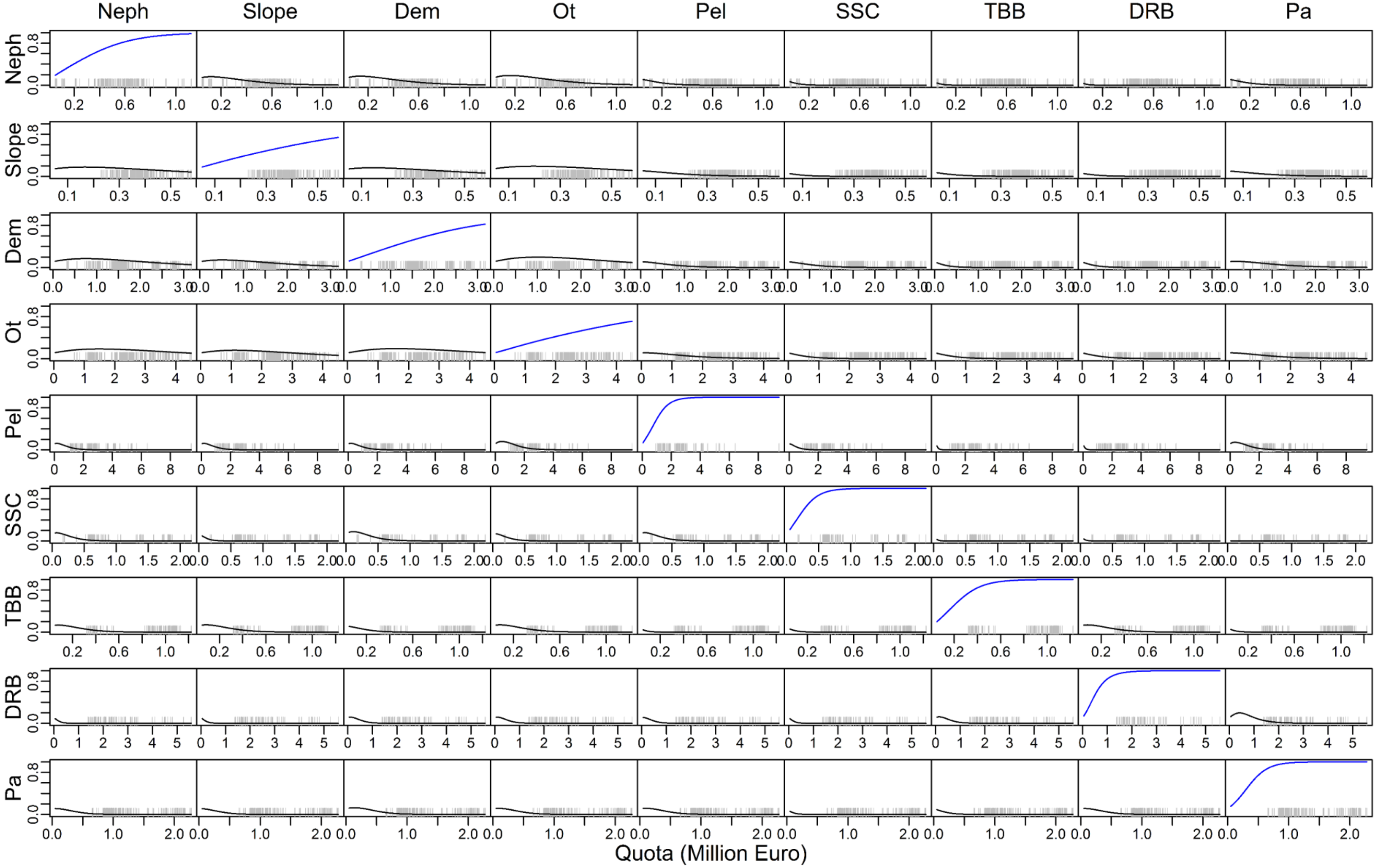


Figure D19. Matrix of transition probabilities for available quota in value.

Appendix E: Declaration

INSTITIÚID TEICNEOLAÍOCHTA NA GAILLIMHE-MAIGH EO
GALWAY-MAYO INSTITUTE OF TECHNOLOGY

I hereby certify that this material, which I now submit for assessment on the programme of study leading to the award of M.Sc./ PhD is entirely my own work and has not been taken from the work of others save and to the extent that such work has been cited and acknowledged within the text of my work.

Signed: ________________________ Candidate

ID No: ***G00268012***

Date: ***31st July 2013***

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