Quantifying Catch Depletion Rates in the Isle of Man Queen Scallop (*Aequipecten opercularis* L.) Fishery.

Sam Dignan

In partial fulfilment of the requirement of the M.Sc. in Marine Environmental Protection

September, 2013.

Supervisors: Dr. J. Hiddink & Dr. L. Murray

PRIFYSGOL
BANGOR
UNIVERSITY

DECLARATION

This work has not previously been accepted in substance for any degree and is not being currently submitted for any degree.

This dissertation is being submitted in partial fulfilment of the requirement of the M.Sc. in Marine Environmental Protection.

The dissertation is the result of my own independent work / investigation, except where otherwise stated.

Other sources are acknowledged by footnotes giving explicit references and a bibliography is appended.

I hereby give consent for my dissertation, if accepted, to be made available for photocopying and for inter-library loan, and the title and summary to be made available to outside organisations.

Signed:

Date: 20/09/2013

Quantifying Catch Depletion Rates in the Isle of Man Queen Scallop (*Aequipecten opercularis* L.) Fishery.

Abstract

The Isle of Man Queen scallop fishery is of great importance to the Manx economy, as such it is vital that the fishery be managed in a targeted manner and protected in such a way that its benefits are maintained into the future. Satellite Vessel Monitoring Systems (VMS) combined with fisheries logbooks, in providing an abundant, near real-time, spatially and temporally explicit account of fishing activity are crucial in achieving this. This study, in seeking to better understand fishers' behaviour, aimed to contribute to the knowledge regarding the fishery and help achieve its optimal management. In essence this study treats a fishing vessel as a predator foraging optimally and examines fishers' behaviour in this context. Therefore, 1) Catches per Unit Efforts (CPUEs), 2) fishing time and 3) vessel size and power (using VCUs as a proxy) were modeled with increasing distance from port. Additionally, CPUEs were also examined across the relevant open season and efforts made to examine the rate at which catches became depleted, 1) across the open season and 2) as more effort was added to the system. Distance from port and total trip distances were shown to have strong relationships with, CPUEs, fishing time and vessel size, with all increasing in conjunction with distance travelled. In addition catches were shown to decrease across the open season for dredges but not for trawls, a fact that was cemented by the differing catch depletion rates between the two gear types. While CPUE based stock assessment does have its disadvantages, it is currently the most efficient means of getting much needed spatially and temporally refined fisheries data in near real-time. It is the accuracy and decreased response time that combined VMS and logbook data facilitates that makes this form of data so important in terms of optimal management of fisheries.

Author: Sam Dignan,

Address: Tullig,

Leap,

Co. Cork,

Ireland.

Tel: 07716325615

Email: samueldignan@gmail.com

Acknowledgements

I would like to take this opportunity to thank the many people who took time to help me throughout the course of this project. Firstly to Dr. Lee Murray, for the enormous amount of assistance he has given me at all stages of the project, Dr. Jan Hiddink, for his assistance during the project and also the use of his R script which was greatly appreciated, Dr. Gwladys Lambert and Dr. Andy Davies for their help with R and ArcGIS respectively, and to all the members of Bangor University, in particular the fisheries group, who have assisted me in any way. I would also like to express my thanks to the Manx Government for allowing me to use their fisheries data. I would like to thank all my fellow masters' students, in particular Kris Calder and Rod Finlayson, my housemates, for making life outside of college here as relaxing and interesting as they did. On a more personal level I would like to thank my parents Jean and Niall and brothers Seán, Féidhlim, Dónal and Tádhg, for their support through all phases of my journey to this point. Lastly, to Heather Boyle, proof reader, English teacher, friend and companion extraordinaire, I would like to express my most heartfelt thanks and admiration.

Go raibh míle, míle maith agaibh go léir.

Contents

List of Figures

List of Appendices

Glossary

AIC	-	Akaike Information Criterion
CPUE	-	Catch per Unit Effort
GAMs	-	Generalised Additive Models
ICES	-	International Council for the Exploration of the Sea
IFD	-	Ideal Free Distribution
LOA	-	Length overall
LPUE	-	Landings per Unit Effort
MLS	-	Minimum Landing Size
MSC	-	Marine Stewardship Council
MVT	-	Marginal Value Theorem
PDO	-	EU Protected Destination of Origin
TAC	-	Total Allowable Catch
VCUs	-	Vessel Capacity Units
VMS	-	Vessel Monitoring Systems

1 Introduction

In the decade from 2001 to 2011 there was a drop of 17% in the numbers employed aboard UK registered fishing vessels, from 15,000 to 12,400 (MMO, 2011). In the same period effort within the Isle of Man scallop fishery showed an increase of 47%, without an accompanying rise in the number of vessels involved. While there are two species of scallop targeted commercially in this area, the bulk of this increase in effort may be attributed to a response in increased demand for Queen scallops (*Aequipecten opercularis* (Linnaeus, 1758)). The result of this increased demand is current catch rates of more than double the long term average, with 12,000 tonnes being landed between June 2010 to May 2011, and far in excess of the Total Allowable Catch (TAC), 4,000 tonnes, recommended by Murray *et al.*, (2010).

As the fishery for King scallops (*Pecten maximus*) is traditionally, and indeed remains, a much more commercially important fishery, it is in this area that much of previous research has focused (Mason, 1957; 1958; Paul *et al.*, 1981; Jenkins and Brand, 2001; Beukers-Stewart *et al.*, 2003; Shepard *et al.*, 2010), often to the detriment of the Queen scallop fishery. This study aims to, at least in part, rectify this imbalance by providing an overview of fleet dynamics in the fishery, using ecological theory to model fishers' behaviour and decision making, and ultimately to better inform decision makers such that management measures within the fishery may be optimised.

1.1 Queen Scallop (Aequipecten opercularis)

Queen scallops, known colloquially in the Isle of Man as the Manx "Queenie" and marketed as such, live for between eight and ten years (Philipp *et al.*, 2006) and are, at up to 9cm in size (Schmidt *et al.*, 2008), one of the smallest species of scallops to be commercially exploited. The range of the Queen scallop extends from 30°N to 70°N down to a depth of 100m, although they are generally found at depths of between 20 and 45 metres (Brand, 1991; Román *et al.*, 1999), in areas where the sediment is comprised of sand or fine gravel. Queen scallops do not burrow, rather they sit on top of the benthos (Jenkins *et al.*, 2003).

Sediment type is one of a number of factors including (amongst others), flow regimes and food availability, which leads scallops to form dense aggregations, rather than distributing themselves evenly throughout their available range (Brand, 2006a). These aggregations, which may be permanent, with their boundaries delineated by areas of unfavourable conditions for scallop growth, or temporary as a result of variations in larval settlement and the survivorship of post-settlement larval stages, are referred to as beds. Permanent beds are generally found in areas where biogeochemical and physical regimes are favourable to scallop fecundity and, as result of their permanence, they may be targeted accurately by fishers year after year.

Queen scallops are simultaneously hermaphroditic and like all bivalve species practice external fertilisation. Queen scallops may self-fertilise; however, in ideal conditions, fertilisation is dependent on the close proximity of conspecifics, and fertilisation success has been shown to be higher in areas with greater densities of spawning adults (Stokesbury and Himmelman, 1993; Claereboudt, 1999). Spawning around the Isle of Man occurs between June and October (Allison, 1993).

Bivalves in general tend to be poor swimmers (Jonsson *et al.*, 1991); however, adult Queen scallops are proficient swimmers who, having detected approaching danger at a distance of up to 1.5m (Chapman, 1981), exhibit an escape response. This escape response involves three phases, (1.) a rapid vertical ascent into the water column, reaching speeds of between 29 and 40cm/sec (Chapman *et al.*, 1979), (2.) a short horizontal swim and (3.) settlement back to the benthos (Chapman, 1981; Brand, 1991). Jenkins *et al.*, (2003) demonstrated both seasonal and physiological variations in the escape response of Queen scallops. Seasonal fluctuations in the escape response track changes in water temperature, with the highest water temperature and hence the highest level of escape responses being exhibited in late summer/early autumn. It is this escape response that allows Queen scallops to be fished using trawls, as this type of gear requires the individuals to leave the bottom and swim into the mouth of the approaching net.

1.2 Isle of Man scallop fishery

Two species of scallops are fished commercially in Manx waters, King (*Pecten maximus*) and Queen scallops (*Aequipecten opercularis*), with Kings being the more valuable of the fisheries. The Queen scallop fishery, however, has been increasing in relative value since the awarding of Marine Stewardship Council (MSC) certification in 2011, although this was specific to the trawl portion of the fishery. In addition, the Manx "Queenie" was, in 2012, awarded EU Protected Destination of Origin (PDO), adding exclusivity to the product. Efforts to increase the exclusivity of Isle of Man "Queenie" as a brand have resulted in increased demand for the product and an increase in the amount of effort allocated to the fishery.

Within the Manx fishery, Queen scallops are primarily persecuted using two metiers; otter trawling and dredging, with an additional minor proportion caught by beam trawls targeting *Nephrops norvegicus*. The dredge portion of the fishery may be further subdivided into hydraulic dredges and traditional skid dredges. Manx vessels utilise almost exclusively the otter trawl method, however, boats from outside of the Manx fleet do still dredge for Queen scallops. Manx vessels generally undergo day trips with those travelling from Scotland, Northern Ireland, England and Wales spending longer periods of time at sea; however, trips do not generally exceed 3 days.

Otter trawling is carried out from mid-June to October, as it requires the scallops to be active, a trait that is temperature dependent (Jenkins *et al.*, 2003). During these months, as a result of higher water temperatures, scallops are more likely to swim in order to escape approaching fishing gear, which allows them to be caught in trawls (Chapman *et al.*, 1979). Trawling is conducted using nets with an opening of 18m to 32m and a mesh size of between 80mm and 100mm (Murray *et al.*, 2009). In the colder months dredges may catch individuals without them having left the benthos; however, this practice has been declining in recent years.

Landings by Manx vessels into the Isle of Man alone for 2011 totalled 4,529 tonnes and £1,389,904 (Fig. 1). Landings for the year 2011 and 2012 were over double the long term average resulting in concerns for the future of the fishery, especially considering landings from without the Isle of Man have yet to be added to the equation. When these additional pressures are considered, landings for 2011 were in excess of 16,000 tonnes (Fig. 2). The Minimum Landing Size (MLS) for Queen scallops is currently 50mm having been increased from 40mm in 2009; however, proposals are currently in place to raise this by an additional 5mm, to 55mm (Isle of Man Government, 2013). Studies including Richardson *et al.*, (1982), Paul *et al.*, (1981) and Pickett and Franklin, (1975) have shown that scallops, within the latitude range of the Isle of Man, may take anywhere from 14 to 24 months to reach this MLS.

Due to the small size of many of the vessels in the scalloping fleet, weather conditions may be a factor limiting the catch rate of scallops. When weather is favourable, however, and thus not a limiting factor, there is in fact surplus capacity in the fleet, such that production is limited by the ability of the secondary processing industry to handle the volume of landings. During peak periods there may be quotas applied to individual vessels by processors as they may be unable to handle the fleet working at 100% capacity. In addition, this ensures that catches are somewhat dispersed across the season, increasing the job security of those in associated secondary industries. Prices are dependent on a number of factors – with roe on product commanding a premium – and follow seasonal and annual fluctuations.

1.3 Fishers as Predators

Fishermen may be thought of as predators, foraging in such a way as to maximise their prey intake per unit effort. Foragers, in this instance fishers', make decisions based on the premise

of:

COST	**V**	**REWARD**
Fuel Usage		**Catch**
Fuel Prices		**Price for Catch**
Vessel Upkeep		
Crew Costs		

Fluctuations, therefore, in one or more of the inputs to this equation will result in behavioural changes among fishers (Sanchiro and Wilen, 2001). Studies have shown examples of changes such as these in other species like Antarctic fur seals (Boyd *et al.,* 1994) and guillemots (Elliot *et al.*, 2008). Comparisons are often drawn between ecological and economic systems. Speaking in purely economic terms, if the costs in the system exceed the rewards then the system is not profitable. Conversely if rewards can be maximised while seeking to minimise costs, a profitable system may be achieved. Minimising the costs/reward ratio associated with a foraging event is achieved through the optimisation of foraging technique, giving rise to optimal foraging theory. According to this theory foragers' decisions are based purely on a need to maximise the short term accumulation of resources (Stephens and Krebs, 1986). Following on from this concept of profit and loss, in behavioural ecology terms, if for a predator the costs of locating, catching and assimilating the prey item are less than the energetic costs involved, the predator will have a surplus of energy and survive.

Now think on fishing as predation, the foraging trip (fishing trip) is a success (i.e. is profitable) when the costs associated with locating, catching, onboard processing and landing the catch, taking into account vessel and equipment costs, do not exceed the price that the fishermen receives for his catch at the wharf. There are also other secondary costs associated with fishing including crew wages, provisioning costs and legislative costs such as taxes and licensing fees. The rate of capture in fisheries where costs are not homogenously distributed on a spatial scale may be driven as much by economic factors as ecological ones (Hilborn and Kennedy, 1992). The reasons for the spatial variation in costs may include fuel costs as a result of increased transit distance, variations in sea states between areas fishing and increased risk of damage to gear. In a bid to explain this spatial variation in catch rates, Gordon's (1953) economic theory predicts that consistently higher capture rates will be exhibited in areas where there are higher costs associated with fishing.

Fishers as predators compete both intraspecifically (amongst themselves) and interspecifically (with other species) in a bid to assimilate the highest proportion of available resources for themselves as possible. This competition may be increased if, as in this case, the target species has a clumped distribution, as the prey species in effect acts as a spatial anchor increasing the likelihood of interaction between predators (Bell *et al*., 2009). Due to the fact that fishers first agree a set of guidelines under which this competition will take place, such as quotas and spatial or temporal closures, they do not mimic entirely other predatory species. Therefore, while simple predator-prey models, such as Lotka-Volterra equations, may be useful in describing interactions, the fact that these may not be entirely accurate must be taken into consideration (Abrahams and Healey, 1990; McGoodwin, 1991).

Fretwell and Lucas's (1972) theory of Ideal Free Distribution (IFD) would postulate that within a fishery, fishers distribute themselves among patches (fishing grounds) such that resources are evenly distributed amongst them (Gillis and Lee, 2012). Therefore, if fishing ground A has twice the abundance of a desirable resource as fishing ground B, then twice the number of fishers will concentrate their efforts in B. The result of this behaviour would be that average productivity across the two fishing grounds is equalised (Gordon, 1954). As well as fisheries being shown to conform broadly speaking to IFD (Beecham and Engelhard, 2007), IFD has been shown to occur among a wide variety of species (Harper, 1982; Godin and Keenleyside, 1984; Dreisig, 1995). This theory is however overly simplistic, failing to take account of the distance from the vessel's home port to the fishing ground, which is in this instance essentially a component of the search phase of predation. Increased distance from port has associated increases in costs related to searching, reducing the relative amount of time spent fishing. In addition, one of the major assumptions is that all individuals are equally as competitive and have equal opportunities to acquire resources (Kennedy and Gray, 1993). This assumption is obviously not met in a fishery where there is heterogeneity in terms of vessel and gear size and effectiveness, a situation that has often being described in the animal kingdom (Parker and Sutherland, 1986; Grand, 1997).

IFD also predicts that predators have perfect knowledge of the resources available in each patch; however, this is more often than not untrue and predators must often learn about the potential profitability of a patch (Harper, 1982; Milinski, 1984). In terms of fishing, learning time may be centred around the optimisation of gear types and fishing techniques, as well as the acquisition of knowledge on the relative abundance of the patch (Allen and McGlade, 1986). Catch rates during this learning phase, as a result of decreased efficiency, may be reduced to a level somewhat below expectation given only the relative abundance of the area. Learning behaviour in fisheries has been demonstrated on as short a temporal scale as daily, with catch efficiency increasing with enhanced knowledge, albeit punctuated by periodic bouts of "forgetting" (Xiao, 2003).

As resources in an area become depleted, a fisherman may opt to do one of two things: (1.) remain within that patch and increase his effort such that his total catch is maintained, however, CPUE will decrease or (2.) he may elect to relocate his effort in search of higher prey densities and hence higher returns. Charnov's (1976) Marginal Value Theorem (MVT) seeks to predict how much energy, when faced with resource depletion, an individual will allocate to searching within a patch, before abandoning that patch and attempting to locate a newer, more profitable one. This threshold of returns where,

REWARDS + TRANSIT COSTS < COSTS

and at which it is advantageous for the fisher to give up and focus his efforts elsewhere, as it is more profitable to do so, is termed the giving up threshold, or when related to prey abundance, the giving up density. Generally speaking, giving up density will be lower if (1.) prey species are, when compared with alternative patches, abundant within the current patch and (2.) patches are widely spatially dispersed and associated transit costs are high (Parker, 1992).

The key factor in determining giving up threshold is profitability. Different areas have differential associated costs (fuel, weather, potential for gear damage etc.) (Hilborn and Kennedy, 1992). Fishers will not therefore move into an area and begin foraging until it has become profitable for them to do so, i.e. rewards outweigh costs. In reality, despite numerous patches being potentially profitable, given the option of numerous patches they will first select the most profitable patch and proceed to fish it to a level where it falls below the potential profitability of the next most favourable patch; this process will continue until all available patches, where there is a profit to be made, have been exploited. Aside from prey abundance within a patch a number of other factors may come into play such as seasonal fluctuations in prices, which may lead to previously undesirable patches becoming profitable. Additionally, it has been shown, such as in the case of Tasmanian dive-caught abalone fishery, that price rises may lead to fishers moving to exploitable more marginal and potentially more risky areas (Prince, 1989).

Competition is another factor influencing capture rates. Should an area exhibit high Catch per Unit Effort (CPUE) then fishers will be encouraged to aggressively target this area (Hilborn and Kennedy, 1992). Even were the resources in a patch appear to be infinite there comes a point where, due to increased competition as more and more vessels target the patch, returns start to diminish. This drop off due to interference is known as the law of diminishing returns and is a concept widely used in economics; therefore, taking a fishing fleet as the unit of production, one unit of catch per one unit of time will become increasingly more expensive to attain, as a larger number of vessels will be involved in its acquisition. In addition, as resources become depleted, competition for the remainder will increase. In this instance interference may mean that catches drop off at a rate in excess of what would be expected through decreasing abundance alone.

1.4 Vessel Monitoring Systems (VMS) and their uses in the area of Marine Fisheries Management

Initially introduced to assist the enforcement of closed areas and seasonal restrictions on fishing activity (FAO, 1988; Deng *et al*., 2005), the uses of VMS have diversified and become more prevalent (Drouin, 2001). Its uses now include the creation of programs, such as TOREDAS (Saitoh *et al*., 2009), which facilitate the accurate targeting of potentially rich fishing grounds, with Robbins *et al*., (1998) showing that the use of systems may result in marked increases in catches. An additional and growing use of VMS is for the purpose of fisheries management (Dinmore *et al*., 2003; Murawski *et al*., 2005; Lee *et al*., 2010; Rijnsdorp *et al*., 2011), where these systems provide logbook-independent data on the distribution of fishing on both spatial and temporal scales (Witt and Godley, 2007). VMS data has a number of advantages over traditional logbook data including the availability of data in real, or near real, time (Saitoh *et al*., 2011), the accuracy of the spatial representation of data and the autonomous nature of the systems. The autonomy of the systems reduces the potential for human error and removes potential biases that result from the differential filling out of logbook forms (Mullowney and Dawe, 2009).

For the purpose of analysis, VMS data may be used in either its raw form as a series of points, or the paths taken by vessels between sequential data points may be interpolated. There are advantages and disadvantages to both approaches depending primarily on the grid scale utilised in the analysis. With fine scale analysis, raw VMS may fail to identify important events between data points, while interpolation may lead to errors resulting in areas being allocated to incorrect metiers, such as an area which is in actual fact fished being designated unfished (Lambert *et al.*, 2012).

In trawl fisheries to date, VMS data to has primarily been used in estimating fishing effort (Mills *et al.*, 2004; Palmer and Wigley, 2009). Vessels deploy, tow and retrieve their gear at speeds below that at which they steam and this fact may be used to partition data, based on the distance travelled between data points, into bouts of fishing and steaming (Witt and Godley, 2007; Dinmore *et al.*, 2003; Bastardie *et al.*, 2010 Needle and Catarino, 2011).

The degree to which VMS mirrors the situation on the grown is dependent on the time period between VMS "check-ins", known as the polling frequency. Vessels generally do not travel in straight lines between points; as a result, if the polling interval is too great, deviations in the tracks of vessels travelling points will go undetected (Fig.1.). In addition, vessels may slow for reasons other than activities directly associated with fishing including rough seas, proximity to other vessels and the conduction of routine maintenance operations (Mills *et al.*, 2007). Care must therefore be taken when categorising vessel activity based purely on the calculated velocity between points, as the apparent distance between points may be substantially less than the actual distance travelled (Lambert *et al.*, 2012), leading to inaccuracies in the calculated velocity between points, and ultimately to vessel activity being incorrectly assigned. Within a fishery an initial understanding of the actual components of the fishing process, and of fisher behaviour, may allow the more accurate classification of fishing activity (Saitoh *et al.*, 2011). (EC, 2009) sets a standard for polling frequency of every two hours and requires all vessels in excess of 15m to have VMS installed; however, Manx regulations go further in requiring all vessels fishing for scallops within the 12nm limit, regardless of country of origin, be fitted with VMS (Isle of Man Government, 2013).

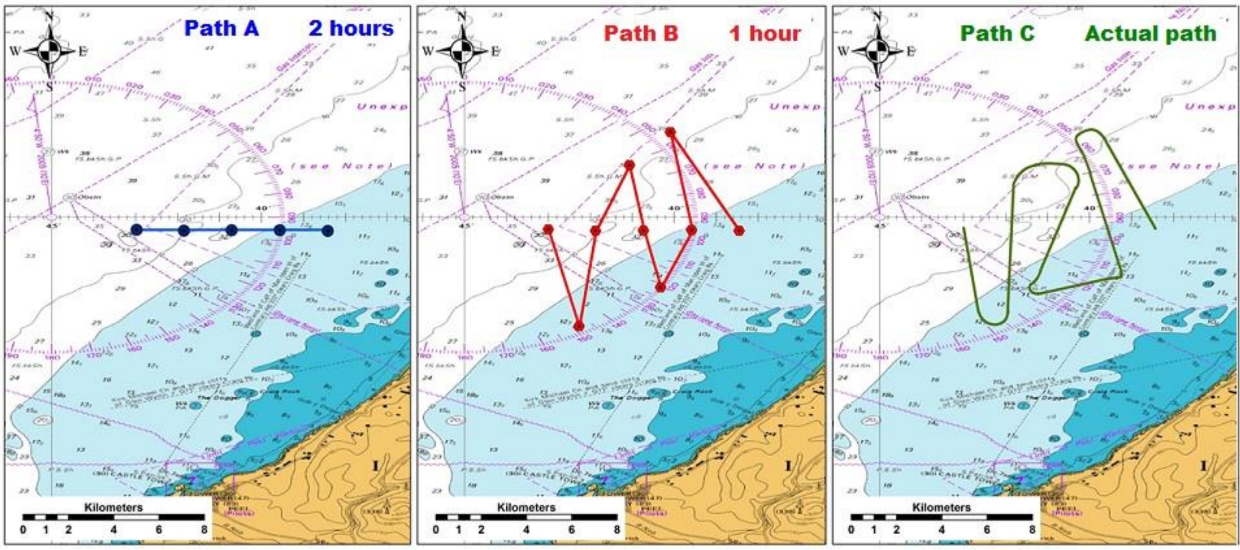


Fig. 1. Difference in interpolated paths for a theoretical fishing vessel off the North-west coast of the Isle of Man. (Polling interval Path A = 2 hours, Path B = 1 hour, Path C = actual path).

The grid scale at which analysis is conducted is crucial when quantifying fish distribution and activity (Lambert *et al.*, 2012). For the sake of accuracy, the finest resolution possible should be used; however, this may not always be feasible due to the increased computing power required of analysis at this level. In any case, analysis must be conducted at sufficiently fine resolution that distribution of fishing effort may be identified and the pattern does not appear merely random (Dinmore *et al.*, 2003); previous studies from Hill *et al.*, (1999), Hiddink *et al.*, (2006a), Reiss *et al.*, (2009) and Lambert *et al.*, (2011) have used grid scales of 5nm^2, 9km^2, 1nm^2 and 1km^2 respectively. Whatever the grid scale used, with VMS not being designed originally for the purpose of fisheries management and with polling frequency often being less than ideal, appropriate processing and standardisation is vital to ensure maximal results from the available data (Murray *et al.*, In press).

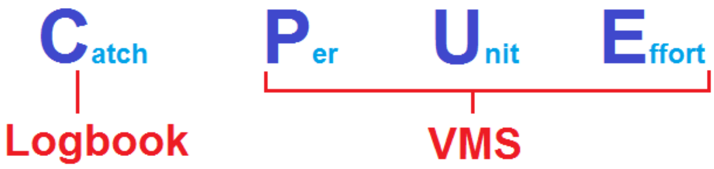
1.5 Utilising Logbook Data for the purposes of Fisheries Management

Logbook schemes have been widely used in the fishing industry for decades and are ideal in providing a large amount of useable data such as CPUE and Landings per Unit Effort (LPUE), fishing strategies and vessel and crew details. Logbooks, however, are not available in near real-time and are not spatially refined with data often only being represented on the spatial scale of ICES statistical rectangles (Bastardie *et al.*, 2010). An additional issue that impacts the accuracy of logbook data is potential bias due to the human component integral to the system, with research showing consistent underreporting of by-catch (Johnson *et al.*, 1999). It is therefore crucial that clear protocol is followed when collecting logbook data in order to ensure that all vessels are reporting in a similar manner and any ambiguity is minimised. When it comes to logbook schemes it is essential that contact be maintained with participants and any ambiguities are swiftly resolved to ensure that recording of data is as consistent as possible across all vessels.

An additional disadvantage of logbook schemes is that restrictions on the frank reporting of data, which may include instances where quotas and restricted areas are not adhered to and also where skippers feel that they may in reporting fully their activities be relinquishing a commercial advantage, may inhibit the accuracy of the results. Inaccurate or inconsistent data could lead to management measures being implemented, which are either inadequate or which, in the worst case, adversely affect the industry in that area.

1.6 Combining VMS and Logbook Data

While VMS data has its deficiencies when used in isolation for scientific purposes, many of these can be reduced or overcome by combining it with logbook data. The resulting combination of data may be used to attain accurate representations of both effort and catches on spatial and temporal scales (Bastardie *et al.*, 2010; Lee *et al.*, 2010; Murray *et al.*, 2011). In effect, the combination represents the Catch, data being supplied from logbooks, Per Unit Effort, data from the vessel monitoring system.



The resolution of logbook data is coarse, with an ICES triangle having sides of 30nm; however the data may, in combination with VMS, be attributed to scales of 5nm or less, significantly increasing its resolution. To date the major use of linked VMS and logbook data in scientific communities has been to assign fishing gear types to data related to fishing effort (Lee *et al.*, 2010). However, linked VMS and logbook data is increasingly been utilised to define fluctuations, on both temporal and spatial scales, in landings within a fisheries. Ultimately, information of this type may be used to inform management decisions (Bastardie *et al.*, 2010).

Fishery-dependent data, of which VMS and logbook are examples, often fail to take account of the fact that the total abundance of a target species often decreases more rapidly than CPUE (Hilborn and Walters, 1992). This effect is more pronounced in fisheries where fishers target highly aggregated species (Quirijns *et al.*, 2008). An additional issue is that fishers may, through increased knowledge (Xiao, 2003), or technological advances (Bishop, 2006), become more efficient in their targeting of a species with the result that decreases in overall abundance may be masked. Data must therefore be corrected to account for the effects of individual fishers' behaviour, the differential success rates of particular vessels and possible improvements in technology (if conducting analysis on a temporal scale), before it is suitable for use in the measurement of total abundance of target species (Murray *et al.*, 2013).

Despite its limitations, if treated appropriately, this type of analysis affords scientists the opportunity to vastly increase the accuracy of fisheries models, particularly in instances where there is a strong spatial component to the analysis (Die and Ellis, 1999).

1.7 Management Uses of VMS and Logbook Data

VMS and logbook data may, when used correctly, provide management with spatially specific estimates regarding the intensity and distribution of fishing effort, allowing prompt responses to fluctuations within a fishery (Guilin, 2005; Deng *et al*., 2005; Murawski *et al*., 2005). The fact that VMS data is available in near real-time, and can be of immediate use with minimal processing, means that lag periods associated with more traditional forms of reporting have been significantly reduced.

One measure available to management whose effectiveness may be substantially increased through the use of VMS and logbook data is the implementation of spatial closures, primarily due to the explicit representation of fishing effort provided by the data, on both spatial and temporal scales (Fock, 2008; Frid *et al*., 2005; Hiddink *et al*., 2006). Once areas of concentrated fishing effort have been identified from the available data, restrictions may be placed on the Total Allowable Catch (TAC) in that area, up to and including complete prohibition (Murawski *et al*., 2005). These spatial closures may be either permanent or timed to coincide with, or avoid periods of sustained effort. As the data allows for the accurate mapping of effort, management may decide to site spatial closures to exclude effort from either areas of low effort, or so called “pristine” environments, or areas of concentrated effort. In the case of temporal restrictions on effort, differential effort levels at intervals throughout the season may be identified (Chang, 2011) and, closures may be timed to coincide with crucial phases in the life history of either the target or other affected species, with the former being the case in the Queen scallop fishery in the Isle of Man.

VMS and logbook data may also be used to restrict entry to the fishing fleet to vessels above an agreed upon threshold, as it imparts details related to engine size and power. The data allows the effort of vessels of a given size class to be quantified and, as larger vessels target species more efficiently, the potential impacts of each size class to be identified. Management may then decide to restrict entry to the fleet to vessels below a certain length (Hilborn, 2012), or, in the Isle of Man fleet, below a certain engine power threshold.

1.8 Hypotheses

The associated ecological theory discussed above led to the below hypotheses which were investigated through the use of VMS and logbook data as described in the methods section of this report.

"Within the Isle of Man Queen scallop fishery, as distance travelled from port increase, CPUE will also increase."

"Within the Isle of Man Queen scallop fishery, as distance from port increases, time spent fishing will increase."

"Within the Isle of Man Queen scallop fishery, CPUE will vary temporally across the open season."

"Within the Isle of Man Queen scallop fishery, larger vessels fish further from port."

1.9 Aims and Objectives

The general aims of this study were threefold:

1. To build on the base of knowledge available regarding fishers' behaviour in the Isle of Man "Queenie" fishery
2. To better understand the factors influencing fishers' behaviour with a view to optimising the management of the fishery
3. To act as a case study into potential uses of VMS and logbook data in the area of marine fisheries management.

The specific methodological aims of the study were to:

1. Process and join the VMS and logbook data and identify the most suitable methodology for its analysis
2. Determine fishing effort and the landings associated with that effort
3. Calculate the CPUE for each voyage in the dataset
4. Analyse the resulting CPUE in R-statistics using Generalised Additive Models (GAMs)
5. Identify the factors which contributed most to fluctuations in the calculated CPUE
6. Define what drives fishers within the fishery in question to behave in the way that they do.

2 Methods

2.1 Joining VMS and Logbook data

Data came from the UK database and were available for all vessels from 2011 and 2012 for the ICES statistical rectangles 38E5, 37E5 and 36E5. Four gear types were represented in the dataset: otter trawls, mechanical dredges, hydraulic dredges and beam trawls. VMS and logbook data were combined in Microsoft Access based on activity date and vessel name, allowing the representation of data such as that in (Fig. 2), which depicts the distribution of data points by fishing gear type. Vessel names were then anonymised so that fishing activity and data related to catches could not be attributed to individual vessels.

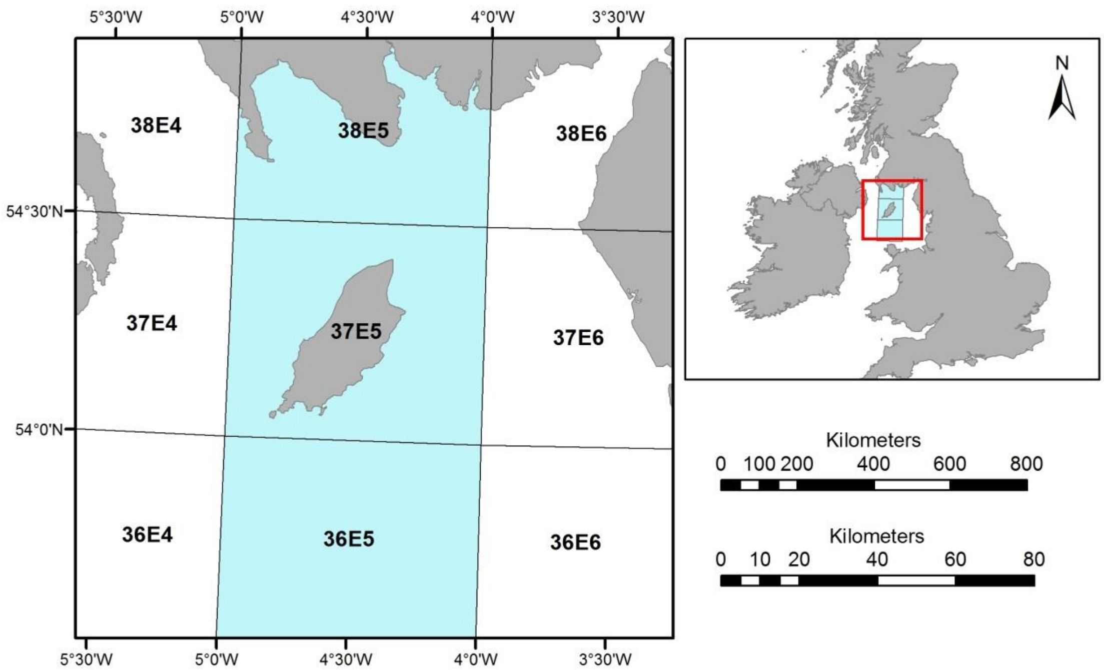


Fig. 2. Location of the I.C.E.S. statistical rectangles from which the data used in this study originated in 2011 and 2012.

2.2 Calculating distance from departure port and overall trip distance

Spatial calculations were conducted using a combination of R and ArcGIS. Firstly, all coordinate data was converted from the geographic coordinate system WGS_1984 into the projected coordinate system OSGB_1936. The change from a geographic coordinate system to a projected one was necessary as distance calculations cannot be carried out in the former. Shapefiles were created, again in OSBG_1936, in Arc Map Version 9.3.1; the first shapefile was created to represent all areas of land within the required range and the second, a bounding shapefile, to delineate the boundaries of the data frame. Within R-3.0.1 the coordinates system of the data frame was defined as OSBG_1936 and the shapefiles imported.

The shapefiles were then rasterised with a resolution of 1000m being chosen as the most acceptable balance between the required level of accuracy and the computing power available. While a higher resolution would lead to more accurate results, the computing power and time required was prohibitive. In addition, the accuracy at a resolution of 1000m was deemed sufficient as all data points were affected to the same extent meaning comparison between points was not compromised. Both shapefiles were then converted into raster form, a process known as rasterisation. The rasters were then inverted and combined to create a single raster, which assigned a value of 0 to all areas within the land shapefile and a 0 to all areas outside of the land shapefile but within the boundary shapefile. As well as making analysis easier, this helped with computing as a much greater volume of memory is required to store a 1 when compared with the volume required to store a 0.

An additional transition layer was created, giving the conductance values between cells, based on the distances between cell centres (Fig. 3). This transition layer only allowed travel between raster cells of the same value meaning that vessels could only travel between raster cells depicting water (raster cell value = 0) and would deviate upon encountering a cell depicting land (raster cell value = 1). Thus distance between coordinate points avoiding all areas of land could be represented.

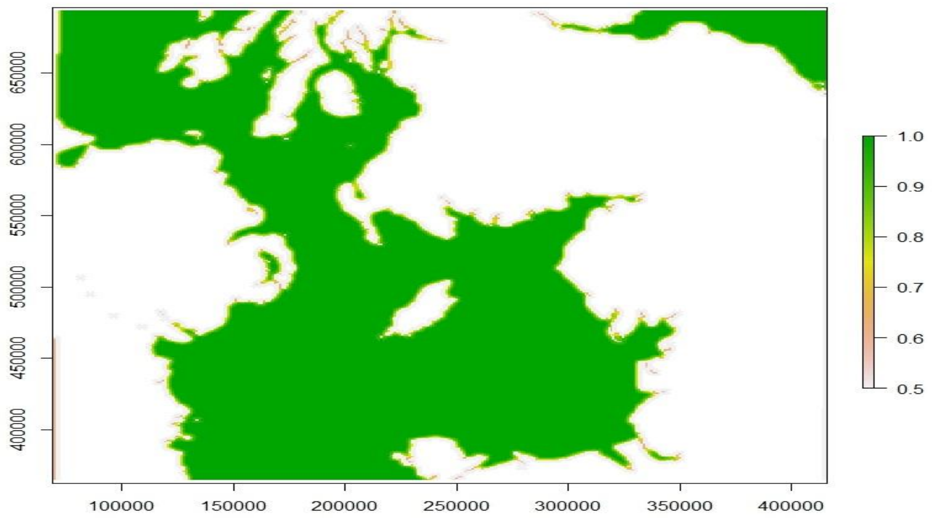


Fig. 3. Transition raster showing the conductance values between cells with 1 being high conductance and 0 being no conductance.

Within the transition layer a vessel could travel a maximum of 16 directions between raster cells, a limitation imposed by the gdistance vignette. The maximum of 16 directions was chosen for the analysis as it, while requiring substantially longer to compute when compared with 8 possible directions, represented a disproportionately great increase in accuracy; this was as a result of the increased transit options between raster cells (Fig. 4).

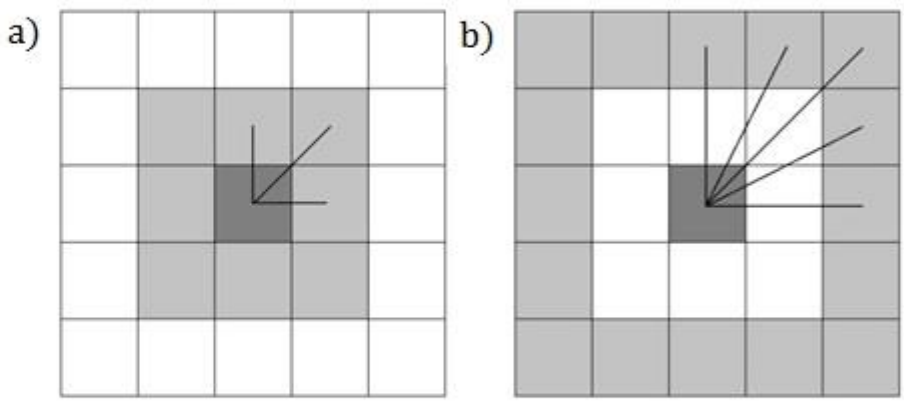


Fig. 4. (A) Transit options between raster cells as a result of inputting 8 directions in R and (B) Possible transit between raster cells as a result of inputting 16 directions.

It should be noted that it was necessary to apply a geo-corrections to account for the fact that diagonally connected cells have their centres further apart than horizontally and vertically connected cells (Fig. 5), and this was done within R.

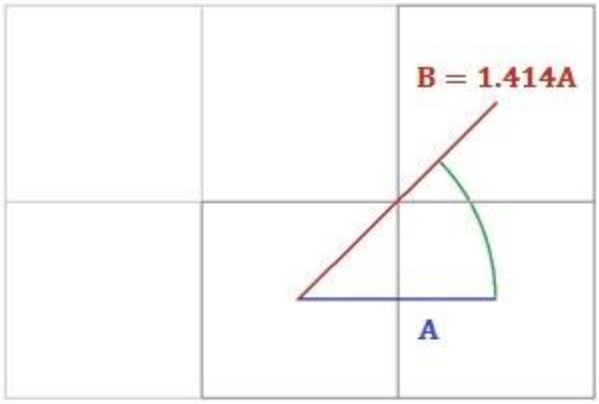


Fig. 5. The distance between raster cell centres for horizontally and vertically connected cells A and diagonally connected cells B.

The results of a distance from port interpolation for all data points departing from the port of Amlwch, with and without this geo-correction being applied are depicted in (Fig. 6).

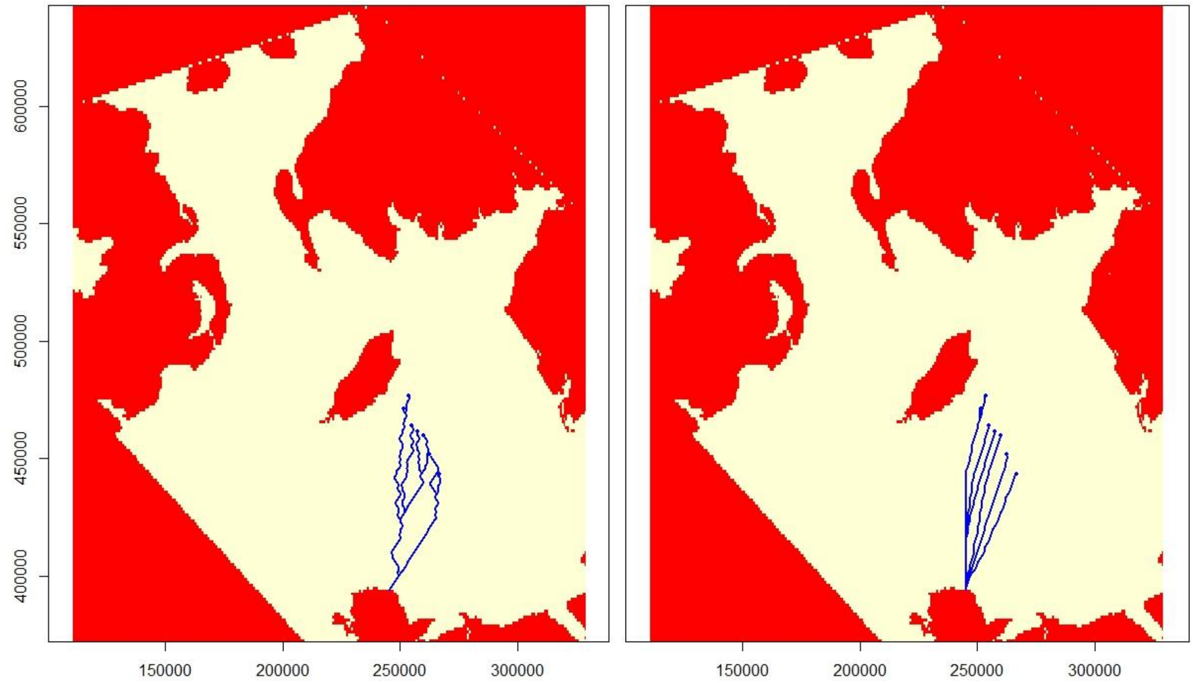


Fig. 6. Interpolated vessel tracks, for the port of Amlwch, without A, and with B, appropriate geo-correction being applied (with 16 directions is used being used in each case).

The data to be analysed was then imported and the central point to which all distances were to be calculated defined. This central point consisted of the coordinates for one of the departure ports in the dataset, with distances being calculated separately for all data points departing from each port represented in (Fig. 7). The entire procedure was then repeated for each point but this time the distance to the landing port was calculated. The landing ports within the dataset are depicted in (Fig. 7). The trip distance was then calculated; this was taken to be the distance from the port of departure to the most distant VMS point, plus the distance from that particular VMS point to the landing port. This approach was necessary as a result of the fact that many vessels do not necessarily depart from and land into the same port.

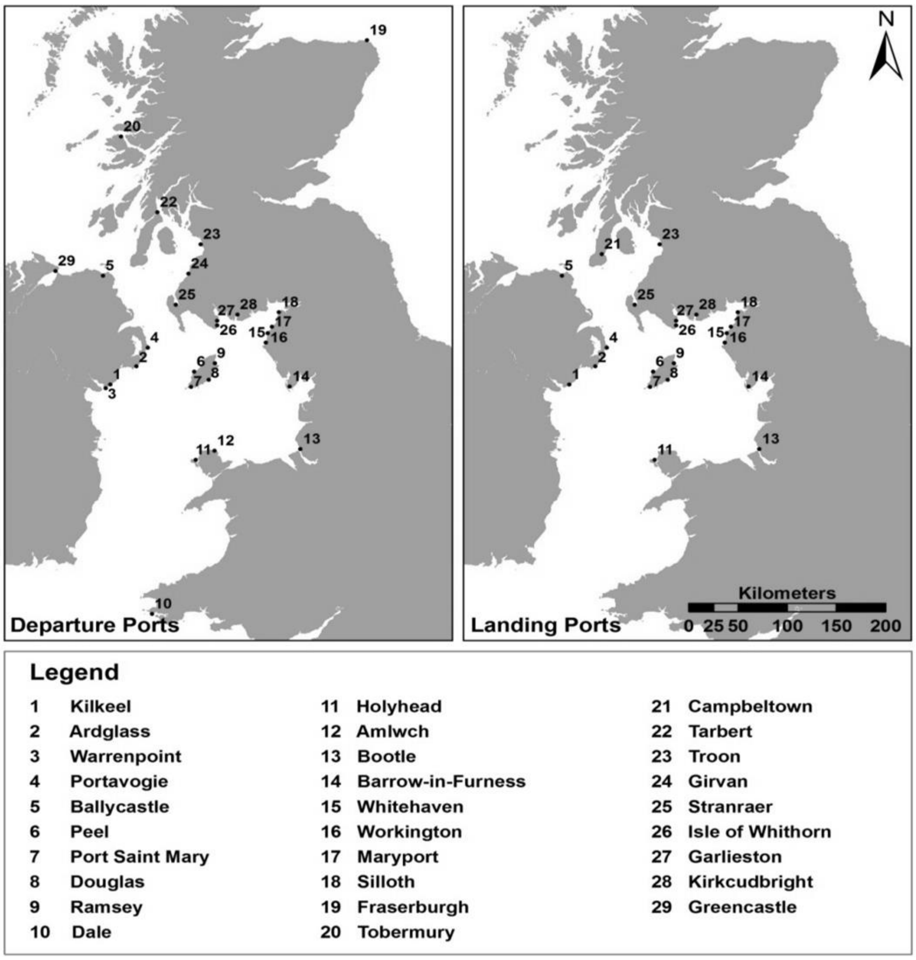


Fig. 7. Departure and landing ports to which the distance travelled from each VMS record was calculated.

2.3 Calculating Fishing Time

Fishing time was calculated as the amount of time a vessel spent at between 1 and 4 knots, as most of the fishing effort, using the métiers in question, in this fishery is conducted within this speed range. This split the data into fishing and steaming components for each voyage, with fishing activity being depicted in (Fig. 8).

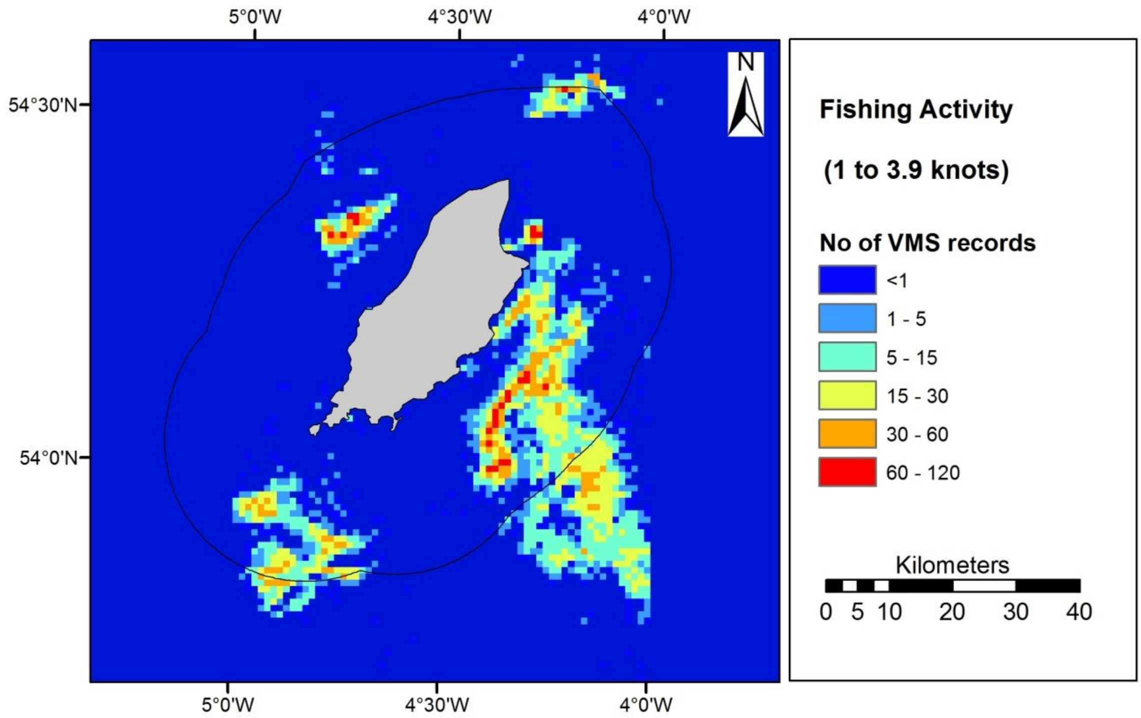


Fig. 8. Gridded raster depicting the number of occurrences, within of VMS points attributed to fishing activity based on the vessel speed (1 to 3.9 knots = Fishing, >3.9 knots = Steaming).

2.4 Calculating Catch per Unit Effort (CPUE)

For each voyage ID the total landings were calculated; this had to be done using unique activity ID for voyages that occurred over more than a single day, as in cases like this there were more than logbook entry related to a single voyage. Subsequently, the landed weight for each voyage was divided by the calculated total amount of time spent fishing for that voyage in order to attain the CPUE for the voyage; the calculated CPUE is presented in kg hr^{1}.

$$CPUE = \frac{Total\ Landings}{Calculated\ Fishing\ Time}\ \text{kg hr}^{-1}$$

2.5 Further Data Handling

Trawlers targeting Nephrops comprised a small proportion of the data set. These were removed as they were not specifically targeting Queen scallops and thus direct comparisons could not be drawn between them and métiers for which Queen scallops were the primary target species. Days from the start of the fishing season was calculated separately for trawlers and dredgers. The season for trawlers within the 12nm limit opens on the 1st of June while the dredge season opens on the 1st of September, and both run until the 31st of March. Within the open season there are curfews limiting daily fishing activity as well as potential restrictions as a result of byelaws, periodically implemented predominantly in a reactionary manner, aimed at safeguarding the integrity of the fishery.

2.6 Allocation of Voyages to Fishing Grounds

As a result of the distribution of the target species, fishing activity is also often highly aggregated, as can be seen in (Fig. 8); therefore in order to compare between areas of within the study range it was necessary to identify and designate fishing grounds. This was in some cases quite straightforward, as some grounds were immediately obvious. Where it was not obvious where a division existed, areas were further subdivided on the basis of bathymetry, substrate type and their geographic location (i.e. whether they were inside or outside the twelve nautical mile limit); the resultant fishing grounds allocated may be seen in (Fig. 9). Each of the fishing trips were subsequently assigned to a fishing ground; where a fishing trip took place across more than one fishing ground the entire trip was allocated to the area in which the majority of fishing took place

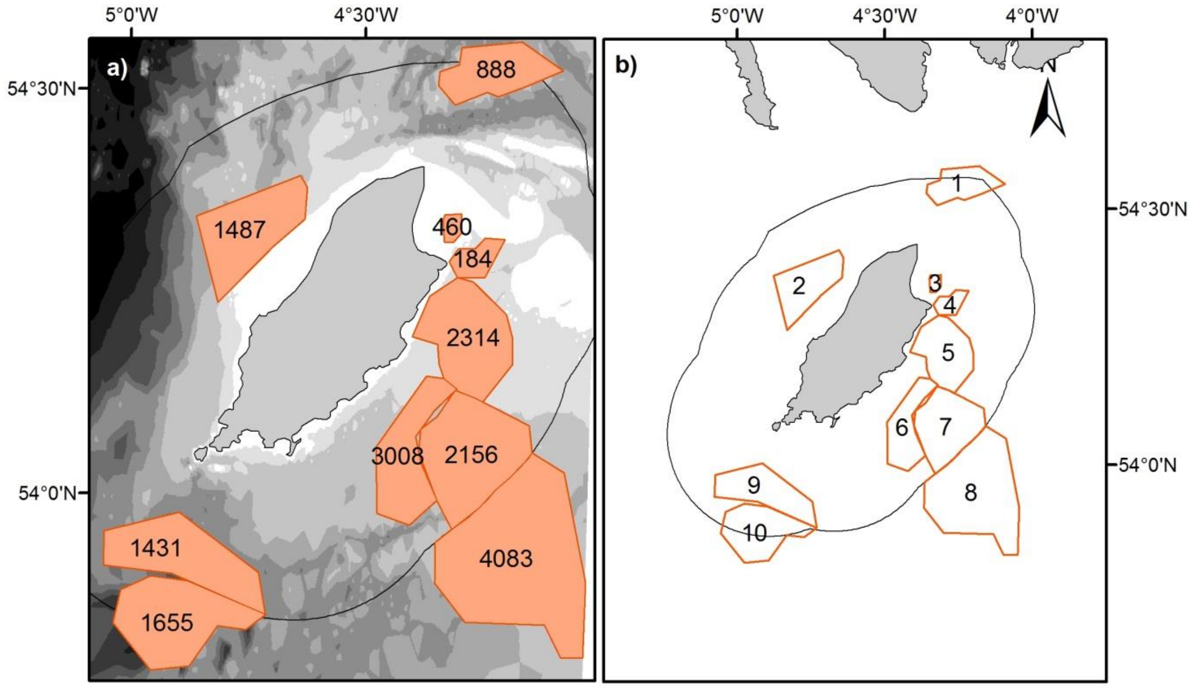


Fig. 9. a) The number of VMS records, assigned to the fishing metier, in each area identified, on the basis of concentrated fishing activity, bathymetry and benthic sediment type, as a fishing ground and b) the fishing ground codes assigned to each area.

2.7 Generalised Additive Modeling

2.7.1 Catch per Unit Effort (CPUE) and Trip Distance

To investigate whether CPUE was a factor driving the distances which vessels travelled from their home port, CPUEs were compared through the use of a Generalised Additive Models (GAMs) in R; modeling was conducted with the 'mgcv' package (Wood and Augustin, 2002; Wood, 2006) and all data from the years 2011 and 2012. Three possible models were identified and tested:

(Model 1)

$CPUE_{VMS.tot}$~ s(trip distance) + s(VCUs, by = trawl/dredge) + s(days since, by = year) + fishing ground + trawl/dredge + year

(Model 2)

$CPUE_{VMS.tot}$ ~ s(trip distance) + s(VCUs, by = trawl/dredge) + s(month, by=year) + trawl/dredge + year

(Model 3)

$CPUE_{VMS.tot}$ ~ s(trip distance, by = year) + s(VCUs, by = trawl/dredge) + s(month, by = year) + fishing ground + trawl/dredge + year

Where, $CPUE_{VMS.tot}$ = Catch per Unit Effort calculated from VMS and logbook data using total time, trip distance = distance from departure port to the most distant VMS record plus the distance from the most distant VMS record to the landing port in kilometres, trawl/dredge = fishing gear type, (included as a factor in which Vessel Capacity Units (VCUs) calculated as: (Length overall (LOA) x Beam) + (Engine Power (kWh)x 0.45), were nested using 'by'), year = year of fishing record (the time terms, month, and days since the start of the relevant fishing season, were nested within the factor year using 'by'), fishing ground = the fishing ground in which the fishing activity took place, where a fishing trip took place across more than one fishing ground the entire tip was allocated to the area in which the majority of fishing took place; 's' denotes isotropic smooths. A separate smooth was fitted for each year by nesting days since and month within the factor year while, by nesting VCUs with trawl/dredge, a separate smooth was fitted for both trawlers and dredgers. Models were fitted using a gamma error distribution and a log link. In addition a 2-way ANOVA was conducted to determine if CPUEs were significantly different between both gear types and years. While the data did not meet the assumptions of normality, a 2-way ANOVA was still deemed more statistically powerful than the non-parametric equivalent; as a result the significance level was raised to 0.01 in order to reduce the likelihood of a type I error.

2.7.2 Distance from Departure Port and Fishing Time

The relationship between the distance a vessel travelled from port and the amount of time it devoted to actual fishing activity (velocities between 1 and 4 knots), was investigated using two models:

(Model 4)

Fishing time ~ s(trip distance) + s(month) + s(VCUs, by = trawl/dredge) + s($CPUE_{VMS.fish}$) + s(days since, by = year) + vessel + trawl/dredge + year

(Model 5)

Fishing time ~ s(trip distance) + s(month) + s(VCUs, by = trawl/dredge) + s($CPUE_{VMS.fish}$) + s(days since, by = year) + vessel + departure port + trawl/dredge + year

Where, fishing time = amount of time in hours spent by the vessel at between 1 and 4 knots, trip distance = distance from departure port to the most distant VMS record plus the distance from the most distant VMS record to the landing port in kilometres, month = month, trawl/dredge = fishing gear type, (included as a factor in which Vessel Capacity Units (VCUs) calculated as: (Length overall (LOA) x Beam) + (Engine Power (kWh)x 0.45), were nested using 'by'), $CPUE_{VMS.fish}$ = Catch per Unit Effort calculated from VMS and logbook data using only fishing time, year = year of fishing record (days since the start of the relevant fishing season was nested within the factor year using 'by') vessel = a unique vessel identifier, departure port = the port form which the vessel departed; 's' denotes isotropic smooths. A separate smooth was fitted for each year by nesting days since the start of the relevant fishing season within the factor year while two separate smooths were fitted for trawlers and dredgers by nesting VCUs within trawl/dredge. As before all models were fitted using a gamma error distribution and a log link.

2.7.3 Catch per Unit Effort and Days Since the start of the Season

In order to investigate whether catch rates varied across the open season the Catch per Unit Effort calculated from the time spent fishing was analysed with regards to the number of days that the particular season had been open (see Section 2.5). As the seasons for trawling and dredging are different modeling was carried out on both gear types separately. Additionally, modeling was restricted to 211 days for dredgers, the duration of the open season within the 12nm limit, and to 151 days for trawlers, as it is within this period that all activity excepting a single voyage in December 2012 is carried (Appendix 2). The same candidate models were selected in each case so that the results could be subsequently compared.

(Model 6)

$CPUE_{VMS.fish}$ ~ s(days since, by = year) + s(trip distance, by = year) + s(VCUs,) + s(fishing ground) + year

(Model 7)

$CPUE_{VMS.fish}$ ~ s(days since, by = year) + s(trip distance, by = year) + s(VCUs,) + s(fishing ground) + year + vessel + departure port

Where, $CPUE_{VMS.fish}$ = Catch per Unit Effort calculated from VMS and logbook data using only fishing time, days since = days from the start of the relevant fishing season, trip distance = distance from departure port to the most distant VMS record plus the distance from the most distant VMS record to the landing port in kilometres (see Section 2.2), (both days since and trip distance were nested within the factor year using "by"), VCUs = Vessel Capacity Units (VCUs) calculated as: (Length overall (LOA) x Beam) + (Engine Power (kWh) x 0.45), year = year of fishing record, vessel = a unique vessel identifier, departure port = the port from which the vessel departed; 's' denotes isotropic smooths. Separate smooths were fitted for each year by nesting days since the start of the relevant fishing season and trip distance within the factor year. As before all models were fitted using a gamma error distribution and a log link.

2.7.4 Distance from Departure Port and Vessel Capacity Units (VCUs)

The maximum distances travelled from the port of departure for each fishing trip were analysed using GAMs in order to account for the effects of gear type (whether trawling or dredging), different departure ports and fishing grounds, time of the year and the differential behaviour of individual fishing vessels. Two models were identified and tested to see which best fitted the data:

(Model 8)

Distance ~ s(VCUs, by = trawl/dredge) + s(month, by = year) + s(fishing ground) + vessel + trawl/dredge + year

(Model 9)

Distance ~ s(VCUs, by = trawl/dredge) + s(month.no, by = year) + s(fishing ground) + vessel + departure port + trawl/dredge + year

Where, Distance = maximal distance from the port of departure for a particular fishing trip, trawl/dredge = fishing gear type, (included as a factor in which Vessel Capacity Units (VCUs) calculated as: (Length overall (LOA) x Beam) + (Engine Power (kWh)x 0.45), were nested using 'by'), year = year of fishing record (the time term, month, was nested within the factor year using 'by'), fishing ground = the fishing ground in which the fishing activity took place, vessel = a unique vessel identifier, departure port = the port form which the vessel departed on a particular fishing trip; 's' denotes isotropic smooths. A separate smooth was fitted for each year by nesting month within the factor year while the same was attained for both trawlers and dredgers by nesting VCUs within trawl/dredge. Models were again fitted using a gamma error distribution and a log link. Variation between trawlers and dredgers in terms of length, weight, power and ultimately VCUs were further analysed using appropriate statistical testing, namely ANOVA or Kruskal-Wallis, dependent on normality being achieved or otherwise.

2.8 Catch Rates and Total Effort

Catch per Unit Effort is, in effect, the measure of total catch standardised by the amount of effort required to catch such. As a result, comparing total effort for a given time period – in this case analysis was done on weekly values – against the average CPUE for that period uncovers fluctuations in catches within the fishery. The rate at which catch rates declined, increased or stayed level may therefore be taken as the catch depletion rate with regards to increased effort. It was expected that as effort in the system increased there would be a resultant effect on catches beyond the ideal 1:1 increase which might be attained in the absence of falling abundances or increased competition.

Therefore, the total effort (fishing time in hours $week^{-1}$) was calculated along with the average CPUE for all voyages undertaken in that week; this was done separately for each gear type and year. The resultant dataset was analysed using simple linear regressions in IBM SPSS with a view to identifying the scale, nature and significance of any possible interactions between the two variables. The results were then represented graphically. As catch depletion rates relating to changes in catches over time had already been quantified, as described in (Section 2.7.2), and as weekly averages showed a similar pattern, it was not deemed necessary to conduct further statistical analysis on those variables.

3 Results

3.1 Catch per Unit Effort (CPUE) and Trip Distance

Three Generalised Additive Models were conducted with the response variable CPUE of scallops. Model 3 (deviance explained = 50.6%) explained significantly more deviance than Model 1 (deviance explained = 50%) (ANOVA, $F = 12.22$, $p<0.001$) and Model 2 (deviance explained = 50.3%) (ANOVA, $F = 11.242$, $p<0.001$) and had a lower Akaike Information Criterion (AIC) score (35845.3 compared to 35878.7 and 35861.9 respectively); as a result CPUE was predicted using Model 3. When Model 3 was fitted to the data 50.6% of deviance was explained, with significant effects of distance ($p<0.001$), vessel size and gear type ($p<0.001$), time ($p<0.001$) and fishing ground ($p<0.001$) and a marginally significant effect of individual vessels ($p<0.1$). The results showed that CPUE was higher for vessels fishing further from port (Fig. 10). CPUE by dredging was significantly higher than the corresponding value for trawling with two way analysis of variance on $CPUE_{fish}$ showing significant main effects for both gear type (2-way ANOVA, $F = 16.241$, $p<0.001$) and year (2-way ANOVA, $F = 131.22$, $p<0.001$), as well as the interaction between the two (2-way ANOVA, $F = 71191.472$, $p<0.001$).

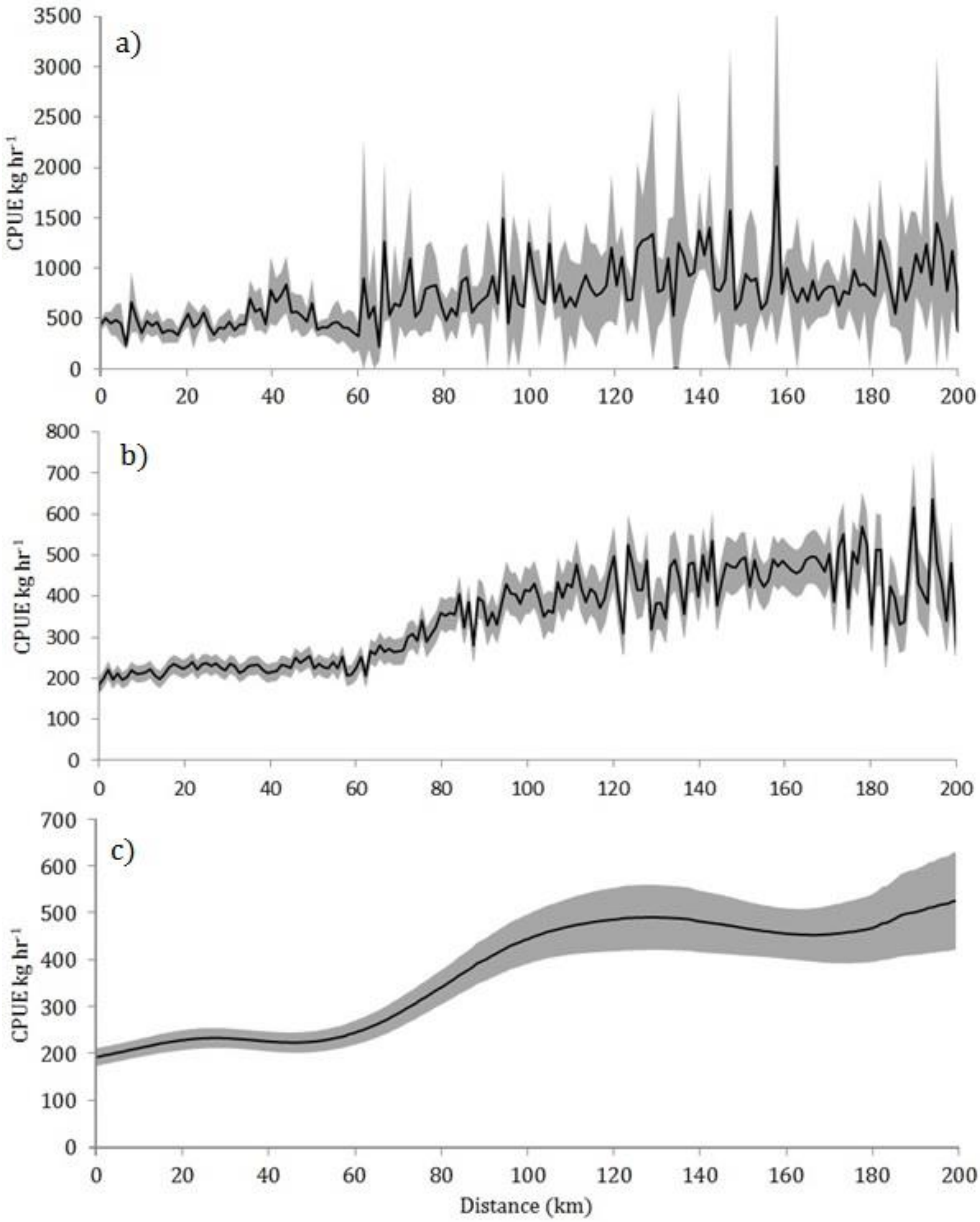


Fig. 10. Mean CPUEs for individual fishing trips, with corresponding total trip distance for 2011 and 2012, including both trawlers and dredgers, based on a) non-standardised data, b) data standardised to remove vessel effects and c) mean CPUE for all voyages averaged across all vessel classes, gear types, years and days from the start of the fishing season. Shaded area indicates ±2 standard errors.

3.2 Distance from Departure Port and Fishing Time

Two Generalised Additive Models were fitted to the dataset. Model 5 (deviance explained = 65.7%) explained significantly more deviance than Model 4 (deviance explained = 49.2%) (ANOVA, $F = 2438.7$, $p<0.0001$) and had a lower Akaike Information Criterion (AIC) score (-3347.8 compared to -3337.6). The relationship between fishing time and distance travelled from the port of departure was investigated using Model 5. Model 5 showed significant effects of all factors, vessel size and gear type ($p<0.0001$), days since the start of the fishing season ($p<0.0001$) fishing ground ($p<0.0001$), unique vessel ID ($p<0.001$) and departure port ($p<0.001$), while the effects of month were shown to be marginally significant ($p= 0.0151$). The results from Model 5 showed that as vessels travelled further from port they spent an increasing period of time fishing, although after 100km distance the effects of increasing distance became proportionally less compared with similar increases in distances closer to port (Fig. 11). Fishing time was shown to be significantly higher for trawlers when compared to dredgers (ANOVA, $F = 316.454$, $p<0.001$).

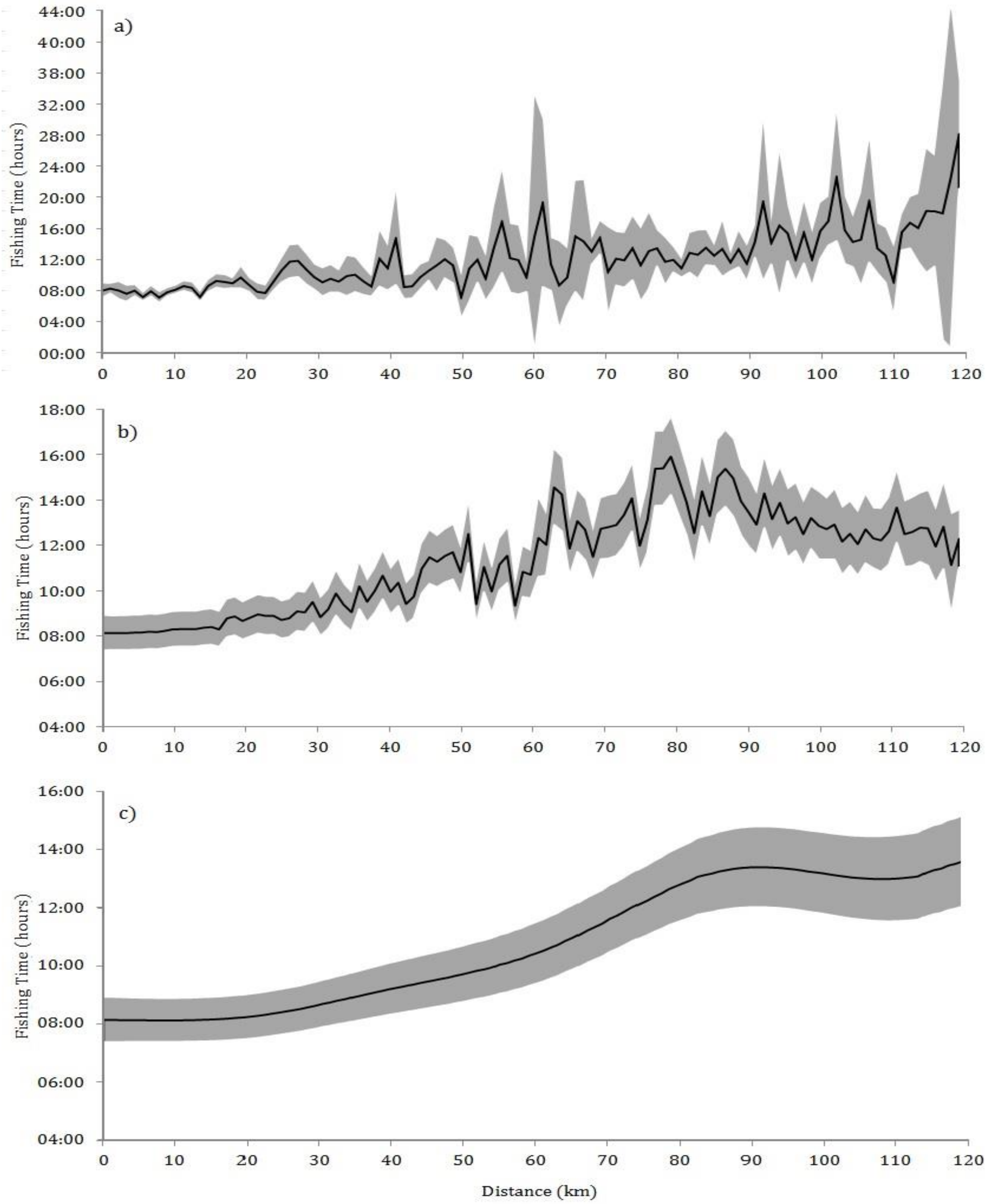


Fig. 11. Mean fishing time in hours, with corresponding mean maximum distances from departure port for 2011 and 2012, including both trawlers and dredgers, based on a) non-standardised data, b) data standardised to remove vessel effects and c) mean fishing time from port for all voyages averaged across all vessel classes, gear types, departure ports, fishing grounds, years and days from the start of the fishing season. Shaded area indicates ±2 standard errors.

3.3 Catch per Unit Effort and Days since Season Opening

Fluctuations in Catch per Unit Effort in relation to the number of days since the fishing season opened were investigated separately for trawlers and dredgers, through the use of two Generalised Additive Models. Both models explained the deviance in the dredge fishery to a much higher degree than in the trawl fishery. For the dredge fishery Model 6 explained 65.9% of deviance, significantly less than Model 7 at 66.6% (ANOVA, $F = 19.646$, $p < 0.001$). In the case of the trawl fishery Model 6 was again poorer in explaining the variance with 32.7% explained as opposed to 33% for Model 7 (ANOVA, $F = 5.5981$, $p < 0.01$). The Akaike Information Criterion (AIC) scores for both dredges (12405.15) and trawls (23029.79) were also lower when using Model 7 when compared to Model 6 (12423.77 and 25117.93 respectively). Hence the data was analysed using Model 7. Analysis conducted on the dredge fishery showed significant effects of all factors in the model at the $p < 0.001$ level; days since ($p<0.001$), year ($p<0.001$), trip distance ($p<0.001$), VCUs ($p<0.001$), fishing ground ($p<0.001$), vessel ($p<0.001$) and departure port ($p<0.001$). The trawl fishery showed similar results for days since ($p<0.001$), year ($p<0.001$), trip distance ($p<0.001$), VCUs ($p<0.001$) and fishing ground ($p<0.001$), however here, vessel ($p = 0.0306$) and departure port ($p = 0.028$) were only significant at the $p<0.05$ level. The results showed that there was a general decrease in catch rates by dredgers across their open season but that catch rates from trawlers fluctuated but did not follow a particular trend (Fig. 12).

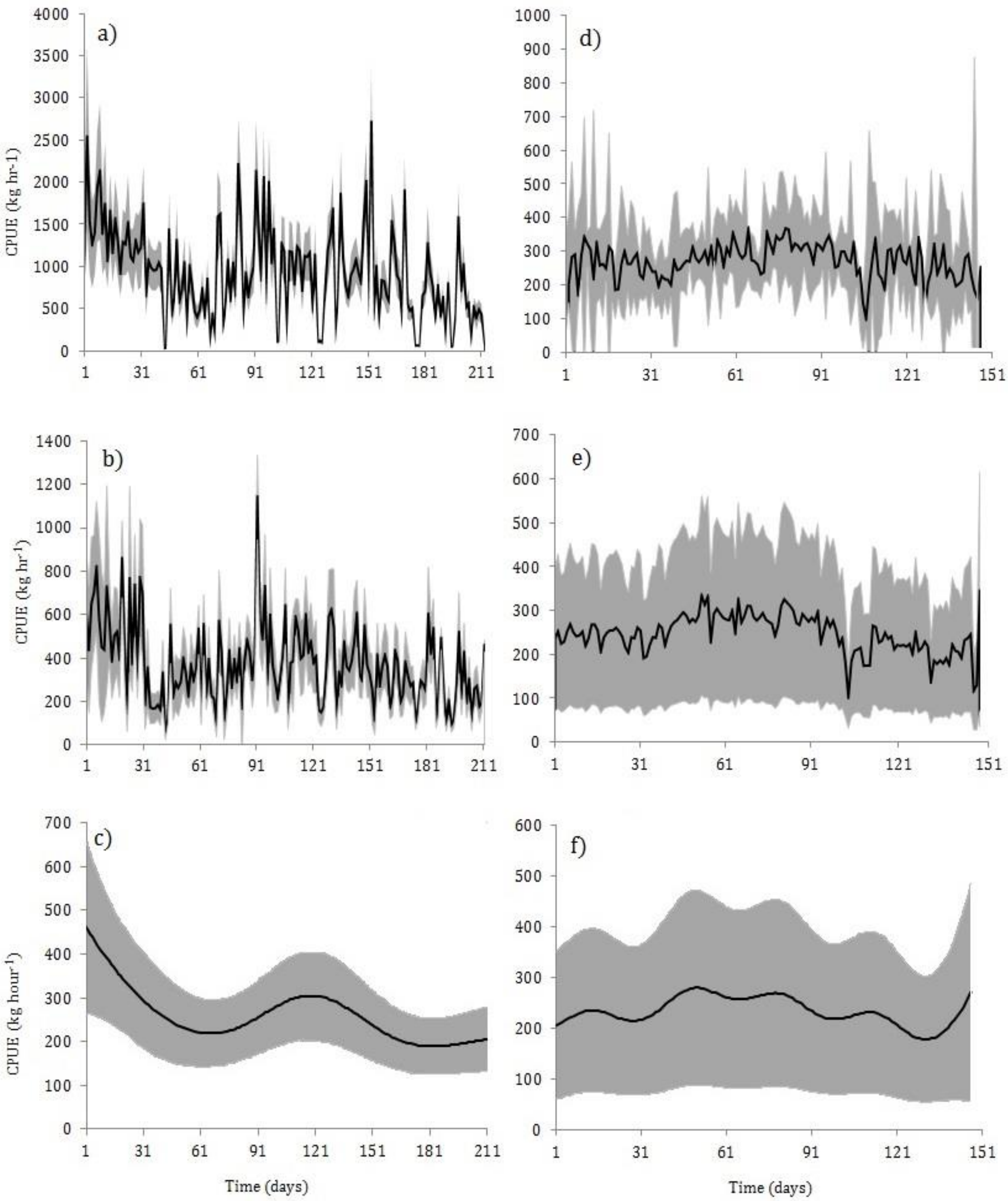


Fig. 12. Mean daily catch per unit efforts and the number of days the fishing event took place form the date of season opening, in 2011 and 2012 combined, for dredgers, based on a) non-standardised data, b) data standardised to remove vessel effects and c) mean CPUE averaged across all fishing grounds and trawlers, based on d) non-standardised data, d) data standardised to remove vessel effects and f) mean CPUE averaged across all fishing grounds. Shaded area indicates ±2 standard errors.

3.4 Vessel Capacity Units (VCUs) and Distance from Port

Two Generalised Additive Models were fitted to the dataset. Model 9 (deviance explained = 60.1%) explained significantly more deviance than Model 8 (deviance explained = 44.2%) (ANOVA, $F = 1780.4$, $p<0.001$) and had a lower Akaike Information Criterion (AIC) score (22282.46 compared to 23255.48). Maximum distance travelled from port was therefore estimated using Model 9. Model 9 showed significant effects of all factors, vessel size and gear type ($p<0.001$), time ($p<0.001$), fishing ground ($p<0.001$), unique vessel ID ($p<0.001$) and departure port ($p<0.001$). The results showed a generally increasing trend in which on average larger vessels, represented here by Vessel Capacity Units (VCUs), travelled further from their respective departure ports (Fig. 13). Dredgers were shown to be significantly longer (ANOVA, $F = 934.207$, $p<0.001$), heavier (Kruskal-Wallis, $\chi^2 = 912.306$, $df = 1$, $p<0.001$) and more powerful (Kruskal-Wallis, $\chi^2 = 868.722$, $df = 1$, $p<0.001$), and to have correspondingly higher VCUs (Kruskal-Wallis, $\chi^2 = 950.056$, $df = 1$, $p<0.001$) than trawlers (Fig. 14). Hence, as would be expected from the results of Model 9, they generally travelled further from port, both in terms of distance from departure port (Kruskal-Wallis, $\chi^2 = 404.688$, $df = 1$, $p<0.001$) and total trip distance (Kruskal-Wallis, $\chi^2 = 162.296$, $df = 1$, $p<0.001$).

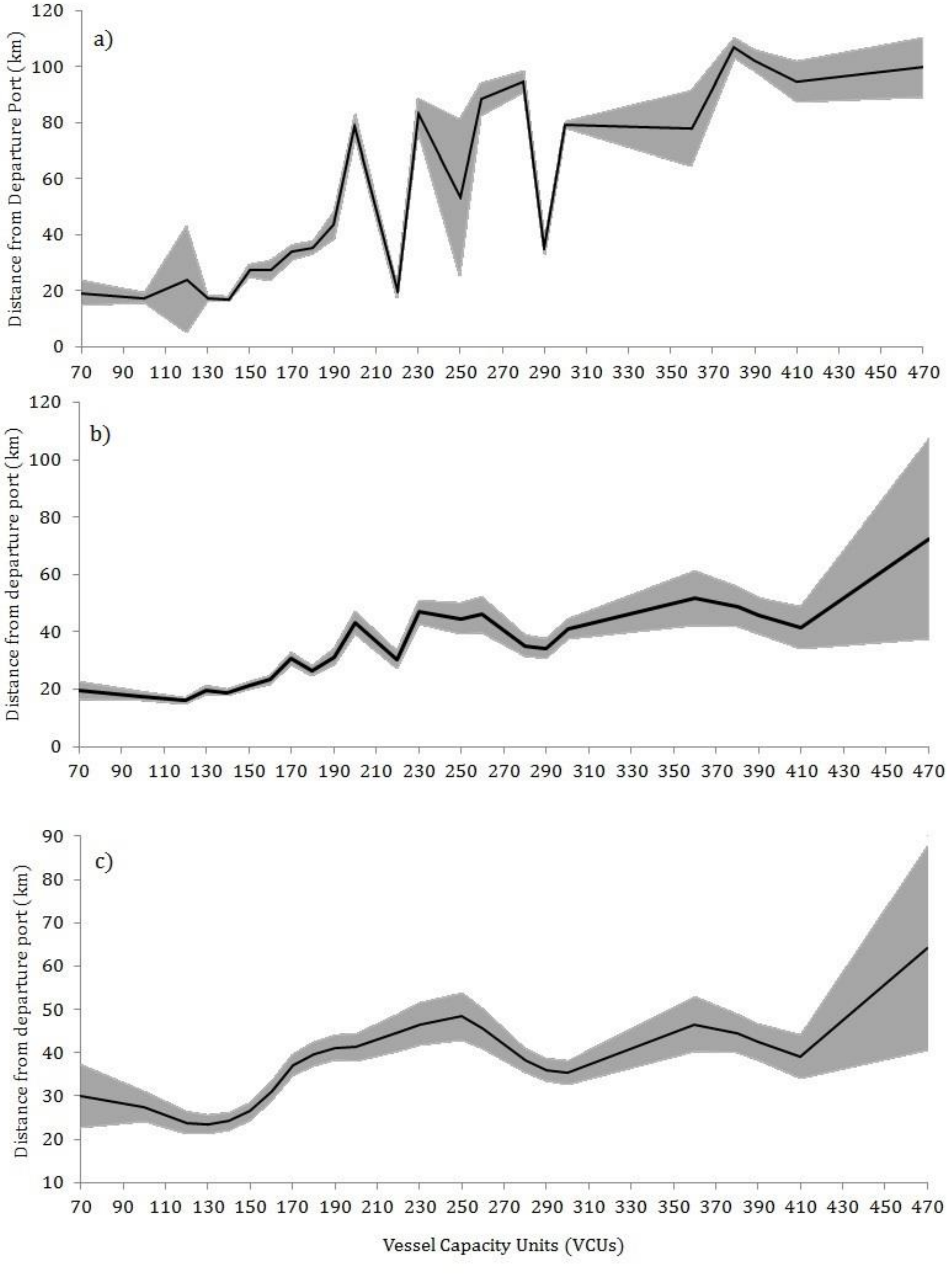


Fig. 13. Mean maximum distances from departure ports, with corresponding mean VCUs (grouped in 25 VCU blocks) for 2011 and 2012, including both trawlers and dredgers, based on a) non-standardised data, b) data standardised to remove departure port effects and c) mean distance from port for all voyages averaged across all vessel classes, gear types, departure ports, fishing grounds, years and days from the start of the fishing season. Shaded area indicates ±2 standard errors.

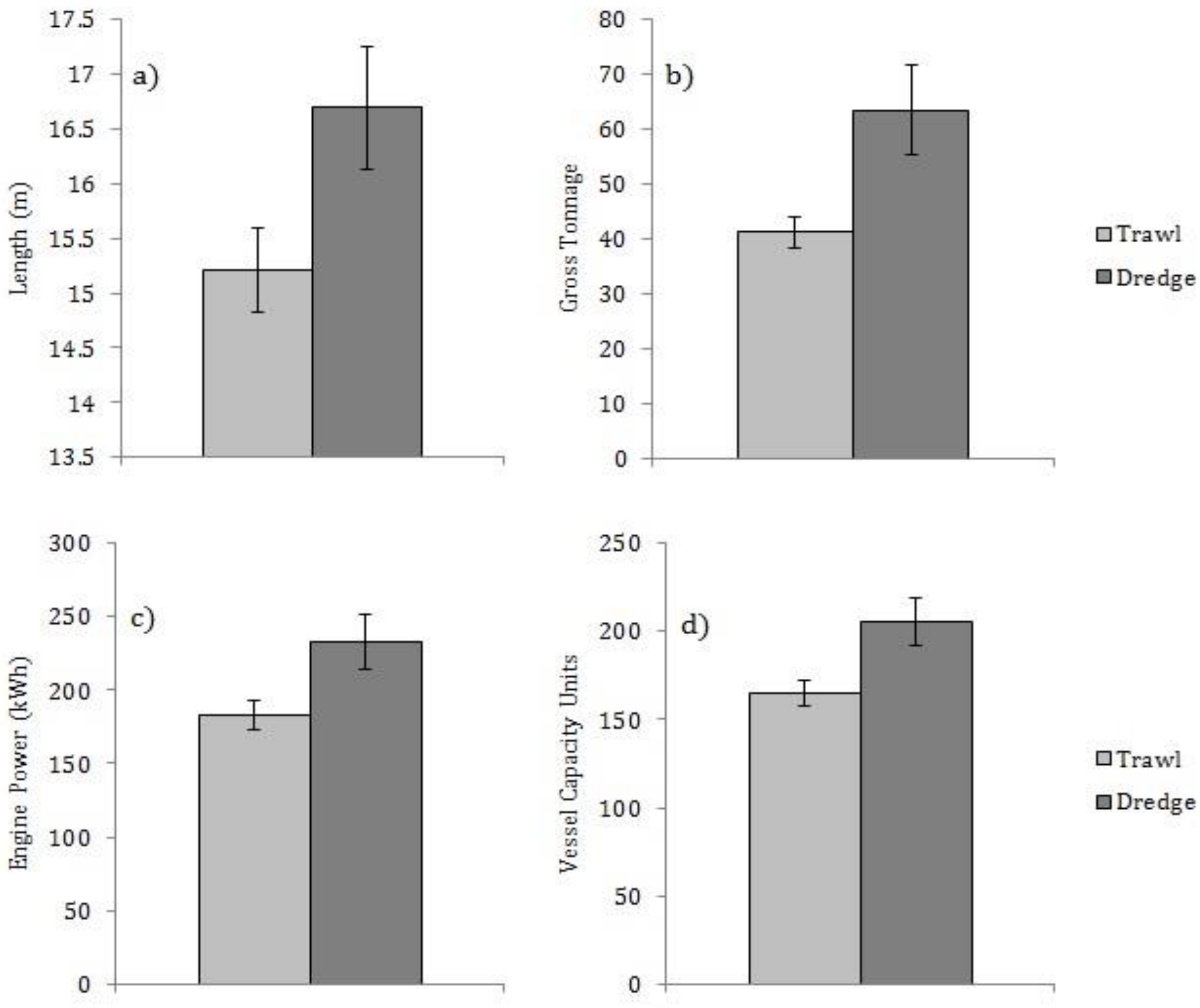


Fig. 14. Mean values for a) length, b) gross tonnage, c) engine power and d) vessel capacities units for both trawlers and dredgers in 2011 and 2012. Error bars show ±1 standard error.

3.5 Catch Rates and Total Effort

Simple linear regression analyses were conducted to investigate the link between total weekly effort and average weekly CPUEs (in effect standardised landings). The trawl fishery showed a positive relationship between effort and landings for both 2011 (n=21, F = 13.699, p =0.002, r^2 = 43.9%) and 2012 (n=22, F = 21.331, p<0.001, r^2 = 51.6%) and for the two years combined (n=43, F = 19.922, p<0.001, r^2 = 32.7%)(Fig. 15), while the opposite was true of the dredge fishery. Here, both 2011 (n=46, F = 11.560, p = 0.001, r^2 = 20.8%) and 2012 (n=49, F = 13.495, p = 0.001, r^2 = 22.3%) as well as the combined data (n=95, F = 22.509, p<0.001, r^2 = 19.5%) showed significant, if weak, negative relationships with effort (Fig. 15).

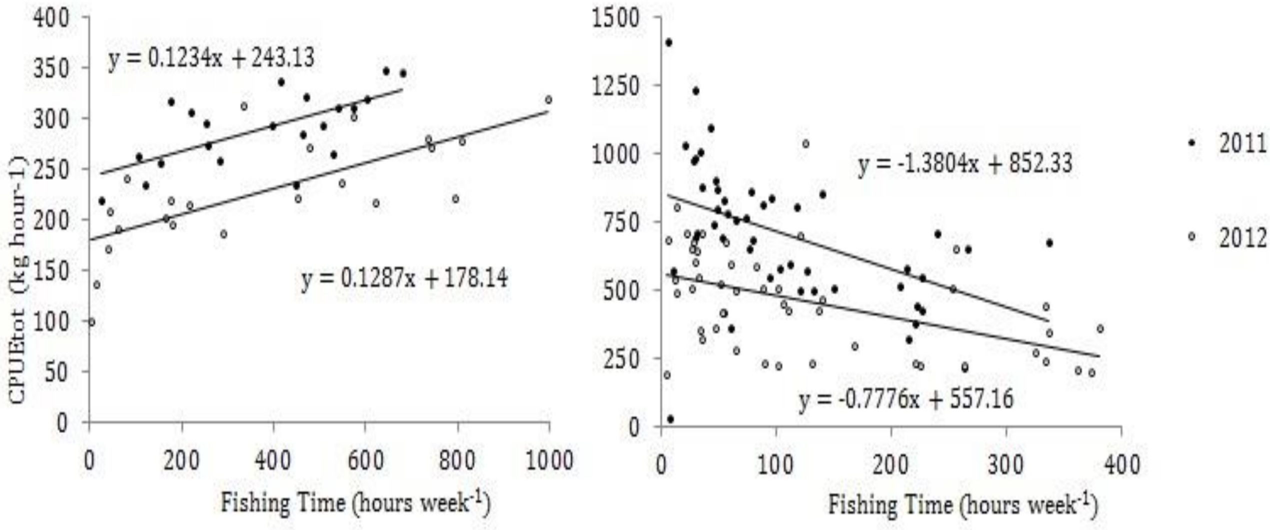


Fig. 15. Weekly average standardised catches (i.e. CPUE) with corresponding total effort in hours of fishing time calculated from VMS data for trawls (left) and dredges (right).

4 Discussion

4.1 Catch per Unit Effort (CPUE) and Trip Distance

The significant relationship between trip distance and catch per unit effort provides proof of the fact foragers, in this case fishers, will increase the search component of their foraging effort if it is believed benefits will ultimately be achieved in doing so (Stephens and Krebs, 1986). Indeed, fishers' will only take on the costs associated with increased transiting time, if they believe the results achieved will outweigh the sum of the returns that may be available closer to their home port, plus the increased costs associated with a wider search radius (Sampson, 1991). With (Fig. 10) illustrating increasing catch rates increasing with distance from port in the fishery, fishers may find it beneficial to travel further in search of increased catches. Studies have shown that when faced with declining resources Antarctic fur seals, rather than staying in place and expending more energy competing for the diminishing resource, increased their foraging trip distance and duration (Boyd, 1998). This reduction in the level of intraspecific competition further offshore may also help explain the increasing CPUE. Evidence for such an increase in CPUE as a result of decreased competition has been provided by Rijnsdorp *et al.* (2000a and 2000b), which showed catch rates in a Dutch beam trawl fishery to have increased, despite no apparent increase in overall abundance, in the face of decreased competition. Additionally, studies have shown that predators may increase their foraging trip efficiency by first locating areas of high prey density and then repeatedly returning to that area (Hamer *et al.*, 2001; Irons, 1998). Returning to an area past experiences have shown to have high catch may allow a skipper to simplify the cost benefit analysis associated with the trip. This foraging area fidelity may also lead to vessel effects as a particular vessel may be disproportionately successful when compared to the fleet as a whole and when conducting analysis these must be standardised for.

Model 3 also showed significant effects of gear type. When this relationship was investigated it was shown that generally dredgers fished further from port than trawlers. There may be a number of reasons for this such as vessel size and proximity to ports from which dredging is traditionally carried out. More importantly, it was illustrated that the catch per unit effort for dredging activities was significantly higher than it was for trawlers. This higher catch efficiency may allow dredgers to more easily offset the costs of increased travel and facilitate their fishing further off shore. Within the Manx scallop fishery there is also of course a link to vessel size, with dredgers being substantially larger than trawlers; this is discussed further in (Section 4.4).

The trawl fishery in this instance would appear to mirror closely the theory of Ideal Free Distribution (Fretwell, 1972), as evidenced by (Appendices 8 & 9). While this is purely a graphical representation and statistical analysis has not been carried out, none of the slopes in the trawl fishery would appear to differ significantly from 1. A slope of 1 in this instance is evidence of the fishery conforming to IDF as has been previously shown in a number of Canadian fisheries (Gillis et al. 1993; Gillis and Frank 2001). The free movement of effort within the fishery may be key to this; further evidence of this fact is that the dredge fishery where movement is restricted from 31st March to the 1st September does not appear to similarly conform to IDF (Appendix 9). Additionally, the fact that the area in which it does conform most closely is in fishing ground 8, the only area of which the entirety lies outside the 12nm limit and hence, which is free from seasonal restrictions on movement would provide further evidence of this.

4.2 Distance from Departure Port and Fishing Time

In much the same way as CPUE must increase with trip distance, the same is true of the time spent fishing, unless of course the increase in CPUE is such that the extra transit costs will be covered by it alone. The increase in fishing time with greater distances being travelled from port is not however proportional, with the relative increases in fishing time becoming less with distance, as evidenced by (Fig. 12). With increasing distance foraging intensity is reduced, due in no small part to the inclusion of times ill-suited to fishing, i.e. night, but also as the relative proportion of the fishing trip dedicated to transit time being less when compared to the trip duration as a whole. Boyd (1999) found similar behaviour to be manifested in the behaviour of Antarctic fur seals, where the distance travelled per foraging trip was correlated with both increased trip duration and a reduction in foraging intensity. In addition fishers' may seek to, in utilising the added downtime associated with greater trip duration for the purposes of slow speed transit, reduce the overall energy costs associated with the voyage and in this way increase the net profitability of the foraging excursion.

As a longer trip duration reduces the relative contribution of transiting to the overall costs, surely then to go longer is better? Why then do vessels return to port? Factors limiting trip duration may be fuel and hold capacity, rates of deterioration of the catch and factors related to crew wellbeing (Sampson, 1991). In effect a skipper will therefore formulate trip duration to ensure sufficient time is spent fishing to cover all cost and turn a profit. Studies have shown fishers to be risk adverse (Holland and Sutinen, 1999) and, taking risk as having the potentially to incur large costs to the vessel, a skipper may decide to cut trip duration short in the face of, for example adverse weather conditions. This risk avoidance behaviour may be interpreted as an attempt to reduce the likelihood of damage to the vessel

4.3 Catch per Unit Effort and Days since Season Opening

When fishing activity takes place in an area it can be expected that the loss of abundance will lead to reduced catch rates as the season progresses; (Murray *et al.*, 2013) has already shown this to be the case in this area. In this study catch rates for dredgers decreased across the open season according to (Fig. 11c); however, the same cannot be said of catch rates for trawlers (Fig. 11f). Trawls are dependent on increasing water temperature to raise their catch efficiency, through an accompanying increase in the swimming behaviour of the scallops (Jenkins *et al.*, 2003). Therefore, a reduction in the total abundance of scallops as a result of increased pressure may be masked as rising water temperatures increase the catchability of the remainder. An additional factor possibly preventing the trawl fisheries catches from declining is the fact that, with water temperatures being higher, growth will increase in parallel. These increased growth rates may result in a greater number of individuals attaining the minimum landing size (MLS) and becoming part of the commercially viable stock, and may also explain the increased catches by dredgers in November, December and January (Fig. 11c).

Another possible underlying reason behind this apparent increase in catch rates by dredges may be the reduction in fishing effort by trawls. This reduction in pressure is primarily due to the fishery becoming less viable in the face of a reduction in water temperature; in fact in the two years studied there was only a single trawl voyage after the 1st of November. This singular occurrence of trawling activity likely arose as fishers attempted to balance the reduced catch rates expected with higher returns per unit of catch, due to a premium being paid for luxury products, such as scallops, in the approach to Christmas (Appendix 6). This trawling effort in December is an example of a fisher moving into a marginal area, temporally in this instance, in a bid to maximise his gains; this is in essence Charnov's Marginal Value Theorem (Charnov, 1976) in operation and has previously been demonstrated in Australian abalone fisheries (Parker, 1992). The fluctuations in catch rates for the smaller, in terms of vessel size, trawl fleet may also have arisen as a result of inclement weather conditions, as factor which has been shown to be limiting in this fishery (Murray *et al.*, 2011).

An additional factor that may cause fluctuations in catch rates is the fact that, when movement occurs, a learning phase is necessary to optimise catch efficiency within the parameters of the new area. All foragers, in order to optimise their foraging efforts, must undergo some form of learning phase, and this has previously been demonstrated in a number of different marine species, (Burger *et al*., 1980; Greig *et al*., 1983) including fishers (Xiao, 2004). In fishing, this learning period includes the optimisation of gear set-ups, fishing patterns and the acquisition of knowledge relating to distributions of target species' in an area (Allen and McGlade, 1986).

4.4 Vessel Capacity Units and Distance from Port

Beyond the obvious fact that larger vessels travelled further from port due to the fact that it is safer and more practicable for them to do so, when compared to smaller vessels, they have generally higher catch efficiency; this allows them to lower the per unit cost of their catch, in part offsetting a portion their of transiting costs. In fact, when faced with the increased catch efficiency of a larger vessel a more marginal area may become less so. In effect this means that vessel or gear characteristics may overcome marginality in an area. In addition, larger vessels possess greater storage facilities allowing them to accommodate greater catches before necessitating a return to port, with smaller vessels being less well adapted, much like many seabirds whose foraging efforts are often limited by the amount they can carry back to the nest (Angelier *et al*., 2007). Aside from the obvious fact of the substrate being suitable, the lower per unit effort catches of trawlers may retain their effort close inshore, where the breakeven point is lower. Additionally, dredging is a more energetically costly form of fishing as it necessitates towing gear through the sediment thereby increasing friction, leading to higher associated gear maintenance costs as a result of wear and breakages, particularly in the face of recent increases in the worldwide price of steel. The increased cost of gear maintenance may preclude particular gear types from fishing in some areas (Hillborn and Kennedy, 1992). There was evidence of spatial disparity in the gear type used with fishing grounds one, two and three being fished almost exclusively by trawls, these fishing grounds occur in areas where the seabed is smooth facilitating trawling activity (MSC, 2011).

Values paid for trawl caught scallops in the Isle of man were extremely competitive when compared to the price paid to dredgers primarily landing into Scotland (Appendix 6), especially considering the average trip distance for dredgers was nearly double that of trawlers, in effect meaning the higher price available in Scotland was offset by increased transit costs.

4.5 Catch Rates and Total Effort

In fisheries where there is a single target species, fish, by relatively homogenous vessels across similar fishing grounds, it is to be expected that effort will be distributed in such a way that profit rates across all areas are equalised (Holland and Sutinen, 1997). This form of behaviour has previously been shown in the British Columbia salmon purse-seine fishery (Hilborn and Ledbetter 1979), by Japanese and American tuna purse-seiners (Campbell *et al.*, 1993) and in the Hecate Strait, British Columbia trawl fishery (Gillis *et al.*, 1993) and this study provided some evidence of this occurring in the Manx queen scallop trawl fishery (Appendix 7). There was also evidence that even as effort was added to the system, catches in the trawl fishery continued to increase (Fig. 15), a fact that belies decreasing abundances. It is likely that catches in this instance did not become depleted as a result of the fact that, although effort was increasing the season was short and sharp enough, taking place primarily within only four months (Appendix 1), to sustain such catch rates without them going into decline.

In the longer dredge fishery the opposite was true as catches decreased, as would be expected, in line with likely decreasing abundances. This decrease in the catch rates within the dredge fishery may also be a product of the fact that dredgers are generally more destructive to the environment when compared to trawls (Gray, *et al.*, 2007). As such benthic disturbance with high levels of dredge disturbance may be disproportionate when compared with similar levels of otter trawling. Another extenuating factor is that otter trawl CPUEs were generally lower than dredges and may in effect have been missing individuals, allowing them to be captured on subsequent passes. It should however be noted that the period of lowest catch rates in the dredge fishery coincided with months where one would expect weather conditions to be at their most adverse, and weather has previously been shown to be a limiting factor in the Manx King scallop fishery (Murray *et al.*, 2011). Whatever the underlying causes this study has shown the disparity between catch rates in the two fisheries, and would recommend separation between the two gear types is maintained in any future studies.

4.6 Advice for Management

Sources have proposed that fisheries in effect manage themselves through the practice of nomadic fishing. This practice entails fishing an area until it becomes marginal in relation to the fishery as a whole; closely related to giving up threshold, this means a fisher moving to what were initially more and more marginal areas as abundances and catch rates across the system fall. Indeed the initial area that had been marginalised will become less so, as either its stocks recoup or its relative marginality falls. An additional issue with this practice is that in fishing dense aggregations, even with near real-time analysis, reductions in abundances may be masked until they in effect reach a “cliff”. When density reaches a low enough level a positive feedback loop may be created whereby low spawning stock densities, a factor critical to the reproductive success of sedentary species such as scallops (Stokesbury and Himmelman, 1993; Claereboudt, 1999), lead to poor recruitment, which in turn leads to further reductions in abundances. The risks involve with passive management of fisheries are therefore too great, with an active legislative approach being more desirable.

As a result of its relatively inexpensive nature, there is often an overreliance on CPUE as a means of stock assessment; however this necessitates a number of assumptions including a linear relationship between CPUE and abundance (Branch *et al.*, 2006). However, as can be seen in the case of the trawl fishery, CPUE based estimates of abundance may not be entirely accurate. Here catch rates increased in the face of increased effort, an increase in which would use trigger a decline in abundance. The phenomenon of CPUE remaining at a high level while abundances decline is known as hyperstability (Harley *et al.*, 2001), and it was just this phenomenon which likely led to the complete collapse of the Newfoundland cod fishery (Rose and Kulka, 1999). When using CPUE as a measure of abundance one must be mindful that other factors may be masking declining abundances. While the masking agent in this case was likely increasing water temperature, it could also be increases in catch efficiency due to gear innovations (Rahikainen and Kuikka, 2002), more effective methods of targeting (Robins *et al.*, 1998) or increased knowledge of the fishery (Xiao, 2004). VCUs or nominal measurements with no regard to gear or boat innovations, may therefore be ill suited to provide a true reflection of fishing power. True fishing power may, as a result of innovation, increase substantially over time such that nominal effort no longer represents an acceptable degree of accuracy. This concept of nominal versus true fishing power is a major restriction on the effectiveness of vessel size restrictions within a fishery. In order for fleet restrictions such as these to be an effective management tool it is therefore necessary to continuously update the concept of nominal fishing effort.

It is therefore vital that, when conducting estimates of abundance, as holistic an approach as possible is taken in order to decrease the likelihood of potentially confounding factors.

4.7 Limitations and Recommendations

As can be seen from previous studies (Jenkins *et al.*, 2003) the catchability of scallops in trawls is strongly correlated with water temperature. In this instance standardised catches (CPUE) of scallops across the trawl season appeared to increase, despite what should be a decrease in abundance in response to increased fishing pressure. It is therefore crucial that any future studies in particular looking at the trawl fishery, which being MSC certified is of vital importance, take into account fluctuations in water temperature. While water is thermodynamically stable enough to resist short term fluctuations in temperature, a cold spring may in effect delay the fisheries' peak effectiveness, meaning increased competition with dredgers when their season opens. In order to safeguard returns in the predominantly Manx based trawl fishery, worth £1,389,904 from Manx vessels alone to the Manx economy (DEFA, 2013), management might in response to slower warming of the surrounding water recommend that the opening of the dredge season be similarly delayed.

More accurate measurement of trip distance than the "there and back again" approach adopted in this study might lead to more accurate results; however these might not be proportional to the increase effort, both personnel and computing wise, that would be required. The author believes that the approach adopted here was more accurate than the more traditional GIS based grid square analysis, often adopted in studies where distance measurements are required, and as a result is a useful advancement on such. The two hour polling interval of the data in this study was found to be adequate, as analysis was a carried out on a reasonably large spatial scale. It is likely that inaccuracies in the data were averaged out across the fishery, such that trends which were present remained detectable. However, should finer scale analysis be required, such as within fishing grounds, an increased polling interval would be highly desirable. While VMS data was available for all years from 2007 in the statistical rectangles in question, it was not of consistent quality. Care must be taken at all stages in capturing and processing the data to ensure the end results are ultimately comparable. As the present high quality is expanded in the coming years, repeat analysis would be interesting in determining whether the trends observed occur over longer temporal scales. Additionally should water temperatures rise as is predicted due to global climate change, scallops may be commercially viable from the point of trawl fishery for longer periods in the summer and autumn. Should the trawl season become extended it is vital that management maintain vigilance to ensure safe catch limits are not surpassed.

An additional improvement that could help to better understand the behaviour of fishers is in seeking to quantify the costs economically. It is the ultimately monetary profit that fishers' are chasing and as such it is in this monetary sense that all variables should be considered, i.e. what is the monetary cost of inclement weather? etc. Value per Unit Effort (VPUE) therefore, might potentially be a better indicator of returns, as it allows the price to be included within the data on the same temporal scale (Poos and Rijnsdorp, 2007). Additionally, given data on fuel prices and the fuel economy of various engine sizes and gear types, the majority of day to day costs could be conserved.

4.8 Conclusion

In summary, all four hypotheses were accepted: catches per unit effort and time spent fishing did increase in conjunction with distance travelled from port, CPUEs did vary temporally across the open season for both fisheries, and larger vessels were shown to fish further from port. In addition, catches by trawlers were shown not to have become depleted, whereas catches from dredgers did exhibit a decline across their respective open seasons. Trawls also exhibited no decline in catch rates as a result of increased effort within the fishery whereas once again dredges did. Trawls were also shown to exhibit conformity to the theory of Ideal Free Distribution, whereby fishers distributed themselves among the available grounds in such a way that returns were equalised across the fishery, whereas no evidence of such was found within the trawl fishery. Modeling conducted during the study emphasised the fact that catch rates and their underlying abundances can fluctuate on short temporal and spatial scales, and reiterated the need for constantly evolving management of the fishery. The study was also, in itself, a useful case study into potential uses of VMS and logbook data for the purpose of fisheries management, an area of study the author feels will only increase in importance into the future.

5 References

- Abrahams, M. V., and Healey, M. C. (1990). Variation in the competitive abilities of fishermen and its influence on the spatial distribution of the British Columbia salmon troll fleet. *Canadian Journal of Fisheries and Aquatic Sciences*, **47**(6), pp. 1116-1121.
- Allen, P. M., and McGlade, J. M. (1986). Dynamics of discovery and exploitation: the case of the Scotian Shelf groundfish fisheries. *Canadian Journal of Fisheries and Aquatic Sciences*, **43**(6), pp. 1187-1200.
- Angelier, F., Bost, C. A., Giraudeau, M., Bouteloup, G., Dano, S., Chastel, O. (2008). Corticosterone and foraging behavior in a diving seabird: The Adélie penguin, *Pygoscelis adeliae*. *General and comparative endocrinology*,**156**(1), pp. 134-144.
- Ansell, A. D., Dao, J. C., Mason, J., (1991). Three European scallops: *Pecten maximus, Chlamys* (*Aequipecten*) *opercularis* and *C.* (*Chlamys*) *varia*. In: Shumway, S. E., editor. Scallops: Biology, Ecology and Aquaculture. Amsterdam: *Elsevier*. pp. 715-51.
- Bastardie, F., Nielsen, J. R., Ulrich, C., Egekvist, J., and Degel, H. (2010). Detailed mapping of fishing effort and landings by coupling fishing logbooks with satellite-recorded vessel geo-location. *Fisheries Research*, **106**(1), pp. 41-53.
- Beecham, J. A., and Engelhard, G. H., (2007). Ideal free distribution or dynamic game? An agent-based simulation study of trawling strategies with varying information. *Physica A: Statistical Mechanics and its Applications*, **384**(2), pp. 628-646.
- Bell, A. V., Rader, R. B., Peck, S. L., and Sih, A., (2009). The positive effects of negative interactions: Can avoidance of competitors or predators increase resource sampling by prey?. *Theoretical population biology*, **76**(1), pp. 52-58.
- Beukers-Stewart, B. D., Mosley, M. W. J., and Brand, A. R. (2003). Population dynamics and predictions in the Isle of Man fishery for the great scallop, *Pecten maximus* L. *ICES Journal of Marine Science: Journal du Conseil*, **60**(2), 224-242.
- Bishop, J. (2006). Standardizing fishery-dependent catch and effort data in complex fisheries with technology change. *Reviews in Fish Biology and Fisheries*, 16: pp. 21-38.

- Boyd I. L., (1999). Foraging and provisioning in Antarctic fur seals: inter-annual variability in time energy budgets. *Behavioural Ecology*, 10(2): pp. 198.208.
- Boyd, I. L., Arnould, J. P. Y., Barton, T., and Croxall, J. P., (1994). Foraging behaviour of Antarctic fur seals during periods of contrasting prey abundance. *Journal of Animal Ecology*, pp. 703-713.
- Branch, T. A., Hilborn, R., Haynie, A. C., Fay, G., Flynn, L., Griffiths, J., ... & Young, M. (2006). Fleet dynamics and fishermen behaviour: lessons for fisheries managers. *Canadian Journal of Fisheries and Aquatic Sciences*, **63**(7), pp. 1647-1668.
- Brand, A. R., (2006). Scallop ecology: distributions and behaviour. *Developments in Aquaculture and Fisheries science*, **35,** 651-744.
- Burger, J., (1980). The transition to independence and postfledging parental care in seabirds. *Animal Behaviour,* **4**, pp. 366–447
- Butman, C. A. (1987). Larval settlement of soft-sediment invertebrates—the spatial scales of pattern explained by active habitat selection and the emerging role of hydrodynamical processes. *Journal of Oceanography and Marine Biology*, **25**, pp. 113-165.
- Butman, C. A., Grassle, J. P., and Webb, C. M. (1988). Substrate choices made by marine larvae settling in still water and in a flume flow. *Nature*, **333**, pp. 771-773.
- Campbell, H. F., Nicholl, R. B., and Meyer, G. (1993). Search behavior in the purse seine tuna fishery. *Natural Resource Modeling*, **7**(1), pp. 15-35.
- Chang, S. K. (2011). Application of a vessel monitoring system to advance sustainable fisheries management—Benefits received in Taiwan. *Marine Policy*, ***35***(2), pp. 116-121.
- Chapman, C. J., (1981). The swimming behaviour of queens in relation to trawling. *Scottish Fisheries Bulletin*, **46**: pp. 7-10.
- Chapman, C., Main, J., Howell, T., and Sangster, G.I., (1979). The swimming speed and endurance of the queen scallop *Chlamys opercularis* in relation to trawling. *Progress in Underwater Science*, **4**, pp. 57 – 72.
- Charnov, E. L. (1976). Optimal foraging, the marginal value theorem. *Theoretical population biology*, **9**(2), pp. 129-136.
- Claereboudt, M. (1999). Fertilization success in spatially distributed populations of benthic free-spawners: a simulation model. *Ecological Modeling*, **121**(2), pp. 221-233.
- Deng, R., Dichmont, C., Milton, D., Haywood, M., Vance, D., Hall, N., and Die, D. (2005). Can vessel monitoring system data also be used to study trawling intensity and

population depletion? The example of Australia's northern prawn fishery. *Canadian Journal of Fisheries and Aquatic Sciences*, **62**(3), pp. 611-622.

- Die, D. J., and Ellis, N. (1999). Aggregation dynamics in penaeid fisheries: banana prawns (*Penaeus merguiensis*) in the Australian Northern Prawn Fishery. *Marine and freshwater research*, **50**(7), pp. 667-675.
- Dreisig, H., (1995). Ideal free distributions of nectar foraging bumblebees. *Oikos*, pp. 161-172.
- Drouin, M. (2001). Vessel Monitoring Systems gain ground. *Pacific Fishing*, *22*, pp. 31.
- EC (European Commission). 2009. Green Paper: Reform of the Common Fisheries Policy. EC, Brussels, Com 163. http://ec.europa.eu/fisheries/reform/ (April 2013, date last accessed).
- Elliott, K. H., Davoren, G. K., and Gaston, A. J., (2008). Increasing energy expenditure for a deep-diving bird alters time allocation during the dive cycle. *Animal Behaviour*, **75**(4), pp. 1311-1317.
- FAO. (1988). Fishing operations: vessel monitoring systems. FAO Technical Guidelines for Responsible Fisheries, **1**(1). *FAO*, Rome. pp. 58.
- Fock, H. O. (2008). Fisheries in the context of marine spatial planning: defining principal areas for fisheries in the German EEZ. *Marine Policy*, **32**(4), pp. 728-739.
- Fretwell, S. D. (1972). Population in a seasonal environment, **5**. *Princeton University Press*.
- Frid, C., Paramor, O., and Scott, C. (2005). Ecosystem-based fisheries management: progress in the NE Atlantic. *Marine Policy*, **29**(5), pp. 461-469.
- Gillis, D. M., and Frank, K. T., (2001). Influence of environment and fleet dynamics on catch rates of eastern Scotian Shelf cod through the early 1980s. *ICES Journal of Marine Science*, **58**: pp. 61–69.
- Gillis, D. M., and van der Lee, A. (2012). Advancing the application of the ideal free distribution to spatial models of fishing effort: the isodar approach. *Canadian Journal of Fisheries and Aquatic Sciences*, **69**(10), pp. 1610-1620.
- Gillis, D. M., Peterman, R. M., and Tyler, A. V., (1993). Movement dynamics in a fishery: application of the ideal free distribution to spatial allocation of effort. *Canadian Journal of Fisheries and Aquatic Science*, **50**, pp. 323–333.
- Godin, J. G. J., and Keenleyside, M. H., (1984). Foraging on patchily distributed prey by a cichlid fish (Teleostei, Cichlidae): a test of the ideal free distribution theory. *Animal Behaviour*, **32**(1), pp. 120-131.

- Gordon, H. S. (1953). An economic approach to the optimum utilization of fishery resources. *Journal of the Fisheries Board of Canada*, **10**(7), pp. 442-457.
- Gordon, H. S. (1954). The economic theory of a common-property resource: the fishery. *The Journal of Political Economy*, **62**(2), pp. 124-142.
- Grand, T. C., (1997). Foraging site selection by juvenile coho salmon: ideal free distributions of unequal competitors. *Animal Behaviour*, **53**(1), pp. 185-196.
- Greig, S. A., Coulson, J. C., Monaghan, P., (1983). Age-related differences in foraging success in the herring gull (*Larus argentatus*). Animal Behaviour, **31**,pp. 1237–1243.
- Gulin, D. (2005). Fishing vessels monitoring systems. In *ELMAR, 2005. 47th International Symposium*, pp. 369-372).
- Harper, D. G. C., (1982). Competitive foraging in mallards: "Ideal free' ducks. *Animal Behaviour*, **30**(2), pp. 575-584.
- Haynes, E. B., and Hitz, C. R. (1971). Age and growth of the giant Pacific sea scallop, *Patinopecten caurinus*, from the Strait of Georgia and outer Washington coast. *Journal of the Fisheries Board of Canada*, **28**(9), pp. 1335-1341.
- Hiddink, J. G., Hutton, T., Jennings, S., and Kaiser, M. J. (2006). Predicting the effects of area closures and fishing effort restrictions on the production, biomass, and species richness of benthic invertebrate communities. *ICES Journal of Marine Science: Journal du Conseil*, **63**(5), pp. 822-830.
- Hiddink, J. G., Jennings, S., and Kaiser, M. J. (2006a). Indicators of the ecological impact of bottom-trawl disturbance on seabed communities. *Ecosystems*, **9**(7), pp. 1190-1199.
- Hilborn, R. (2012). The evolution of quantitative marine fisheries management 1985–2010. *Natural Resource Modeling*, **25**(1), pp. 122-144.
- Hilborn, R. and Walters, C.J. (1992). Quantitative fisheries stock assessment: choice, dynamics and uncertainty. *Chapman and Hall*, New York.
- Hilborn, R., and Kennedy, R. B. (1992). Spatial pattern in catch rates: a test of economic theory. *Bulletin of Mathematical Biology*, **54**(2), pp. 263-273.
- Hilborn, R., and Ledbetter, M. (1979). Analysis of the British Columbia salmon purse-seine fleet: dynamics of movement. *Journal of the Fisheries Board of Canada*, **36**(4), pp. 384-391.
- Hill, A. S., Veale, L. O., Pennington, D., Whyte, S. G., Brand, A. R., and Hartnoll, R. G. (1999). Changes in Irish Sea benthos: possible effects of 40 years of dredging. *Estuarine, Coastal and Shelf Science*, **48**(6), pp. 739-750.

- Holland, D. S., Sutinen, J. G. (1999). An empirical model of fleet dynamics in New England trawl fisheries. *Canadian Journal of Fisheries and Aquatic Sciences*, **56**(2), pp. 253-264.
- Irons, D. B., (1998). Foraging area fidelity of individual seabirds in relation to tidal cycles and flock feeding. *Ecology*, 79, pp. 647–655
- Isle of Man Government (2013). Proposals for amendments to the Sea Fisheries (Queen Scallop Fishing) Bye-Laws 2010. Isle of Man, Department of Environment, Food and Agriculture, Consultation Paper.
- Jenkins, S. R., and Brand, A. R. (2001). The effect of dredge capture on the escape response of the great scallop *Pecten maximus* (L.): implications for the survival of undersized discards. *Journal of experimental marine biology and ecology*, **266**(1), pp. 33-50.
- Jenkins, S. R., Lart, W., Vause, B. J., and Brand, A. R., (2003). Seasonal swimming behaviour in the queen scallop (*Aequipecten opercularis*) and its effect on dredge fisheries. *Journal of experimental marine biology and ecology*, **289**(2), pp. 163-179.
- Johnson, D. R., Yeung, C., and Brown, C. A. (1999). Estimates of marine mammal and marine turtle bycatch by the US Atlantic pelagic longline fleet in 1992-1997. *US Department of Commerce, National Oceanic and Atmospheric Administration, National Marine Fisheries Service, Southeast Fisheries Science Center*.
- Jonsson, P. R., Andre, C., and Lindegarth, M. (1991). Swimming Behavior of Marine Bivalve Larvae in a Flume Boundary-Layer Flow-Evidence for near-Bottom Confinement. *Marine Ecology-Progress Series*, **79**(1-2), pp. 67-76.
- Kamenos, N. A., Moore, P. G., and Hall-Spencer, J. M. (2004). Maerl grounds provide both refuge and high growth potential for juvenile queen scallops (*Aequipecten opercularis* L.). *Journal of Experimental Marine Biology and Ecology*, **313**(2), pp. 241-254.
- Kennedy, M., and Gray, R. D., (1993). Can ecological theory predict the distribution of foraging animals? A critical analysis of experiments on the ideal free distribution. *Oikos*, pp. 158-166.
- Lambert, G. I., Jennings, S., Hiddink, J. G., Hintzen, N. T., Hinz, H., Kaiser, M. J., and Murray, L. G. (2012). Implications of using alternative methods of vessel monitoring system (VMS) data analysis to describe fishing activities and impacts. *ICES Journal of Marine Science: Journal du Conseil*, **69**(4), pp. 682-693.

- Lambert, G. I., Jennings, S., Kaiser, M. J., Hinz, H., and Hiddink, J. G. (2011). Quantification and prediction of the impact of fishing on epifaunal communities. *Marine Ecology Progress Series*, **430**, pp. 71-86.
- Lee, J., South, A. B., and Jennings, S. (2010). Developing reliable, repeatable, and accessible methods to provide high-resolution estimates of fishing-effort distributions from vessel monitoring system (VMS) data. *ICES Journal of Marine Science: Journal du Conseil*, **67**(6), pp. 1260-1271.
- Mason, J. (1957). The age and growth of the scallop, *Pecten maximus* (L.) in Manx waters. *J. mar. biol. Ass. UK*, 36(473), pp. 492.
- Mason, J. (1958). The breeding of the scallop, *Pecten maximus* (L.), in Manx waters. *Journal of the Marine Biological Association of the United Kingdom*, **37**(03), pp. 653-671.
- McGoodwin, J. R., (1991). Conceptualizing Human Fishers as Predators in Marine Ecosystems Some Cautionary Notes for Fisheries Management. *Maritime Anthropological Studies*, 4(2): pp. 62-71.
- Milinski, M., (1984). Competitive resource sharing: an experimental test of a learning rule for ESSs. *Animal Behaviour*, **32**(1), pp. 233-242.
- Mills, C. M., Townsend, S. E., Jennings, S., Eastwood, P. D., and Houghton, C. A. (2007). Estimating high resolution trawl fishing effort from satellite-based vessel monitoring system data. *ICES Journal of Marine Science: Journal du Conseil*, **64**(2), pp. 248-255.
- Mills, C., Rogers, S. I., Tasker, M. L., Eastwood, P. D., and Piet, G. J. (2004). Developing the use of satellite fishing vessel monitoring system data in spatial management. In *ICES Journal of Marine Science Annual Science Conference* (Vol. **22**, p. 25).
- MMO (2012). UK Sea Fisheries Statistics 2011. A report produced for the Marine Management Organisation, pp 140. Last accessed: 26 April 2013. http://www.marinemanagement.org.uk/fisheries/statistics/documents/ukseafish/2011/final.pdf
- Moore, J. D., and Trueman, E. R., (1971). Swimming of the scallop, *Chlamys opercularis*(L.). *Journal of Experimental Marine Biology and Ecology*, **6** (3), pp. 179-185.
- MSC (2011). Assessment Report for Isle of Man Queen Scallop Trawl and Dredge Fishery Client: Isle of Man Government Version 3: Public Comment Draft Report.

- Mullowney, D. R., and Dawe, E. G. (2009). Development of performance indices for the Newfoundland and Labrador snow crab (*Chionoecetes opilio*) fishery using data from a vessel monitoring system. *Fisheries Research*, **100**(3), pp. 248-254.
- Murawski, S. A., Wigley, S. E., Fogarty, M. J., Rago, P. J., and Mountain, D. G. (2005). Effort distribution and catch patterns adjacent to temperate MPAs. *ICES Journal of Marine Science: Journal du Conseil*, **62**(6), pp. 1150-1167.
- Murray, L. G., Hinz, H., and Kaiser, M. J. (2010). Predicted impacts of proposed management measures in the Isle of Man's *Pecten maximus* fishery. *Report to the Isle of Man Government, Department of Environment, Food and Agriculture*.
- Murray, L. G., Hinz, H., and Kaiser, M. J. (2011). Functional response of fishers in the Isle of Man scallop fishery. *Marine Ecology Progress Series*, **430**, pp. 157-169.
- Murray, L. G., Hinz, H., Hold, N., and Kaiser, M. J. (2013) The effectiveness of using CPUE data derived from Vessel Monitoring Systems and fisheries logbooks to estimate scallop biomass, *ICES Journal of Marine Science*. DOI:10.1093/icesjms/fst099.
- Murray, L.G., Hinz, H. and Kaiser, M.J. (2009). The Isle of Man *Aequipecten opercularis* Fishery: Science and Management Fisheries and Conservation report No. 10, Bangor University. pp. 33.
- Needle, C. L., and Catarino, R. (2011). Evaluating the effect of real-time closures on cod targeting. *ICES Journal of Marine Science: Journal du Conseil*, **68**(8), pp. 1647-1655.
- Palmer, M. C., and Wigley, S. E. (2009). Using positional data from vessel monitoring systems to validate the logbook-reported area fished and the stock allocation of commercial fisheries landings. *North American Journal of Fisheries Management*, **29**(4), pp. 928-942.
- Parker, G. A., and Sutherland, W. J., (1986). Ideal free distributions when individuals differ in competitive ability: phenotype-limited ideal free models. *Animal Behaviour*, **34**(4), pp. 1222-1242.
- Parker, Geoffrey A. (1992)"Marginal value theorem with exploitation time costs: diet, sperm reserves, and optimal copula duration in dung flies." *American Naturalist*: pp. 1237-1256.
- Paul, J. D., Brand, A. R., and Hoogesteger, J. N. (1981). Experimental cultivation of the scallops *Chlamys opercularis*(*L.*) and *Pecten maximus*(*L.*) using naturally produced spat. *Aquaculture*, **24**, pp. 31-44.

- Philipp, E. E., Schmidt, M., Gsottbauer, C., Sänger, A. M., and Abele, D., (2008). Size- and age-dependent changes in adductor muscle swimming physiology of the scallop *Aequipecten opercularis*. *Journal of Experimental Biology*, **211**(15), pp. 2492-2501.
- Pickett, G. A., and Franklin, A. (1975). The growth of queen scallops (*Chlamys opercularis*) in cages off Plymouth, South-West England. *ICES CM (K25)*.
- Prince, J. D. (1990). The fisheries biology of the Tasmanian stocks of *Haliotis rubra*. *University of Tasmania*.
- Quirijns, F. J., Poos, J. J. and Rijnsdorp, A. D. (2008). Standardizing commercial CPUE data in monitoring stock dynamics: Accounting for targeting behaviour in mixed fisheries. *Fisheries Research*, **89**: pp. 1-8.
- Rahikainen, M., Kuikka, S. (2002). Fleet dynamics of herring trawlers change in gear size and implications for interpretation of catch per unit effort. *Canadian Journal of Fisheries and Aquatic Sciences*, **59**(3), pp. 531-541.
- Reiss, H., Greenstreet, S. P., Sieben, K., Ehrich, S., Piet, G. J., Quirijns, F., and Kröncke, I. (2009). Effects of fishing disturbance on benthic communities and secondary production within an intensively fished area. *Marine Ecology Progress Series*, **394**, pp. 201-213.
- Richardson, C. A., Taylor, A. C., and Venn, T. J. (1982). Growth of the queen scallop *Chlamys opercularis* in suspended cages in the Firth of Clyde. *J. mar. biol. Ass. UK*, **62**, pp. 157-169.
- Rijnsdorp, A. D., Dol, W., Hoyer, M., and Pastoors, M. A., (2000a). Effects of fishing power and competitive interactions on the effort allocation on the trip level of the Dutch beam trawl fleet. *ICES Journal of Marine Science*, **57**: pp. 927–937.
- Rijnsdorp, A. D., Poos, J. J., and Quirijns, F. J. (2011). Spatial dimension and exploitation dynamics of local fishing grounds by fishers targeting several flatfish species. *Canadian Journal of Fisheries and Aquatic Sciences*, **68**(6), pp. 1064-1076.
- Rijnsdorp, A. D., van Mourik Broekman, P. L., and Visser, E. G., (2000b). Competitive interactions among beam trawlers exploiting local patches of flatfish in the North Sea. *ICES Journal of Marine Science*, **57**: pp. 894–902.
- Robins, C. M., Wang, Y. G., and Die, D. (1998). The impact of global positioning systems and plotters on fishing power in the northern prawn fishery, Australia. *Canadian Journal of Fisheries and Aquatic Sciences*, **55**(7), pp. 1645-1651.
- Román, G., Campos, M. J., Acosta, C. P., and Cano, J. (1999). Growth of the queen scallop (*Aequipecten opercularis*) in suspended culture: influence of density and depth. *Aquaculture*, **178**(1), pp. 43-62.

- Rose, G. A., Kulka, D. W. (1999). Hyperaggregation of fish and fisheries: how catch-per-unit-effort increased as the northern cod (*Gadus morhua*) declined.*Canadian Journal of Fisheries and Aquatic Sciences*, **56(**S1), pp. 118-127.
- Saitoh, S. I., Hirawake, T., Radiarta, I. N., Isada, T., Mugo, R., Takahashi, F., Imai, I., *et al*. (2010). New challenge of integrated coastal fisheries information system in southern Hokkaido, Japan. In North Pacific Ecosystems Today, and Challenges in Understanding and Forecasting Change, p. 164. North Pacific Marine Science Organization, *PICES*, Program and Abstracts, 22–31 October 2010, Portland, OR, USA. pp. 313.
- Saitoh, S. I., Mugo, R., Radiarta, I. N., Asaga, S., Takahashi, F., Hirawake, T. and Shima, S. (2011). Some operational uses of satellite remote sensing and marine GIS for sustainable fisheries and aquaculture. *ICES Journal of Marine Science: Journal du Conseil*, **68**(4), pp. 687-695.
- Sampson, D. B. (1991). Fishing tactics and fish abundance, and their influence on catch rates. *ICES Journal of Marine Science: Journal du Conseil*, **48**(3), pp. 291-301.
- Sanchiro, J. N., Wilen, J. E., (2001). A bioeconomic model of marine reserve creation. *J. Environ. Econ. Manag*. **42**, pp. 257–276.
- Schmidt, M., Philipp, E. E., and Abele, D., (2008). Size and age-dependent changes of escape response to predator attack in the Queen scallop *Aequipecten opercularis*. *Marine Biology Research*, **4**(6), pp. 442-450.
- Shephard, S., Beukers-Stewart, B., Hiddink, J. G., Brand, A. R., and Kaiser, M. J. (2010). Strengthening recruitment of exploited scallops *Pecten maximus* with ocean warming. *Marine Biology*, **157**(1), pp. 91-97.
- Stephen, D. W., and Krebs, J. R. (1986). Foraging theory. *Princeton University Press*.
- Stokesbury, K. D., and Himmelman, J. H. (1995). Biological and physical variables associated with aggregations of the giant scallop *Placopecten magellanicus*. *Canadian Journal of Fisheries and Aquatic Sciences*, **52**(4), pp. 743-753.
- Stokesbury, K., and Himmelman, J. (1993). Spatial-distribution of the Giant Scallop *Placopecten magellanicus* in unharvested beds in the Baie des Chaleurs, Quebec. Marine Ecology Progress Series, **96**, pp. 159–168.
- Veale, L. O., Hill, A. S., and Brand, A. R. (2000). An in situ study of predator aggregations on scallop (*Pecten maximus* (*L.*)) dredge discards using a static time-lapse camera system. *Journal of experimental marine biology and ecology*, **255**(1), pp. 111-129.

- Witt, M. J., and Godley, B. J. (2007). A step towards seascape scale conservation: using vessel monitoring systems (VMS) to map fishing activity. *PLoS One*, ***2***(10), e1111.
- Wood. S., N., (2006) Generalized additive models: an introduction with R. Chapman and Hall/CRC, London.
- Wood. S., N., and Augustin, N., H., (2002) GAMs with integrated model selection using penalized regression splines and applications to environmental modeling. *Ecological Modeling*, **157**, pp.157-177.
- Xiao, Y. (2004). Modeling the learning behaviour of fishers: learning more from their successes than from their failures. *Ecological modeling*, **171**(1), pp. 3-20.

6. Appendices

Appendix 1.

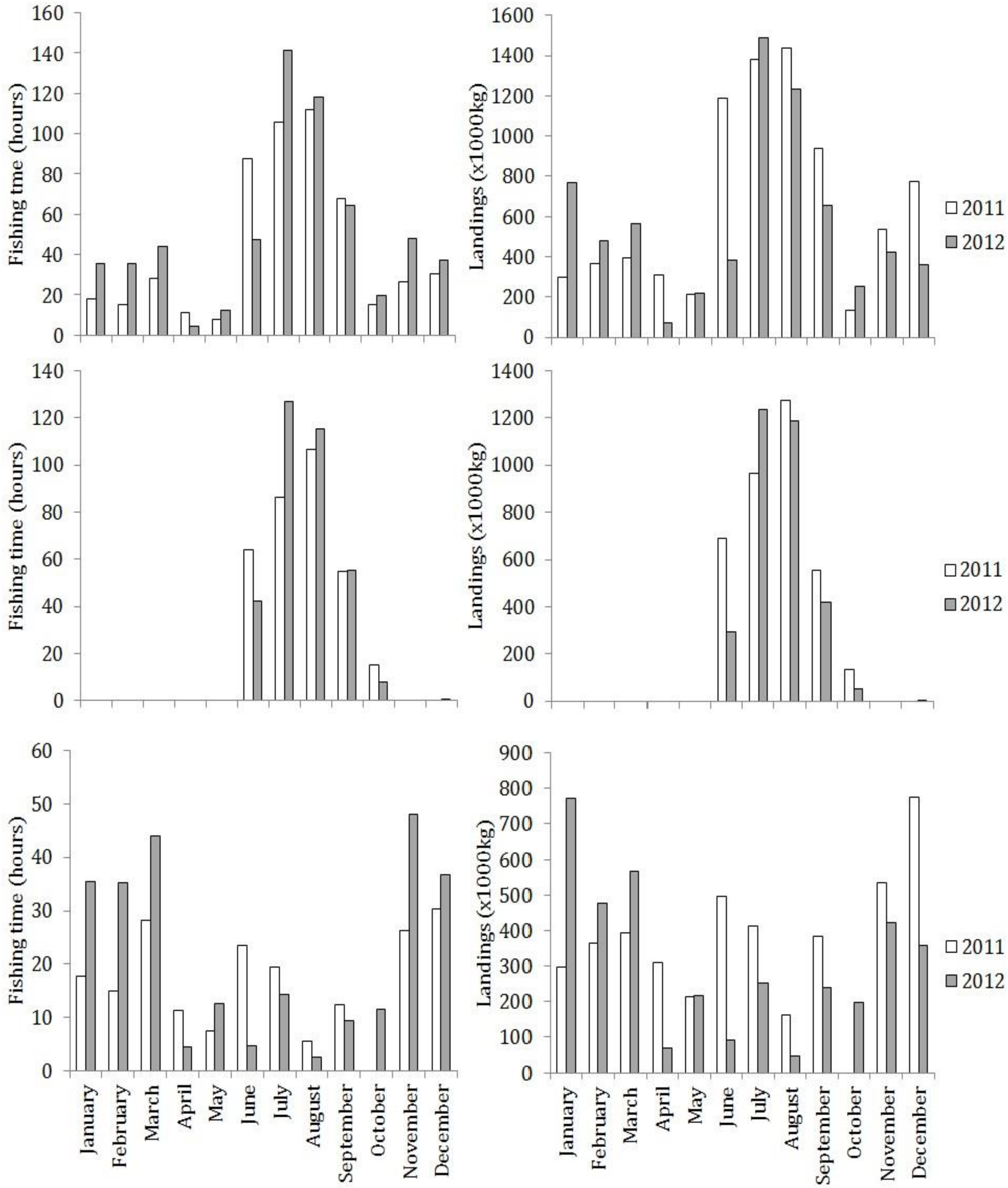
R-script used to calculate trip distance from Vessel Monitoring System data. (Script adapted from one originally received from Dr. J. Hiddink.)

```
graphics.off()
rm(list=ls())

require(maps)
require(mapproj)
require(maptools)
require(proj4)
require(rgdal)
require(raster)
require(gdistance)
require(adehabitatMA)

# define British National Grid projection
EPSG <- make_EPSG()
EPSG[grep("British National Grid", EPSG$note), 1:2]

# read shapefiles
setwd("C:/Distance from Port Calculations/Shapefiles ")
outline=readShapeSpatial("Outline.shp",CRS("+init=epsg:27700"))
land=readShapeSpatial("Land.shp",CRS("+init=epsg:27700"))

# plot maps
windows()
plot(land)
plot(outline,add=T)


### rasterize the shapefiles
#setup the raster
resolution=1000 #m,
xmn=outline@bbox[1,1]
xmx=outline@bbox[1,2]
ymn=outline@bbox[2,1]
ymx=outline@bbox[2,2]
cells=raster(nrows=round((xmx-xmn)/resolution,0),        ncols=round((ymx-ymn)/resolution,0),
xmn=xmn, xmx=xmx, ymn=ymn, ymx=ymx)
windows(width=12,height=12)
par(mfrow=c(1,1))
```

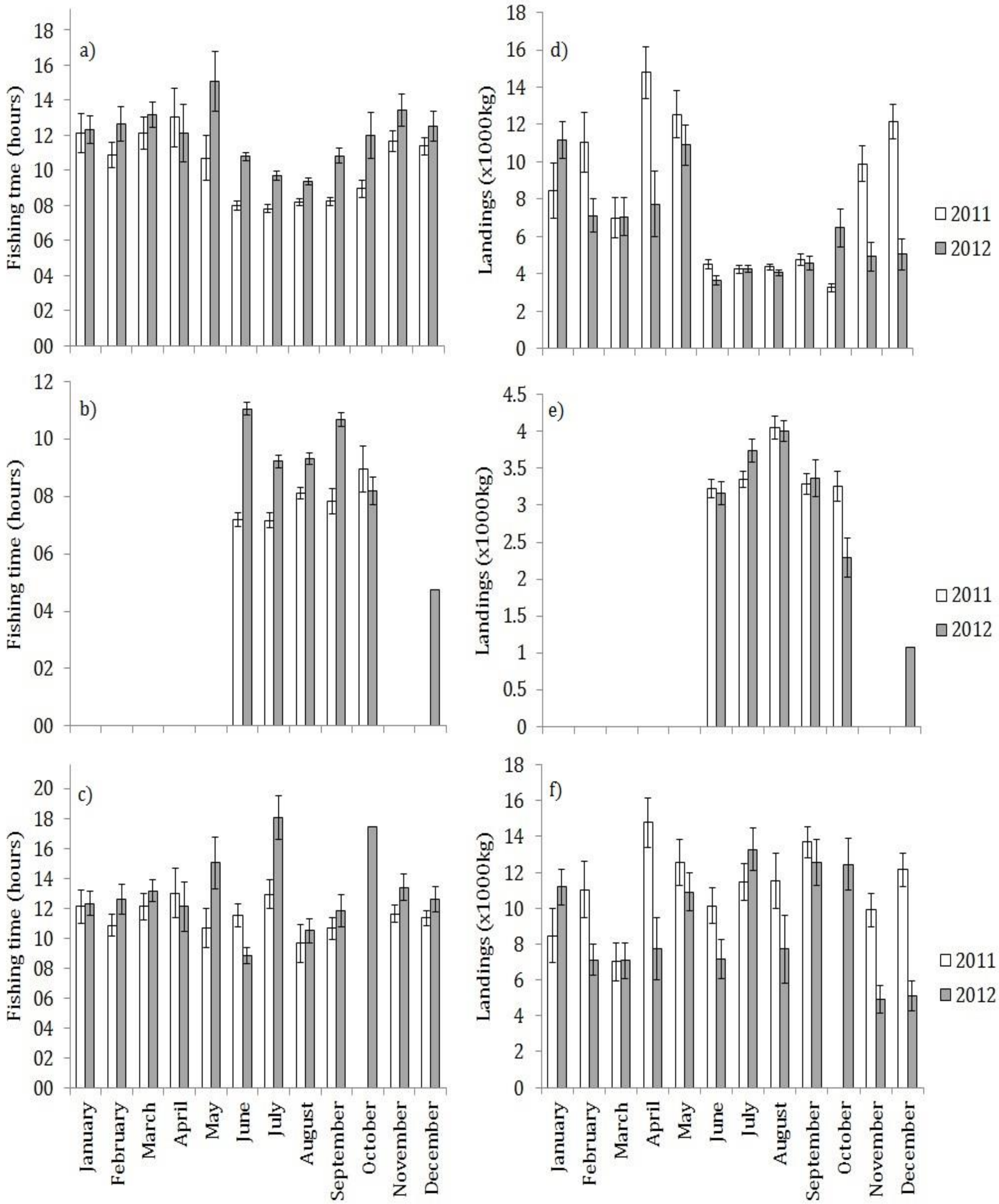
```
# make the rasters
land.raster=rasterize(land, cells,progress='text')

##invert the raster so creeks are 0 and land =1
land.raster[land.raster==1]=0
land.raster[is.na(land.raster)]=1
outline.raster=rasterize(outline, cells,progress='text')
outline.raster[is.na(outline.raster)]=0

# multiply the two rasters to define all passable land excluding outside the study area
land.raster=land.raster*outline.raster
image(land.raster,asp=1)

# create cost surface
tr <- transition(land.raster, mean, directions = 16)

#geocorrection accounting for the fact that the shapefiles have been projected (see "Correcting inter-cell conductance values" segment in the gdistance package vignette)
tr1C <- geoCorrection(tr, type="c", multpl=FALSE, scl=TRUE)
tr2C <- geoCorrection(tr1C, type="r", multpl=FALSE, scl=TRUE)
###read in coordinate data
data<-read.table("C:/Distance from Port Calculations/(Port name).csv",header=T,sep=",")

#create positions dataset for use in the model
positions <- data[,c("Easting", "Northing")]
colnames(positions) <- c("x","y")
coordinates(positions) <- c("x", "y")
#create positions2 dataset (containing Unique IDs for each record) which can then be tied back to output
positions2 <- data[,c("Unique_ID", "Easting", "Northing")]
colnames(positions2) <- c("ID","x","y")
coordinates(positions2) <- c("x", "y")
#remove points that are on land and outside area
positions=positions[extract(x=land.raster,y=positions)==1]
points(positions,pch=19,cex=0.5, col="red")

# define central position to which distance is calculated
(Port name)=SpatialPoints(data.frame(x=297112,y=518358))
points(y~x,data=(Port name),col="yellow",cex=0.5,pch=19)

# calculate distance from points to central point
image(land.raster,asp=1)
output=matrix(ncol=1,nrow=length(positions))

for (counter in 1:length(positions)){

  points(positions[counter,],col="blue",pch=19,cex=0.5)
  if(class(try(shortestPath(x=tr2C, origin==(Port name),goal=positions[counter,], output = "SpatialLines"),silent =F))!="try-error"){
  AtoB=shortestPath(x=tr2C, origin==(Port name),goal=positions[counter,], output = "SpatialLines")
  lines(AtoB, col = "blue", lwd = 2)
  costDist=LineLength(cc=as.matrix(as.data.frame(coordinates(AtoB)[1])),longlat=F, sum=TRUE)
  output[counter,1]=costDist
}}

# tie output back to position2 matches unique IDs to distances using the coordinate data (note as there may be multiple values for the same set of coordinates this may result in duplicate values being generated)
pos_dist <- cbind(as.data.frame(positions),output)
write.table(pos_dist, "pos_dist.txt", row.names=F)
pos <- merge(pos_dist, positions2, by.x=c("x","y"), by.y=c("Easting","Northing"))
```

```
# remove duplicate values of Unique ID
output_joined<-subset(pos,!duplicated(pos[,"Unique_ID"]))

#write to .csv
write.csv(output_joined,"C:/Distance from Port Calculations/(Port name) Output.csv")
```

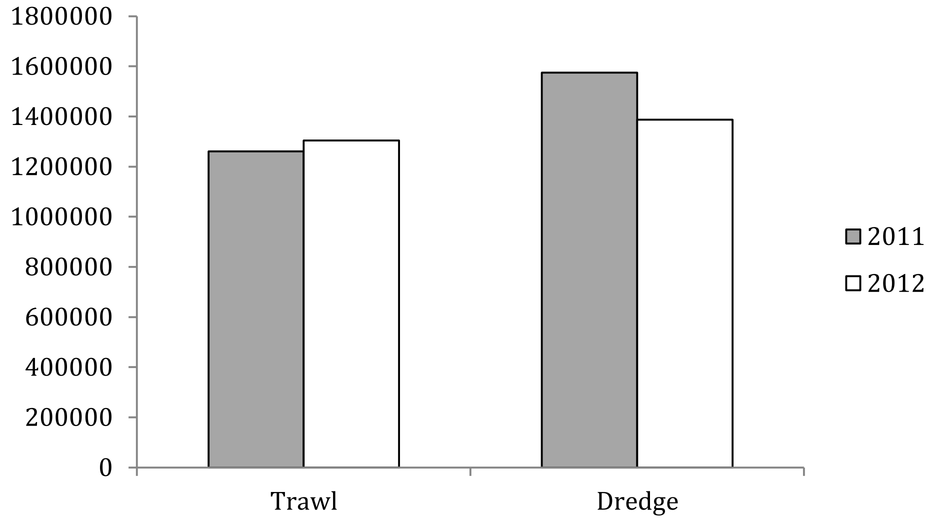
Appendix 1. Monthly total fishing time in hours, in 2011 and 2012, for a) trawls and dredges combined, b) trawls only and c) dredges only and, total monthly landings in tonnes in 2011 and 2012 for d) trawls and dredges combined, e) trawls only and f) dredges only.



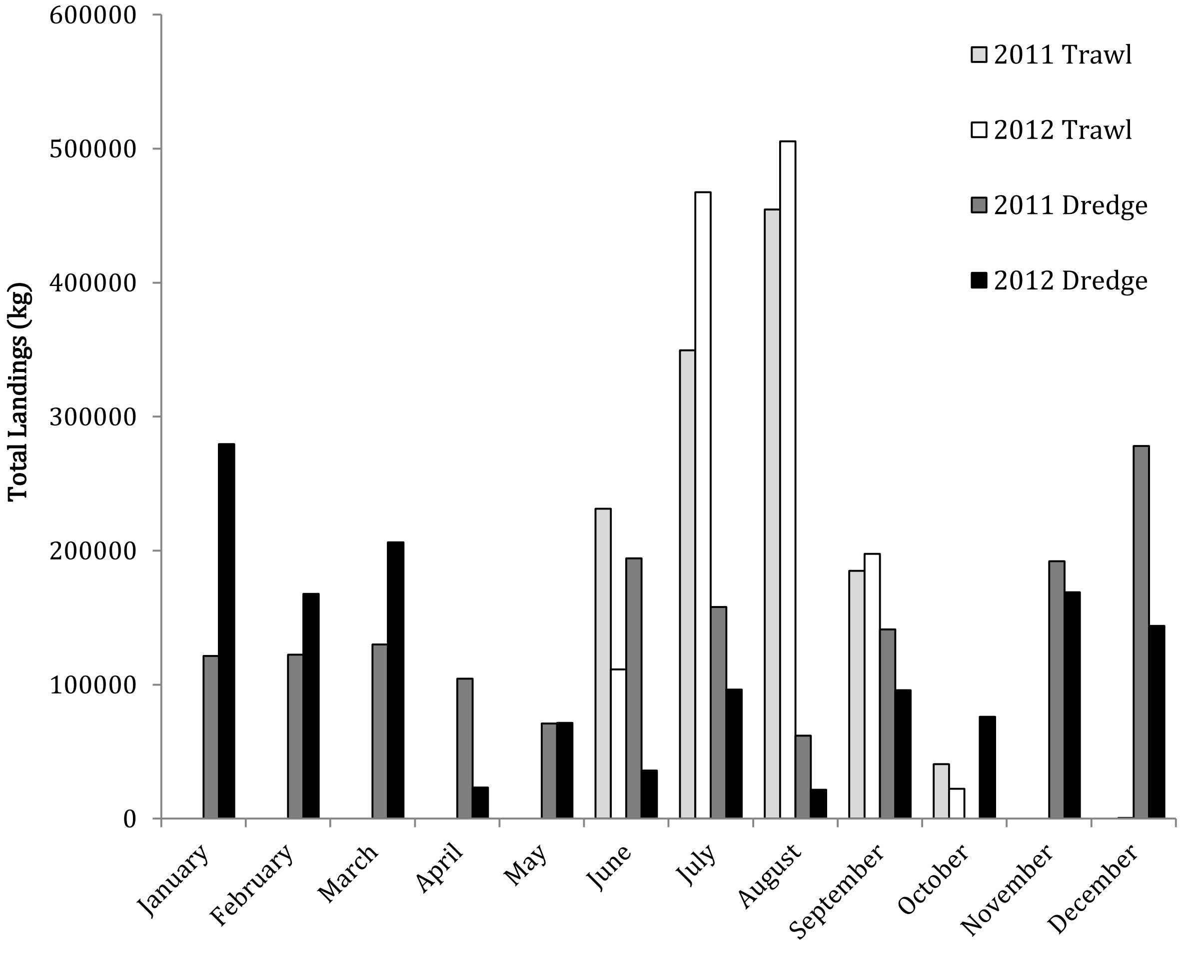
Appendix 2. Monthly average fishing time per voyage in hours, in 2011 and 2012, for a) trawls and dredges combined, b) trawls only and c) dredges only and, average monthly landings per voyage in tonnes in 2011 and 2012 for d) trawls and dredges combined, e) trawls only and f) dredges only. Error bars show ±1SD.



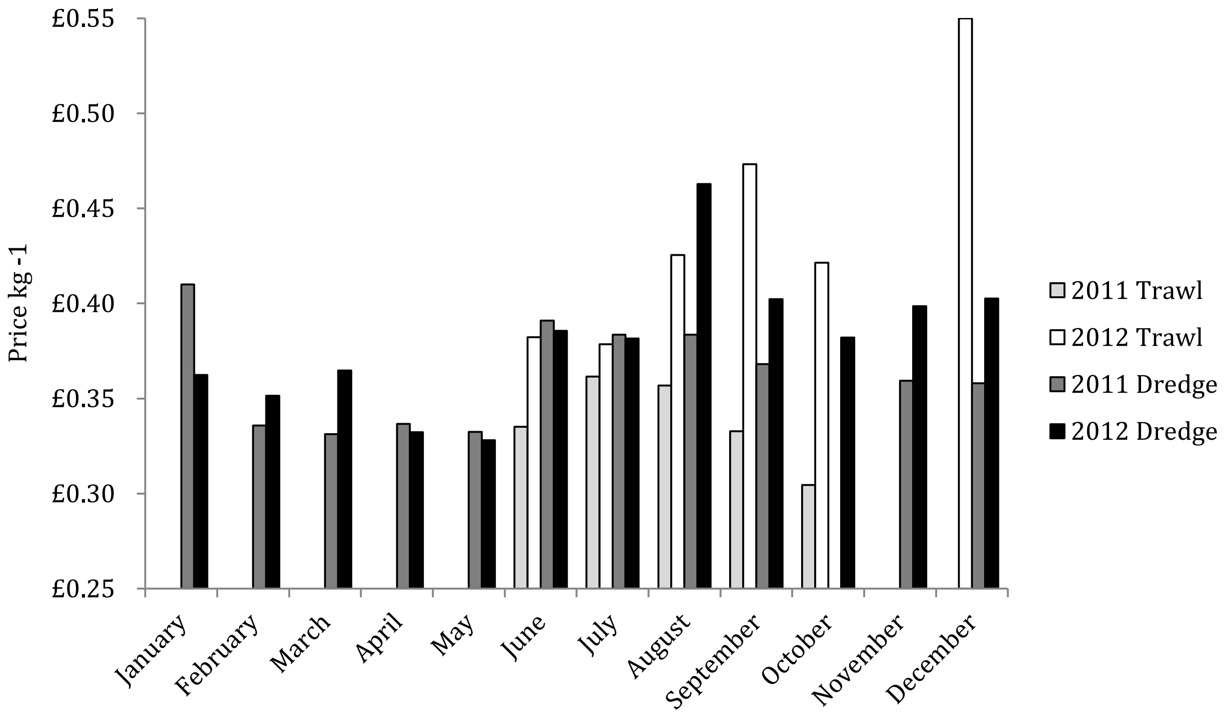
Appendix 3. Total landings, in 2011 and 2012, of Queen scallops from ICES statistical rectangles 38E5, 37E5 and 36E5, arising from trawls and dredges.



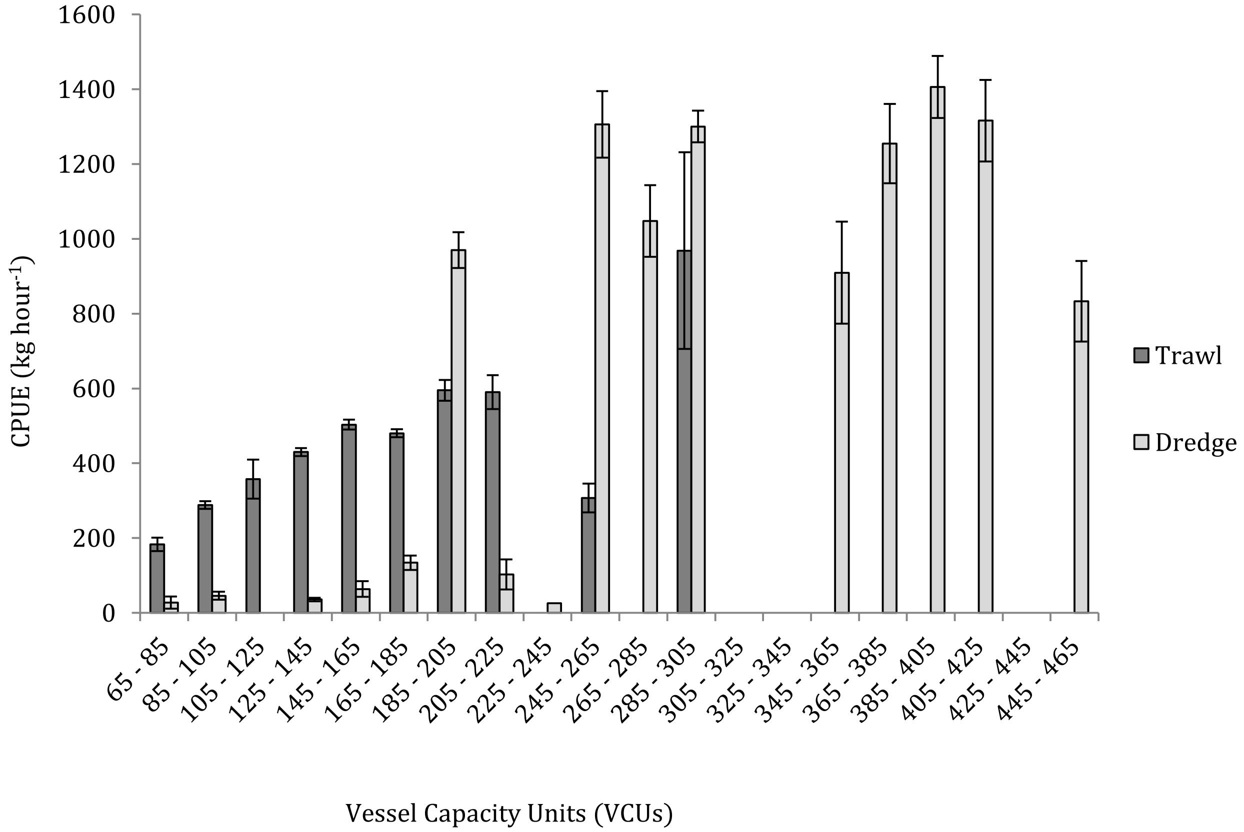
Appendix 4. 2011 and 2012 total monthly landings in kilogrammes of live weight, of Queen Scallops from both trawlers and dredgers, for ICES statistical rectangles 38E5, 37E5 and 36E5.



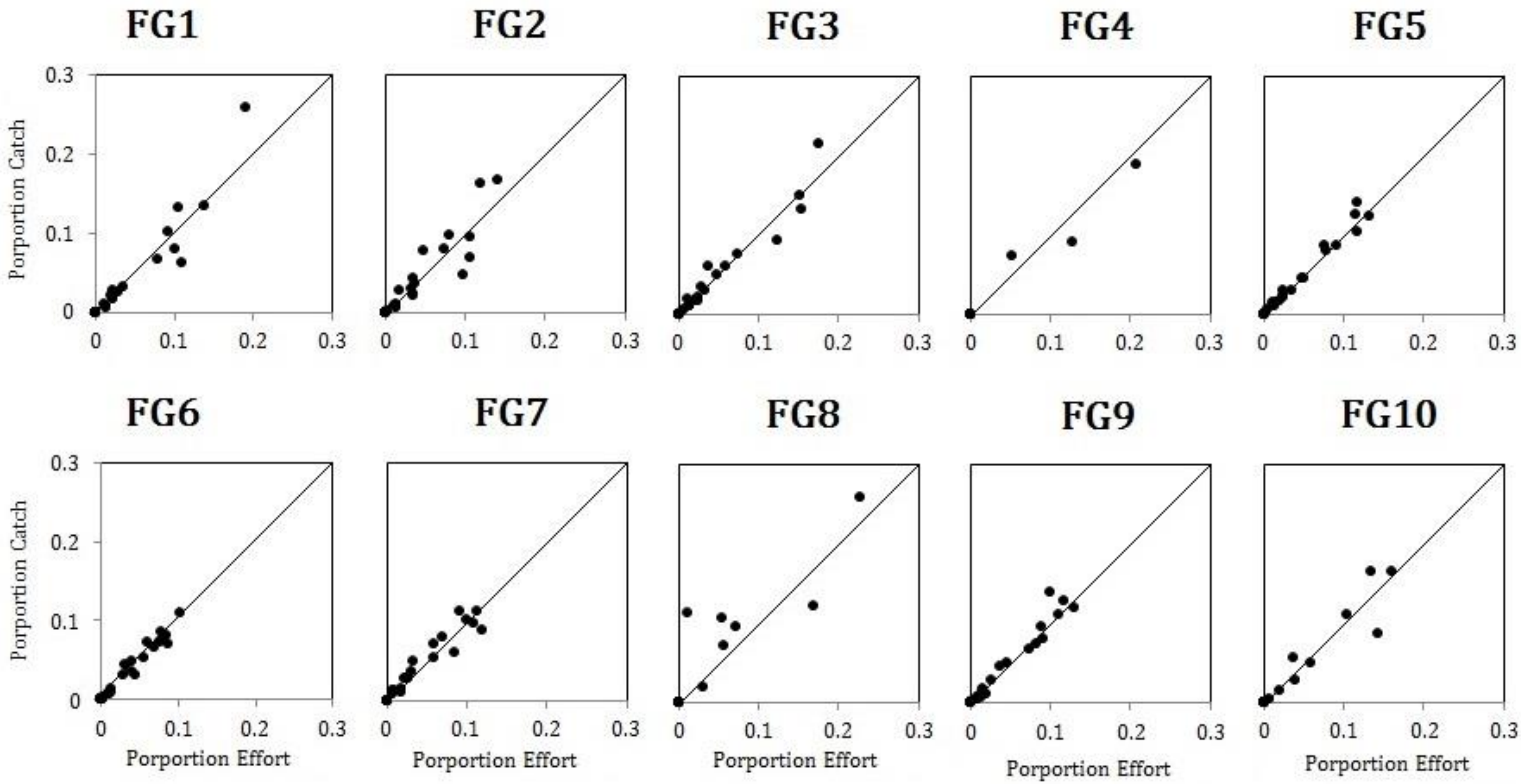
Appendix 5. Average monthly price per kilogramme calculated from logbook entries, from 2011 and 2012, for Queen Scallops landed into both Isle of Man and UK ports by trawlers and dredgers from ICES statistical rectangles 38E5, 37E5 and 36E5.



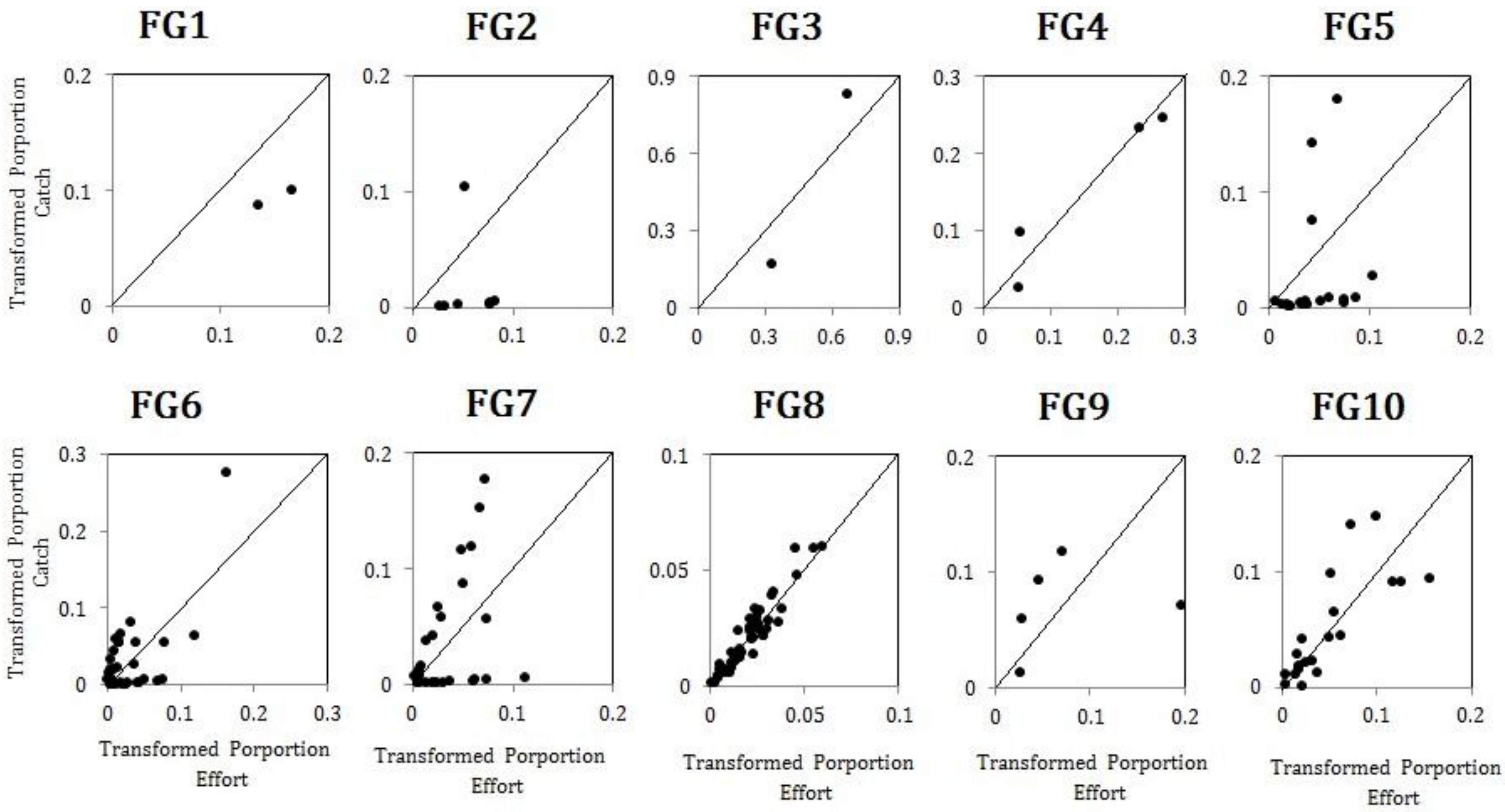
Appendix 6. Average CPUE for vessels within Vessel Capacity Unit (VCU) classes for both trawlers and dredgers averaged over 2011 and 2012. Error bars show ±1SD



Appendix 7. Portportions of effort and catch, for trawls, observed across the ten fishing grounds in 2011 and 2012. All porportions were calculated on the basis of weekly summaries. The diagonal line represents the 1:1 prediction of Ideal Free Distribution.



Appendix 8. Portportions of effort and catch, for dredges, observed across the ten fishing grounds in 2011 and 2012. All porportions were calculated on the basis of weekly summaries. The diagonal line represents the 1:1 prediction of Ideal Free Distribution.



Appendix 9. Table of model names, models used, the Akaike information criterion and GCV scores generated and the deviance explained by each model.

Model Name	Model	AIC	GCV	Deviance Explained	
Model 1	$CPUE_{tot}$ ~ s(trip distance) + s(VCUs, by = trawl/dredge) + s(days since, by = year) + fish ground	35878.78	0.41103	50.0%	
Model 2	$CPUE_{tot}$ ~ s(trip distance) + s(VCUs, by = trawl/dredge) + s(month, by=year)	35861.91	0.40873	50.3%	
Model 3	$CPUE_{tot}$ ~ s(trip distance, by = year) + s(VCUs, by = trawl/dredge) + s(month, by = year) + fishing ground	35845.3	0.40646	50.6%	
Model 4	Fishing time ~ s(trip distance) + s(month no) + s(VCUs, by = trawl/dredge) + s($CPUE_{VMS.fish}$) + s(days/since, by = year) + vessel	-3337.649	0.24557	49.9%	
Model 5	Fishing time ~ s(trip distance) + s(month.no) + s(VCUs, by = trawl/dredge) + s($CPUE_{VMS.fish}$) + s(days since, by = year) + vessel + departure port	-3347.834	0.13372	50.2%	
Model 6	$CPUE_{VMS.fish}$ ~ s(days since, by = year) + s(trip distance, by = year) + s(VCUs,) + s(fishing ground) + year	12423.77	0.68578	65.9%	Dredge
		25117.93	0.20505	32.7%	Trawl
Model 7	$CPUE_{VMS.fish}$ ~ s(days since, by = year) + s(trip distance, by = year) + s(VCUs,) + s(fishing ground) + year + vessel + departure port	12405.15	0.67293	66.6%	Dredge
		23029.79	0.1737	33.0%	Trawl
Model 8	Distance departure ~ s(VCUs, by = trawl/dredge) + s(month.no, by = year) + fishing ground + vessel	23255.48	0.33797	44.2%	
Model 9	Distance departure ~ s(VCUs, by = trawl/dredge) + s(month.no, by = year) + fish ground + vessel + depart port	22282.46	0.2418	60.1%	

Appendix 10. List of parameters used in the Models 1 to 9 (see Appendix 9).

$CPUE_{VMS.fish}$ = Catch per Unit Effort calculated from VMS and logbook data using only fishing time

$CPUE_{VMS.tot}$ = Catch per Unit Effort calculated from VMS and logbook data using total time

days since = days from the start of the relevant fishing season

departure port = the port form which the vessel departed on a particular fishing trip

distance = maximal distance from the port of departure for a particular fishing trip,

fishing ground = the fishing ground in which the fishing activity took place

fishing time = amount of time in hours spent by the vessel at between 1 and 4 knots

month = month

trawl/dredge = fishing gear type,

trip distance = distance from departure port to the most distant VMS record + distance from that VMS record to the landing port in kilometres

vessel = a unique vessel identifier

Vessel Capacity Units (VCUs) calculated as: (Length overall (LOA) x Beam) + (Engine Power (kWh)x 0.45))

year = year of fishing record

‘s’ denotes isotropic smooths.