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Tagging study to determine mortality sources on cod in the Irish Sea

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1 INTRODUCTION

Recently there has been progress toward improving exploitation rates on fish stocks through EU regulations and fishery management policy. However, some stocks have not responded as expected to management action and their conservation status remains a concern. For such stocks a better understanding of the interaction between fisheries, the ecosystem and the environment is needed. Cod (*Gadus morhua*) in the Irish Sea (ICES Division 7a) is an example of such a stock with a fundamental need to better understand the factors that have an influence on the population dynamics. The EASME project "Report of a tagging study to determine mortality sources on cod in the Irish Sea (EASME/EMFF/2015/010)" provided this opportunity.

In an effort to recover the Irish Sea cod stock, management measures have been implemented since 2000 through a series of EU regulations. These recovery measures initially focused on protecting the spawning aggregations of cod implementing a closed area for cod from mid-February to end of April in the Western Irish Sea (Commission Regulation (EC) No 304/2000). This was followed by a series of EU regulated management plans, which introduced numerous technical conservation measures, effort limitations and a 25% year on year reduction in Total Allow Catch (TAC). Between 2003 and 2018 ICES advised a zero catch for cod in the Irish Sea.

Despite the implementation of conservation and various cod avoidance measures the stock showed little or no response, raising questions about unaccounted causes of mortality to cod in the study region. Three forms of mortality have been assumed to impact this stock: natural mortality, fishing mortality and unaccounted mortality. While natural mortality was assumed to be constant and fishing mortality had been reduced, the remaining unaccounted (or unexplained) mortality resulted in high uncertainty associated with estimated total mortality values from the stock assessment and scientific advice. Unexplained mortality increased to more than 10 times that of the observed mortality (i.e., commercial catch and constant natural mortality), which severely hampered the ability to forecast stock development as well as the evidence-based management of the stock.

During 2003 – 2016 a divergence in the perception of the state of the stock between the scientific assessment and fishing industry developed (ICES 2016). This was exacerbated by the assessment showing continued high total mortality and assumed fishing pressure, despite reduced effort targeting cod and technical measures to reduce bycatch (ICES 2016). These measures on cod resulted in the significantly reduced fishing effort targeting gadoid species in the Irish Sea (STECF 2018).

A number of initiatives have been established to address this with policy, industry and scientific stakeholders in particular the WKIrish ICES workshop series (ICES 2016, ICES 2017a). The project reported on here has a central role in improving the understanding of cod population dynamics in the Irish Sea with a focus on accounting for all sources of mortality and addressing these. Cod recruitment in the Irish Sea has been severely impeded since the late 1990s and with the lowest observed value in 2016. Higher recruitment was observed however, in 2009 and 2013. These stronger recruitments which led to growth in the stock suggest that under positive environmental conditions there remains potential in the stock to produce higher recruitment resulting in population growth (ICES 2018a).

The development of a new assessment model was completed in 2017 (ICES 2017a). In 2017, the spawning-stock biomass (SSB) was assessed to have surpassed B_{lim} (stock size below which there is a high risk of reduced recruitment) for the first time since the early 1990s, leading to non-zero catch advice from the 2017 and 2018 ICES assessments. Despite the assessments showing reduced fishing mortality, there is little evidence of improvement in the age structure with a paucity of fish 5-years and older in survey datasets and commercial catches (ICES 2018). The assessment also shows a year on year downward revision of the SSB estimate, suggesting the stock growth forecast is over optimistic, as a result of some degree of mortality, or removal from the stock, being missed. This study will aid in explaining the uncertainty in the SSB estimates by examining cod behaviour and mortality patterns.

The current tagging study ultimately aims to investigate and better understand the unaccounted mortality of mature fish and so aid in the assessment and management of the stock. From a management perspective, stock structure needs to be understood as well as the range of movement / migration. Species that exhibit significant mixing post spawning can be subject to high levels of exploitation if spatial ecology, migration and home range are not considered (Neat *et al*., 2014). The ICES Benchmark Workshop series (WKIrish) which aimed to provide ecosystem-based advice for the Irish Sea ecosystem, noted that there was a requirement to improve our understanding of the level of migration of mature fish north and south out of the Irish Sea (ICES 2015).

Our current understanding of cod movements in the Irish Sea and adjoining areas relies on tagging studies pre-2011 (Bedford 1966, Bendell and Randall 2011, Bendell et al., 2009, Neat *et al*., 2014). The current project (a mark-recapture tagging project conducted throughout the Irish Sea from March 2016 to December 2018) is a more comprehensive and temporally focused baseline study for the Irish Sea stock, than previous tagging studies of the region. Initial development of the tagging programme was achieved by reviewing the known the spatial and temporal occurrence of cod in the Irish Sea to inform sampling design. Methods of tagging were reviewed and the most appropriate method selected to achieve the project aims. A review of mark-recapture analysis was undertaken to identify the analytical methods available to address the project objectives. The first phase of tagging included a review of the study design, post-mortem examination of recaptured cod, addressed wider dissemination of project information and altered the reward scheme in an attempt to increase recapture reporting. The analysis of the mark-recapture results has been completed on the current recapture results to explore distribution and movements of tagged fish, improve understanding of Irish Sea cod biology and inform management through exploration of the implications on the stock assessment of the observed movements. The results of the project have been presented in the ICES Working Group on the Celtic Seas Ecoregion (WGCSE), the ICES Workshop on the Impact of Ecosystem and Environmental Drivers on Irish Sea Fisheries Management (WKIrish5) and in 2019 at the ICES Benchmark Workshop on Celtic Sea Stocks for consideration in the stock assessment model of cod in 7e-k (Celtic Sea cod).

2 METHODS

To achieve the overall project objectives the project was separated into four work packages, each of the work package outputs is reviewed below:

Work package 1 Development of a tagging programme – A review of tagging methods appropriate for cod was carried out along with review of pre-existing work, development of a tagging plan, tagging methods and outlining the communication and outreach material.

Work package 2. The tagging campaign – This was planned as adaptive 3 year programme of conventional tagging in the Irish Sea and neighbouring areas by a means of dedicated tagging effort and also taking advantage of the extensive existing and ongoing fisheries observer and research vessel survey programmes. Tagging effort was planned for years 1 (2016) and the first quarter of year 2 (2017) to allow time for recaptures and data analysis.

Work package 3. Data analysis – Fish mark-recapture data was analysed to explore:

- Cod movements and migration patterns in the Irish Sea and neighbouring areas.
- The extent of mixing between populations of cod in the Irish Sea and neighbouring areas, specifically the Clyde area and the North Channel, and determine the southern boundary of the stock as it is necessary to determine if mixing occurs with the west of Scotland and Celtic Sea stocks, as described by ICES.
- The influence of environmental or other factors and parameters in the cod movements and migration patterns.
- Cod growth and population structure of the stock resident in the Irish Sea.
- Fishing mortality of the cod stock in the Irish Sea and potentially for other gadoid stocks in the area, and identify the importance of this information for the assessment of the stock.

Work package 4. Management advice; within this work package the project set out to determine, as far as possible, the sources of mortality for Irish Sea cod, identify important information (such as migration and changes in stock dynamics) and include these objectively within the stock assessment and implication for future management. This was achieved by independent research and through contribution to the routine ICES stock assessment process, benchmarks and workshops.

2.1 Work package 1: Development of a tagging programme

Typically tagging studies create – by marking them – a subset of animals within their population that are known and can be identified by their tags or marks. Following a period of time allowing this marked subset of animals to mix with the rest of the population, their progress is then followed by means of their recapture and reporting, in both space and time to provide information that can be associated with the entire population.

2.1.1 Review of tagging methods

Conventional tagging studies have utilised an array of methodologies to provide information on aspects of fish biology and behaviour. These methods rely on marking and recapture events and have become common since the mid-17th century with a mark-recapture method first used for ecological study in 1896 by Petersen to estimate plaice (*Platichthys platessa*) populations (Petersen 1896). Over time the methods and application of mark-recapture studies have evolved. Initially the technique was used to estimate abundance, developing into a method to assess survivability and sources of mortality and more recently explore species behaviour (Pine *et al.,* 2011). The ability to achieve these applications is linked to advances in tagging technology, with available tagging now ranging from conventional passive non-permanent ink-marks, non-digital plastic tags, micro coded wire tags, to new electronic tagging methods such as radio-frequency identification (RFID) tags and tags recording and storing environmental and positional data such as data storage tags (DSTs) and satellite tags, providing real time behavioural data (Thorstad *et al.,* 2013). In some instances chemical markers using methods such as radiochemical dating or marking with calcium-binding chemicals oxytetracycline, alizarin, or calcein are appropriate, where large numbers of individuals can be tagged and ageing and growth is a focus of the study, as such techniques laydown a marker in the skeletal component used in ageing.

External marker or ID tags are simple plastic tags that are used to identify a fish upon capture and release, and again upon recapture. The use of such external tags for identifying individuals or groups of fish is the oldest recorded and most widely used technique within fisheries research. The justification for any type of tag on a fish is the future recovery or recapture and the adjoining information gleaned. The more advanced external tags can now carry more information on individual fish released than just an ID code, such as the organisation undertaking the study, reporting instructions and information on tag rewards and in a range of colours. Extensive literature on external marker or ID tags used within fisheries research is readily available in reviews such as Parker et al., (1990), McFarlane et al., (1990); Nielsen (1992) and Thorsteinsson (2002) (http://www.hafro.is/catag). New types of tag are continuously being developed to deal with conflicts arising from information requirements on the one hand and practical application (permanency, identifiable, recognisable, effects on fish behaviour, etc.) on the other. The best known examples of external tags used within commercial fisheries research are Petersen discs (Petersen, 1896), Carlin tags (Carlin, 1955), flag tags (Jakobsson, 1970), anchor tags (Jones, 1976, 1979), and the modifications from these (

Figure 1).

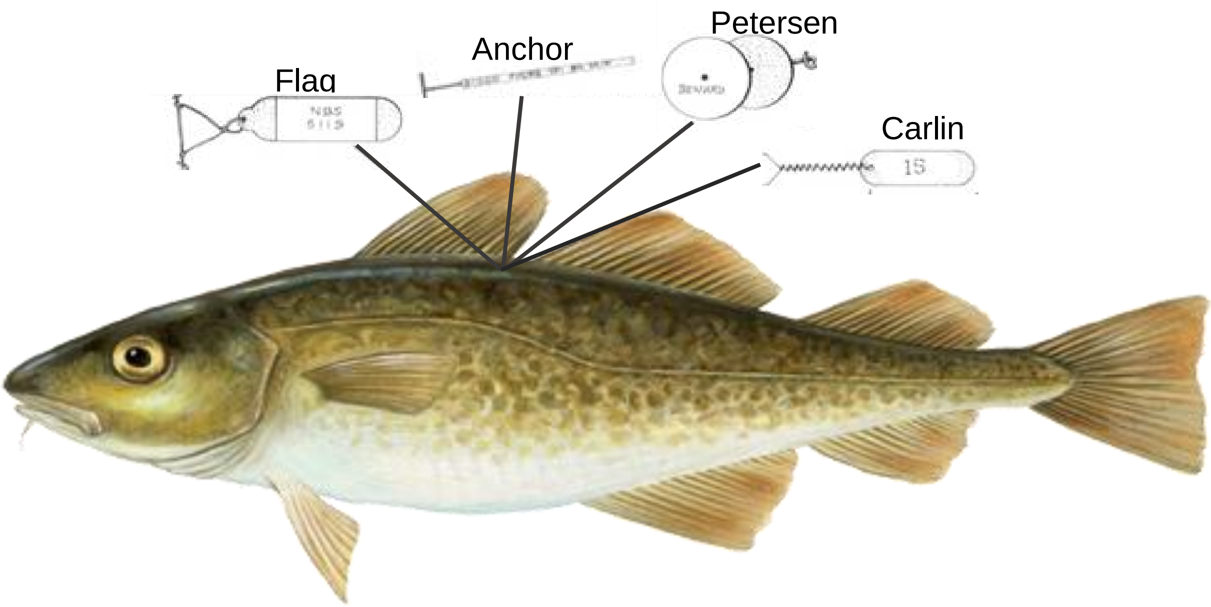

Figure 1. Examples of common external tags used and attachment site (all within dorsal muscle; adapted from McFarlane et al., 1990).

The Petersen disc was one of the first tag types used to study fish populations and is still commonly used today. Although tag construction has changed from different types of material and less expensive the application and design of the tag have remained unchanged. Petersen tagging involves securing two plastic discs either side of the fish under the dorsal fin through the muscle using a wire pin and pliers. The sharpened end of the attachment wire is used to pierce through the dorsal muscular tissue, with the open end of the titanium wire crimped or twisted closed to keep the circular plastic discs at either side of the dorsal muscle, in place. A sufficient gap is left to allow for growth, but not excess movement which can lead to shedding.

Petersen discs have been used widely in previous tagging studies on cod (Trout 1958; Cogswell 1961; Fowler *et al*., 1991). Disadvantages of using Petersen discs is that the flat discs can become fouled with algae and encrusting shellfish. The attaching wire is also fixed and inflexible, which can result in restriction of dorsal muscle growth if fixed too tightly. Application time for this method can also be long due to having to curl and fix the wire pin on either side of the fish.

Carlin disc tags are essentially an anchored spaghetti tag which carries an individual identification disc of the fish and reporting instructions. Carlin tags are very common in monitoring and research work and the most popular spaghetti tag type used in United States fisheries research for over 100 years, predominantly used on salmonid species (Miller *et al*., 2012). A smaller version of the tag is the fingerling tag which has been developed to use on small and juvenile fish. Easy to apply the Carlin tag and requires few tools. The Carlin tag consists of a plastic disc attached to the fish body with stainless steel wire or polythene thread. Between the attachment to the fish and the disc there is an intermediate link which allows tagging of younger fish for visual recapture as adults.

Traditionally made of soft plastic fabric they are now commonly made of PVC plates, shaped as long oval rectangles and called 'flag tags'. The attachment is usually with nylon twine inserted directly through the dorsal musculature of the fish with a curved needle and secured off as a loop allowing the flag to trail behind the dorsal fin. These tags have been used widely on cod within North Sea, English Channel, Irish and Celtic Seas (Bedford 1966; Righton & Metcalfe 2002; Burt *et al*., 2006; Righton *et al*., 2007; Bendall *et al*., 2009), and are not prone to shedding, with exceptional retention rates. However, this approach can make fish prone to infection due to the nature of attachment.

Modern versions of anchor tags such as the Floy t-bar tag are probably the most common tags in use today due to their ease of attachment and are highly applicable for studies on cod (O'Cuaig & Officer 2007; Bendall & Randall, 2011). The t-bar tags are attached to the fish by a nylon monofilament with a T-shaped anchor. The tags are inserted with a tagging gun which can be loaded with just one tag or a clip of a numerical series of tags, making the tagging of individuals or hundreds of organisms quick and easy (Figure 2). Site of attachment is mostly at the base of a dorsal fin. To ensure long-term tag retention, it is important that anchor tags are inserted inward at an angle next to the dorsal fin to penetrate deep enough into the fish that the t-bar interlocks with the skeletal fin rays, and that the tag streamer lies alongside the fish when it swims. The tag itself is most often a cylindrical plastic tube in various colours with an identification code and return instructions written on to it. Due to the ease of attachment tag shedding can prove a problem, therefore double tagging is common practice with these tags to obtain data to estimate tag shedding rates.

More recently, conventional tagging methods have been complemented by electronic tags, such as data storage tags (DST), that can have a variety of sensors; temperature, depth, light, salinity, pressure, pitch and roll, GPS, magnetic and compass. Data collected by DSTs can be used to infer locations of the animal by interrogation of logged data against know environmental parameters - such as recreating movement paths using depth and temperature profiles. The tags can required surgical implantation or where the animal is sufficiently large can be externally attached. DSTs can provide high frequency data, which is particularly useful to monitor movement paths. However, given the special attachment methods the numbers of animals that can be tagged during a single event is much lower than traditional tagging studies.

Figure 2. T-bar anchor tag gun being inserted into the dorsal musculature of a mature cod. (b) Mature cod double-tagged with external t-bar anchor tags (Bendall & Randall 2011).

Following the review of conventional tagging methods to tag gadoids, anchor tags were selected as the most appropriate tagging method to meet the required scale of the tagging programme and objectives for this study. This tagging method was selected owing to the ease of attachment and applicability. Anchor tags were ideally suited to high frequency tagging with low recapture rates. Modern versions of anchor tags such as the Floy t-bar tag are probably the most common tags in use globally today due to their ease of attachment and they are highly applicable for studies on cod (O'Cuaig & Officer 2007; Bendall & Randall, 2011). The tags can be quickly inserted making the tagging of individuals or hundreds of organisms quick and easy. Given that the current study intended to use a range of platforms to tag cod, anchor tags had the added advantage of ease of training for volunteers and minimal expense investment for tagging equipment. In comparison to electronic DST tagging, it was estimated that more than 150 times the number of animals could be tagged for the same cost of tags and 20 times the number of cod could be tagged in the same amount of time as compared to surgically implanting a DST into a cod. Despite these electronic tagging methods being more costly, it was not within the remit of this study.

2.1.2 Tag loss rates

Tag loss may occur with two forms of tag loss from the population considered critical to providing unbiased assessments of stock status. Tagging mortality, the death of a released fish resulting from the capture and tagging process, can bias the assessment as more tags are assumed to be present in the population for recapture than are actually present. Similarly, tag loss from fish after they are tagged (shedding of tags) causes a similar population over-estimation bias. Tag loss during the time at liberty was addressed by Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR; Ziegler 2013) and by Ó'Cuaig and Officer (2007) by the use of double tags. In the current study anchor tags were attached to the left body, at the front and back of the dorsal fin prior to release. Marker tags may vary slightly in terms of tag retention/shedding, biofouling, infection risk, reporting rate, and so some individuals may be double tagged to provide information on this. The rate of loss of a single tag was used to predict double tag loss rates.

2.1.3 Post tagging mortality

Studies investigating tagging mortality in cod tagged with t-bar anchor tags found the overall mortality to be low for both commercial (e.g., Brattey & Cadigan 2004) and recreational (e.g., Weltersbach & Strehlow 2013) caught cod. These studies showed that high survival of post tagging mortality is associated with colder water temperature, shallow capture depths (<180 m) and no visible physical damage. Brattey & Cadigan (2004) noted that the general applicability of their results to other cod tagging studies depends largely on field staff applying consistent methods to select only undamaged, healthy specimens from the catch as well as recognizing when fish are stressed and avoiding tagging at such times. They estimated that the selection of only undamaged healthy fish for tagging can result in substantial numbers of discards from individual catches, typically 5–20% from hand-line catches, mostly due to hook damage and bloating, and as much as 80% from trawl catches. Brattey & Cadigan 2004 specifically advised that the temptation to increase the number of released by tagging fish whose condition is poor should be avoided.

The tagging methodology applied to this study was in line with these previous findings, i.e., focus on fish condition, advised fishing methodology and environmental conditions at the time of capture. This resulted in substantial discards, with 100% discards of some trawl catches during the study, and resulted in much lower than predicted tagging numbers.

Evidence of post tagging mortality rates were assessed at the time of tagging with only undamaged, active fish marked and returned. Retaining fish in tanks on the vessels in controlled conditions was used to determine size based mortality rates. Some post-tagging mortality is a reality of any tagging study, however, using the experience from previous successful tagging studies, every effort was made during the current study to reduce the probability of fish death after tagging. This was to maximize the survival of tagged fish, to ensure the accuracy of reporting of tagging numbers and to increase the potential for good recapture rates. With the focus on fish selection, field experiments to hold tagged fish for prolonged periods of time (~2 hours) showed zero short-term post tagging mortality.

The results of post mortem examination of recaptured fish were discussed with regard to evidence to support the appropriateness of the tagging procedure to ensure viability of the method. All recaptures throughout the project were examined to ensure quality was maintained. For all recaptured tagged fish there was no evidence of mal-effect of tagging. Re-growth of skin around tagging sites, absence of abscess, blood spots and no evidence of necrosis was observed. This evidence supported the view that the tagging protocol was effective.

2.1.4 Study power

A power analysis of the current study to show inter-stock area movements between the Irish Sea and Celtic Sea stock areas was performed. The analysis was performed assuming classical levels of statistical significance (p <0.05) and with a range of effect sizes (small – large) and power (low – high). The power analysis was applied assuming a *Chi*-square goodness of fit statistic for a 2x2 contingency analysis (Rodgers and White, 2007), with the null hypothesis of independence between tagging release site (Irish Sea *vs.* Celtic Sea) and recapture site (Irish Sea *vs*. Celtic Sea) (Table 1). The *Chi*-square Test of Independence is a commonly used and accepted statistical method to examine the association between categorical variables (i.e., whether the variables are independent or related). It is a nonparametric test. The power analysis, as applied, examined the ability of the tagging programme to identify if there are statistically different rates of tagging and recapturing of fish moving between the Irish Sea and Celtic Sea. The power analysis was applied as described in Cohen (1988). The method is common place in analysis of animal movements to allow detection between distinct areas or habitats (e.g. Nichols & Kaiser 2005; Linnane 2005; Grovenberg *et al*., 2011). The method, whilst course, provides a broad overview of movements between management areas. The analysis allows an estimate of the sample size required to detect each combination of effect and power to be determined. The results indicated the range of recaptures required from the current study to explore movements between the adjoining areas was between 15 and 1299 recaptures. The power of the analysis is 1 minus the Type II error probability, where the Type II error is the error that occurs when the test fails to reject a null hypothesis. A small effect indicates smaller differences between populations or categorical variables. An effect size of 0.01 indicates that the distribution of scores for the treated group overlaps completely with the distribution of scores for the untreated group, there is 0% of non-overlap. An effect of 0.1 (small) indicates a non-overlap of 7.7% in the two distributions. A large effect (0.8) indicates a non-overlap of 47.4%.

Table 1. Results of power analysis (2 x 2 contingency test).

		Power		
		High (0.95)	Medium (0.75)	Low (0.50)
Effect	Small (0.10)	1299	694	384
	Medium (0.30)	144	77	43
	Large (0.50)	52	28	15

2.1.5 Analysis of pre-existing tagging data

All records of recaptures of Mark ID tagged cod released in ICES areas 6a (Scottish waters), 7a (Irish Sea), 7e (western English Channel) and 7f – 7g (Celtic Sea) were extracted from the Centre for Environment, Fisheries and Aquaculture Science (Cefas), UK 'Tagfish' database (archived data sets from1964 to 2010), Marine Scotland and from Marine Institute, Ireland datasets. The majority of cod tagged in areas 6a, 7a and 7e-g were caught in coastal waters by commercial trawl (heavy otter, mid-water, bottom pair or beam) or Danish anchor siene and purse seine. All cod were measured to the nearest cm and externally tagged with a mark recovery tag attached to the dorsal musculature at the base of the first dorsal fin. Releases took place mostly during autumn and winter (October to March; Quarters 4 & 1), at the sites shown in Figure 3.

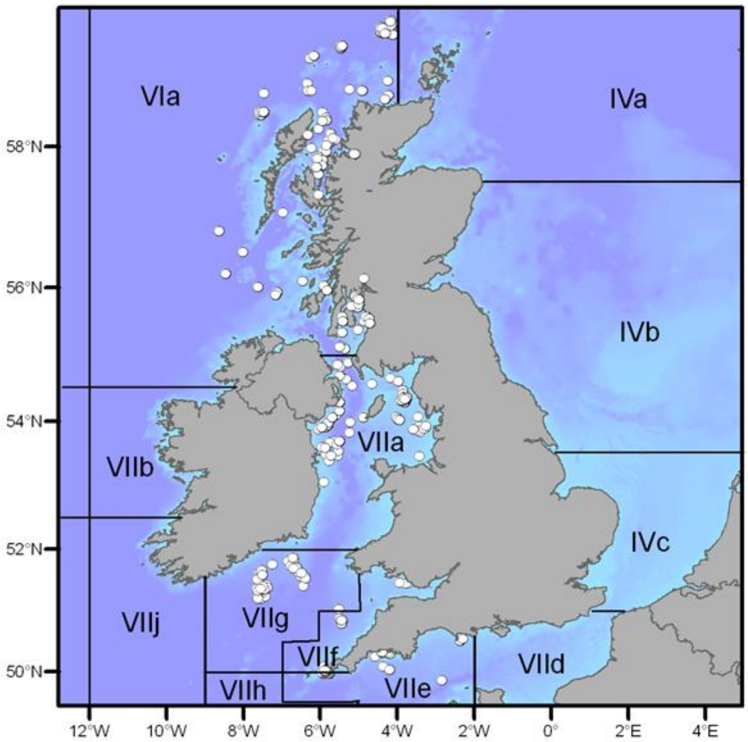

Figure 3. Release positions of Mark ID tagged cod. Release positions (white circles) in ICES sub divisions 6a (6a; West of Scotland), 7a (7a. Irish Sea), 7e (7e western English Channel), and 7f-g (7f-g; Celtic Sea).

In total, release and recapture information for 2209 tagged cod were available (687 in 6a, 1108 in 7a, 141 in 7e, 155 in 7f and 118 released in 7g respectively; Table 2). Release and recapture data for tagged cod spanned mostly the 1970's, 1990's and 2000's. Majority of the mark-recovery data from 6a are from the 1960's and 1970's (54% and 39% respectively). In area 7a (78% of the recaptures) are from tagging in the late 1970's. Data for areas 7e and 7f are mostly from the 1990s (53% of 7e cod and 85% of 7f cod recaptures). All the data for area 7g cod are from tagging in 2007- 2009. It is important to note that the spawning stock biomass of cod in the Irish Sea (area 7a) was around ten times larger in the 1970s than in recent years, whereas the stock in area 7e-k appeared to be less abundant in the 1970s than in the 1990s but have declined in recent years (ICES, 2018a).

Recapture data were sub-divided into quarters of the year according to the recapture season: winter and autumn (Q1 & Q4), spring and summer (Q2 & Q3), (see Bedford, 1966). Recaptures were then placed into size categories dependent on the length of cod at recapture: smaller than 50cm (classed as 'juvenile') or larger than 50 cm (classed as 'adult'). Although the average size and age at maturity in Irish Sea cod has declined since the 1990s (Armstrong *et al*., 2004a), at least 50% of the cod of 50cm and over would have been mature. In the Celtic Sea, first maturity in female cod during 1986-2002 occurred at 50cm whilst around 40% of males were mature at this length (Armstrong *et al*., 2004b).

Recapture positions were plotted in ArcView 9.1 for cod released in ICES area 6a, 7a and 7e-g. The Animal Movement Analysis Extension to Arcview (AMAE: Hooge and Eichenlaub, 2000) was used to estimate of the extent of geographical range for cod in each area by generating kernel probability density function surfaces (KPDF) for 95%, 70% and 50% volume estimates under the three-dimensional

KPDF surface (see Worton, 1987, Seaman and Powell, 1996; Hooge *et al*., 2001). The KPDF method is more typically used in studies of territoriality and home range (Jones, 2005; Righton & Mills, 2006). However, because tag recapture locations are analogous to the density and distribution of the locations of single individuals over time, the technique is extremely applicable to population level mark-recapture data (Righton *et al*., 2007).

Table 2. The number of mark recovery tag recaptures by ICES area of release and seasonal quarter of recapture. Lr and Lc refer to length at release and recapture respectively. Q4 & Q1 are combined to show number of recaptures during the autumn and winter quarters; Q2 & Q3 are combined to show the number of recaptures during the spring and summer quarters.

Area	Lr (cm)	Lc (cm)	Q1	Q2	Q3	Q4	Total	Q4 & Q1 Autumn & Winter	Q2 & Q3 Spring & Summer
4a	<50	<50	7	45	24	51	127	58	69
	<50	>50	12	17	4	3	36	15	21
	>50		132	233	105	54	524	186	338
Total			151	295	133	108	687	259	428
7a	<50	<50	266	61	23	12	362	278	84
	<50	>50	6	5	3	2	16	8	8
	>50		398	234	66	32	730	430	300
Total			670	300	92	46	1108	716	392
7e	<50	<50	16	11	13	14	54	30	24
	<50	>50	19	16	12	10	57	29	28
	>50		1	9	5	15	30	16	14

Table 2 (contd.). The number of mark recovery tag recaptures by ICES area of release and seasonal quarter of recapture. Lr and Lc refer to length at release and recapture respectively. Q4 & Q1 are combined to show number of recaptures during the autumn and winter quarters; Q2 & Q3 are combined to show the number of recaptures during the spring and summer quarters.

Area	Lr (cm)	Lc (cm)	Q1	Q2	Q3	Q4	Total	Q4 & Q1 Autumn & Winter	Q2 & Q3 Spring & Summer
7f	<50	<50	76	8	2	-	86	76	10
	<50	>50	8	13	16	6	43	14	29
	>50		13	7	3	3	26	16	10
Total			97	28	21	9	155	106	49
7g	<50	<50	7	14	2	1	24	8	16
	<50	>50	24	33	14	6	77	30	47
	>50		3	11	-	3	17	6	11
Total			34	58	16	10	118	44	74

The details of Data storage tag (DST) cod releases for each ICES area, by month and year are shown in Table 3. . Individuals were brought slowly to the surface to avoid rupture of the swimbladder and those in good condition were placed into 1000 l deck tanks. Fish suitable for tagging with a DST (length > 45 cm) were then selected. Cod tagged with DSTs were anaesthetised in a shallow (20 cm) bath containing 2-phenoxy-ethanol (0.5ml l-1) before surgically implanting the DST into the peritoneal cavity (details in Righton *et al*., 2006). A spaghetti tag attached to the DST was then placed through the lateral body wall by a curved needle and a conventional tag was attached to the dorsal musculature at the base of the first dorsal fin to act as external identification markers (Righton *et al*., 2006). All fish were placed into a recovery tank before release. In order to encourage the reporting of recaptured tags a reward scheme was set up throughout the commercial fisheries (as for Turner *et al*., 2002; Righton & Metcalfe 2002; Hunter *et al*., 2004; Righton *et al*., 2006 & 2007).

Table 3. Released number and mean length (in cm ±SD) of cod tagged with DSTs by month and year of release in each ICES management area. Numbers are also given for DSTs returned (to date as of January 2012) and tracks successfully reconstructed using the Hidden Markov Model (HMM) for all cod at liberty greater than 10 days.

Area	Year	Month	ICES Rectangle	DSTs	Length	Method of capture	DSTs returned	Cod tracks reconstructed (using HMM)
7a	1999	March	35 & 36 E4	19	64±9	Long line	4	4
	2008	Feb	35 & 36 E4	17	67±6	Mid-water trawl	3	3
	2009	Feb – Mar	35 & 36 E4	80	72±10	Mid-water trawl	18	17
	2010	Mar	36 & 37 E6	44	70±13	Mid-water trawl	9	8
			Total:-	160			34	32

Table 3 (contd.). Released number and mean length (in cm ±SD) of cod tagged with DSTs by month and year of release in each ICES management area. Numbers are also given for DSTs returned (to date as of January 2012) and tracks successfully reconstructed using the Hidden Markov Model (HMM) for all cod at liberty greater than 10 days.

Area	Year	Month	ICES Rectangle	DSTs	Length	Method of capture	DSTs returned	Cod tracks reconstructed (using HMM)
7e	2007	Jan - Feb & May	29 E5 & 28 E7	169	72±7	Fixed gill net & hook and line	27	17
			Total:-	169			27	17
7f	2004	Mar	31 E5 & 31 E6	13	68±10	Otter trawl	1	1
	2008	May	31 E5 & 31 E6	17	67±9	Otter trawl	1	1
	2010	Mar	30 E4 & 30 E5	60	75±8	Fixed gill net	6	6
			Total:	90			8	8

Table 3 (contd.). Released number and mean length (in cm ±SD) of cod tagged with DSTs by month and year of release in each ICES management area. Numbers are also given for DSTs returned (to date as of January 2012) and tracks successfully reconstructed using the Hidden Markov Model (HMM) for all cod at liberty greater than 10 days.

Area	Year	Month	ICES Rectangle	DSTs	Length	Method of capture	DSTs returned	Cod tracks reconstructed (using HMM)
7g	2008	Mar	31 E2 & 32 E2-3	100	77±9	Seine net	10	5
	2009	Mar	31 E2 & 32 E2-3	141	71±9	Seine net	18	14
	2010	Mar	31 E2 & 32 E2-3	50	69±13	Seine net	10	5
			Total:	291			38	24

2.1.6 Geographic reconstruction of DST cod movements

Hydrostatic (tidal) data, derived from the sinusoidal pressure cycle recorded in the depth data when a fish is at rest on the seafloor, was used to enable the geographical reconstruction of an individual cod's movements (termed geolocation). This method is referred to as the Tidal Location Method (TLM, as described in Metcalfe & Arnold (1997); Hunter *et al*., (2004). We used a novel Fokker-Planck based method that combines the TLM with a hidden Markov model to estimate, for each day at liberty, the non-parametric probability distribution of geographic position (Pedersen *et al*., 2008; Righton *et al*., 2008) for 81 out of 100 DST tagged cod recaptured in ICES areas 7a (west & east), 7e, 7f and 7g.

Daily reconstructed positional data for the 81 cod were grouped and sub-divided into quarters of the year as for mark recovery data. All DST cod were released as 'adults' (>50cm). In total 11,170 daily spatial positions were available (7a (east): 1457 days; 7a (west) 4574 days; 7e 966 days; 7f 1135 days; 7g 2533 days respectively). Positions for 'adult' DST tagged cod were plotted for 7a and 7e-g release areas in ArcView 9.1.

For each DST depth dataset (average duration 121d), daily position likelihood surfaces were generated using the hidden Markov method described in Pedersen *et al*., (2008). The majority of datasets (188 of 213) were analysed without constraining model parameters. The remainder were run under using custom parameters to ensure that sufficient tidal data were extracted from the depth data, and that uncertain position estimates (model error) did not entrain the likelihood surfaces across land or into locations that were not consistent with the tag temperature record, or which did not match the daily point estimates of location. The surfaces were then aggregated by calendar month and normalised. Monthly surfaces were then aggregated by tagging region (southern North Sea, eastern Channel, western Channel, central North Sea, western Irish Sea, eastern Irish Sea, Celtic Sea and Bristol Channel) and renormalized. The surfaces were summed for each quarter before plotting on a standard scale.

2.1.7 Virtual recaptures from DST cod movements

In order to directly compare mark recovery data with DST geolocated data, a single reconstructed DST position per month at liberty was extracted for each individual cod track. This gave a sample of 453 geolocations that could be treated as 'virtual recaptures' and avoid potential bias from over-representation of extended migrations from individual cod.

The number of recaptures by ICES area of release and quarter of recapture are shown in Table 4. . Cod remained at liberty on average for six months after tagging (±11 months), travelling an average distance from release to recapture of 56 km (±83 km). The longest time at liberty was 26 months, by a cod recaptured 25 km away from its original release site in 7a during Q1. The greatest distance travelled was by a cod at liberty for 590 days, recaptured 700 km from original release site in 7e during Q1 within ICES management area of 4b (off coast of Sunderland, UK; 55° 60'N 0° 30'W).

Due to the limited number of returns for cod for 7e – f the recaptures of cod in Q4 & Q1 (autumn & winter) were combined, as were the recaptures for Q2 & Q3 (spring & summer; Table 4.). These sub-divisions correspond very broadly to 'spawning' (Q4 & Q1) and 'feeding' (Q2 & Q3) seasons as given by Wright *et al*., (2006) and Righton *et al*., (2007), where the definition of "spawning season" encompasses gonad maturation, spawning migration and the act of spawning itself.

2.2 Spatial distribution from Mark recovery recaptures

In ICES areas 7a and 7g, cod were generally recaptured further away from the point of release during Q2 & Q3 than during Q4 & Q1. In contrast, for ICES areas 7e and 7f, cod were generally recaptured further away from the point of release during Q4 & Q1 than during Q2 & Q3.

- 6a releases

In 6a releases cod showed restricted dispersal close to the area of their release sites during Q1 & Q4 (**Error! Reference source not found.**) while in Q2 & Q3 showed a much wider dispersal from their release sites into deeper offshore waters predominantly to the north west within 6a and north east into 4a (**Error! Reference source not found.**).

- 7a releases

In 7a releases cod showed highly restricted dispersal close to the area of their release sites during Q1 (

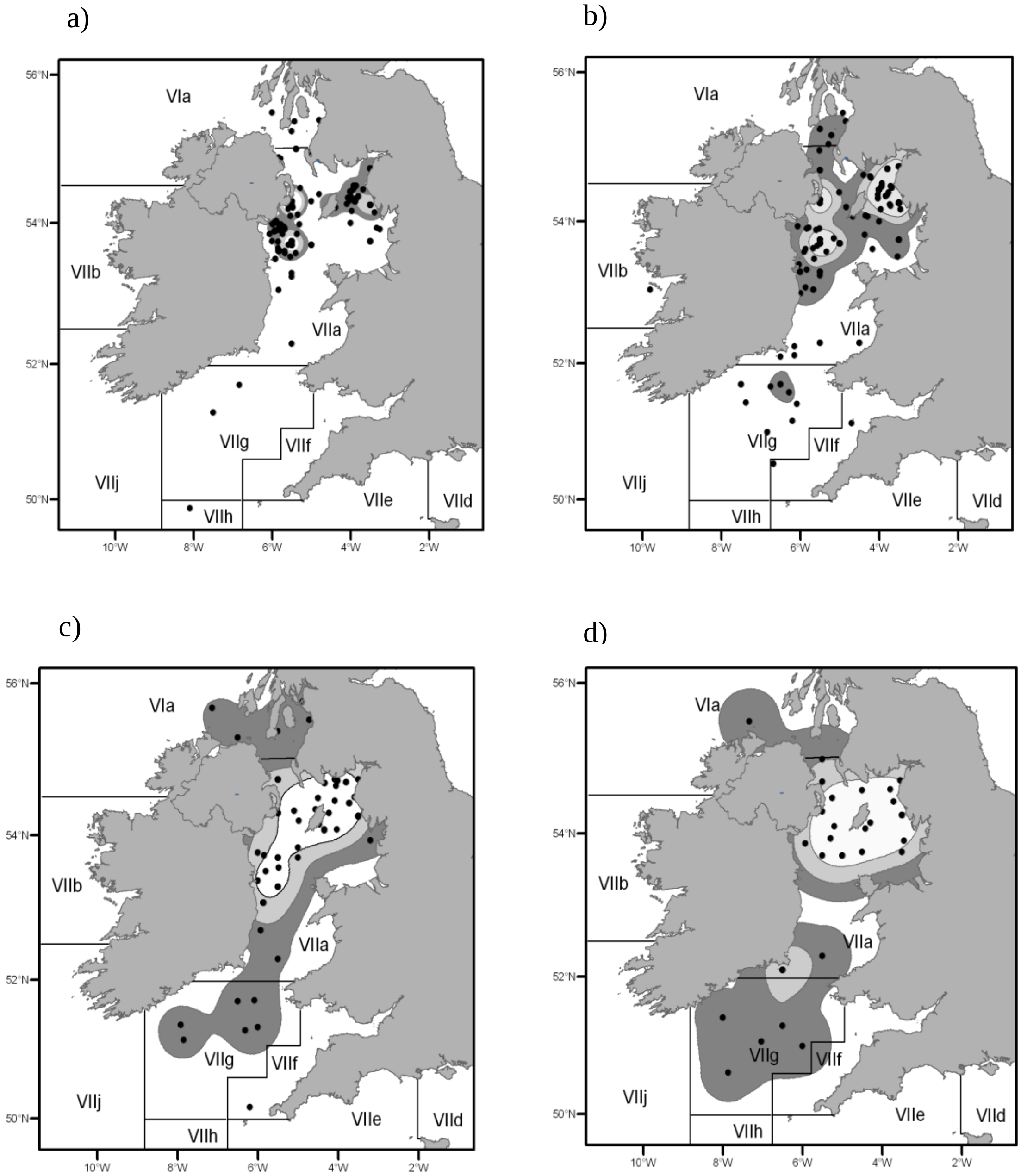

Figure 5), while in Q2, Q3 & Q4 showed a much wider dispersal from their release sites north into 6a and south to the Celtic Sea within 7f-g (

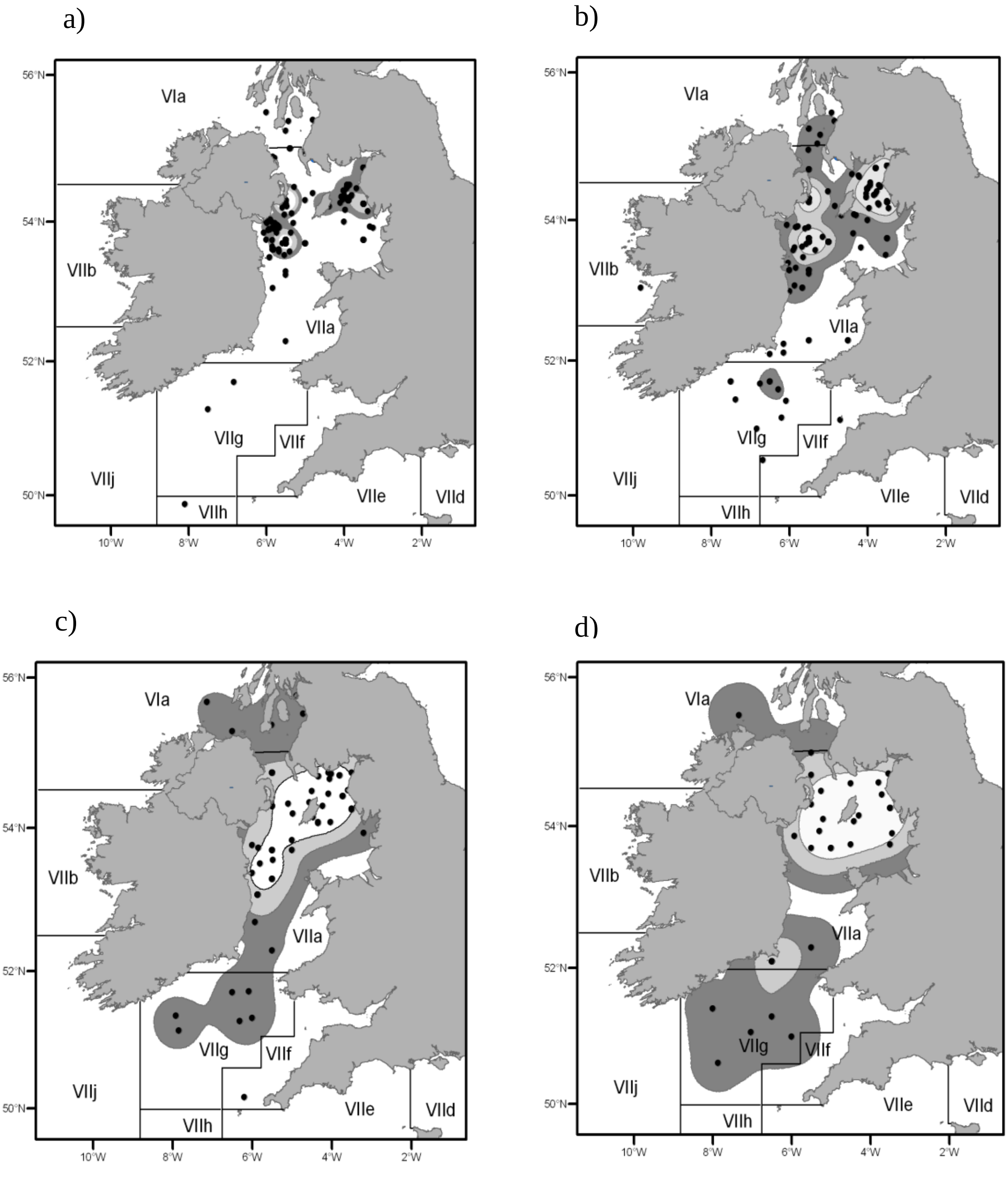

Figure 5).

In relation to site fidelity over time; majority of cod recaptures were within the same year of release (52% during Q1&4; 78% during Q2 & Q3), however 48% of cod recaptures during Q1 & Q4 compared to 22% of cod recaptures during Q2 & Q3 were of cod released within the same season but recaptured the following year (or more) after release.

- 7e releases

In 7e cod were widely dispersed from their release sites over Q1 & Q4 (

Figure 6). 7e. cod were recaptured to the east through 7d as far into southern and central North Sea (4b-c) and north west into the Celtic Sea (within 7f – g). In contrast, it was evident that 7e cod were far more constrained in their dispersal during Q2 & Q3 (

Figure 6), where cod showed a more constrained south west dispersal into Celtic Sea (within 7f – j).

In relation to site fidelity over time; majority of cod recaptures were within the same year of release, however 29% of cod recaptures during Q2 & Q3 were of cod released within the same season but recaptured the following year (or more) after release.

- 7f releases

In 7f cod recaptures during Q1 & Q4 were widely dispersed south and west into 7g, 7h and 7e (

Figure 6). While during Q2 & Q3, 7f cod showed a more concentrated dispersal around the neighbouring boundaries of 7e – h within the Celtic Sea (

Figure 6).

In relation to site fidelity over time; generally cod recaptures were within the same year of release, however 53% of cod recaptures during Q4 & Q1 and 26% of cod recaptures during Q2 & Q3 were of cod released within the same season but recaptured the following year (or more) after release.

- 7g releases

In 7g, cod recaptures were restricted close to their release sites during Q1 (

Figure 7). During Q2, Q3 & Q4, cod dispersed southward away from the coast (

Figure 7), yet remained within close proximity of their release.

In relation to site fidelity over time; majority of cod recaptures were within the same year of release, however 36% of cod recaptures during Q4 & Q1 and 7% of cod recaptures during Q2 & Q3 were of cod released within the same season but recaptured the following year (or more) after release.

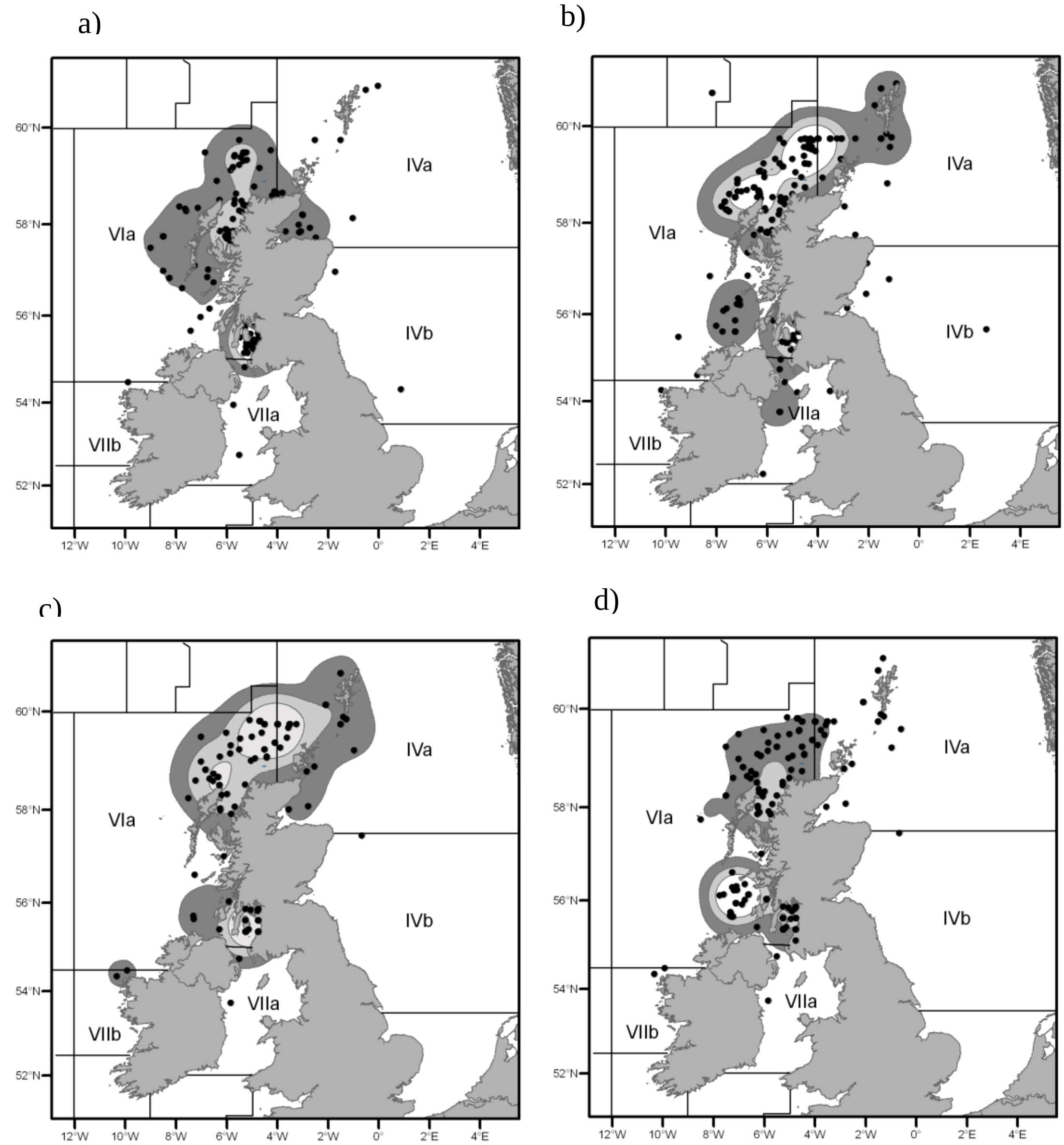

Figure 4. Mark recovery tag recapture positions of cod released in ICES area 6a (Scottish waters). Solid symbols show exact recapture locations, while shading shows the probability density surfaces for 50% (centre white), 75% (mid grey) and 95% (dark grey) of the recaptures. Data shown are for 'adults' recaptured during seasonal quarters (a) Quarter 1; (b) Quarter 2; (c) Quarter 3; and d) Quarter 4.

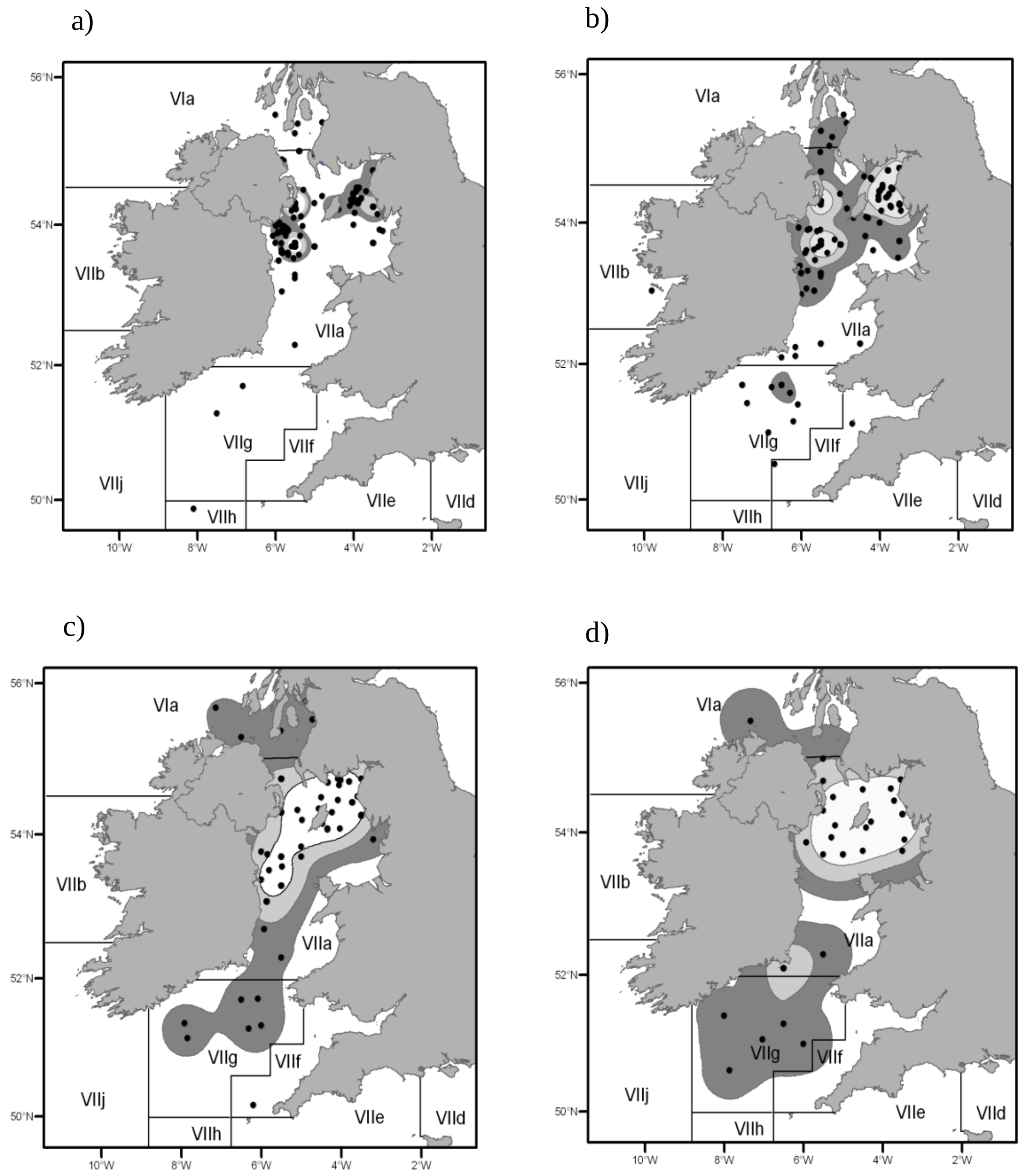

Figure 5. Mark recovery tag recapture positions of cod released in ICES area 7a (Irish Sea). Solid symbols show exact recapture locations, while shading shows the probability density surfaces for 50% (centre white), 75% (mid grey) and 95% (dark grey) of the recaptures. Data shown are for 'adults' recaptured during seasonal quarters (a) Quarter 1; (b) Quarter 2; (c) Quarter 3; and d) Quarter 4.

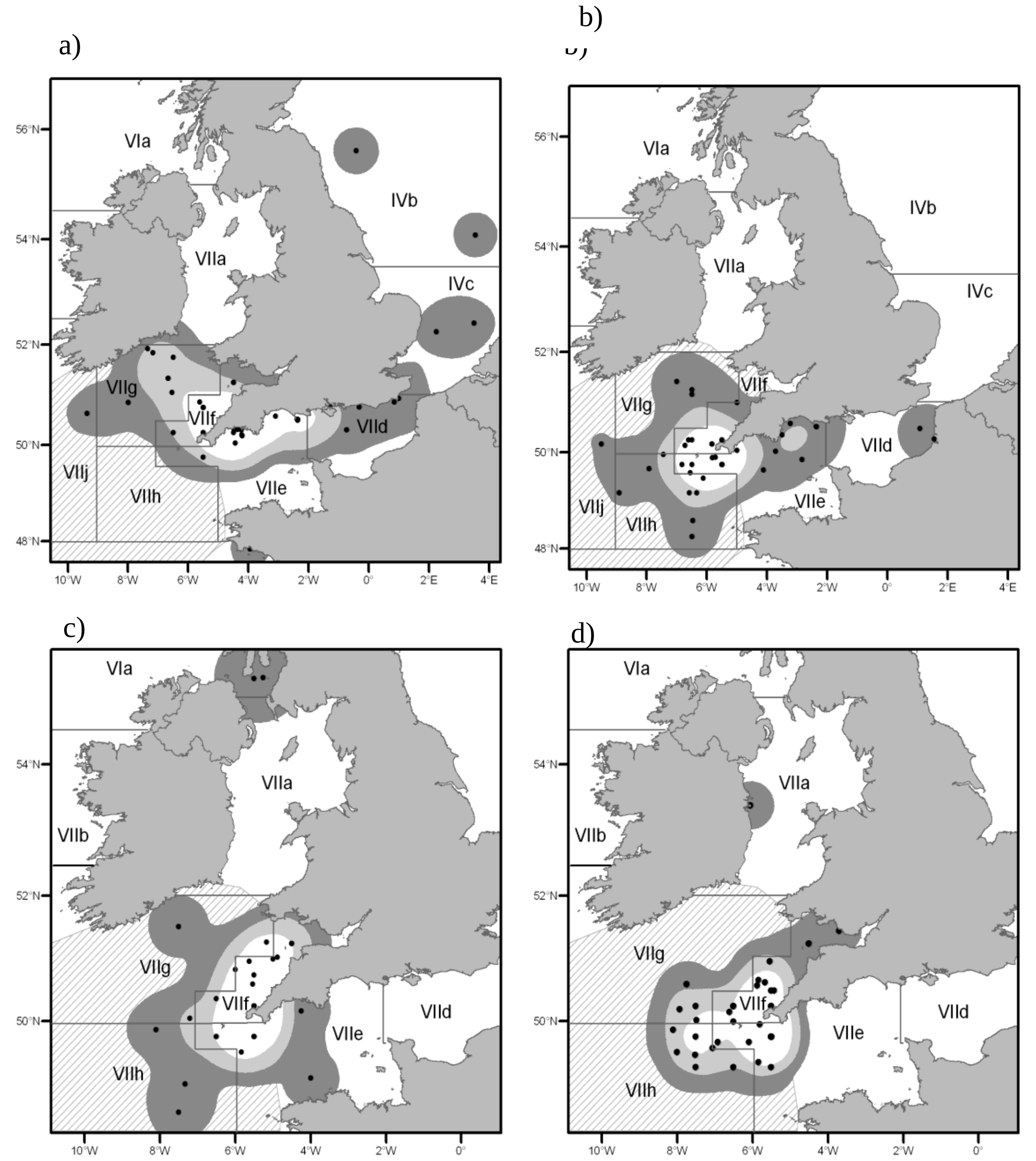

Figure 6. Mark recovery tag recapture positions of cod released in ICES area 7e & 7f (Celtic Sea). Solid symbols show exact recapture locations, while shading shows the probability density surfaces for 50% (hollow white), 75% (mid grey) and 95% (dark grey) of the recaptures. Data shown are for (a) 7e cod recaptured during combined Q4 & Q1 autumn and winter quarters; (b) 7e cod recaptured during combined Q2 & Q3 spring and summer quarters; (c) 7f cod recaptured during combined Q4 & Q1 quarters; (d) 7f cod recaptured during combined Q2 & Q3 quarters.

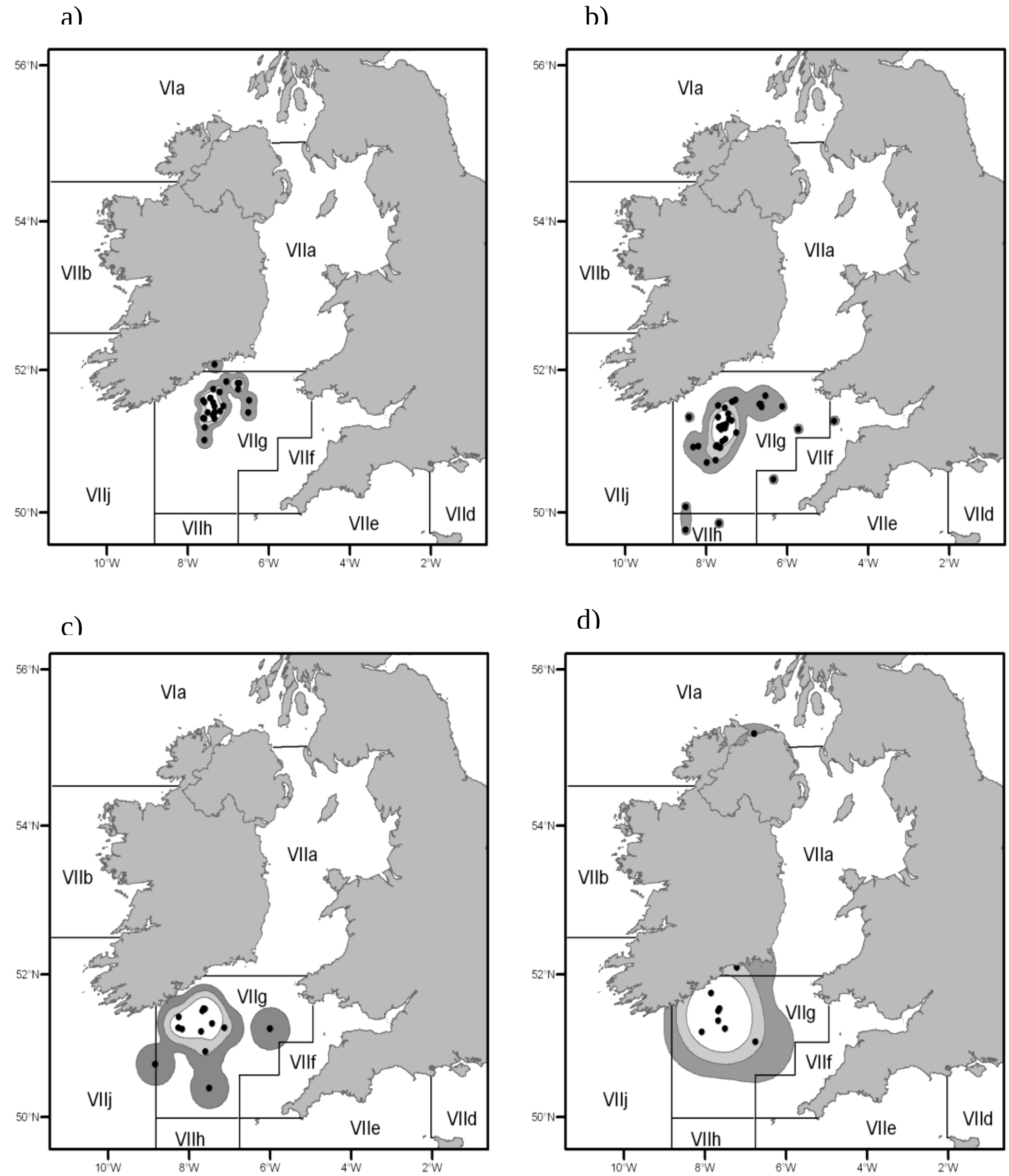

Figure 7. Mark recovery tag recapture positions of cod released in ICES area 7g (Celtic Sea). Solid symbols show exact recapture locations, while shading shows the probability density surfaces for 50% (centre white), 75% (mid grey) and 95% (dark grey) of the recaptures. Data shown are for 'adults' recaptured during seasonal quarters (a) Quarter 1; (b) Quarter 2; (c) Quarter 3; and d) Quarter 4.

2.2.1 Movement of cod between ICES areas

The exchange of cod between the different ICES management areas and seasonal quarters is shown in Table 4. . In ICES areas 6a, 7a and 7g the majority of cod were recaptured within their own management area during Q4 & Q1 and Q2 &

Q3. For 6a an exchange of cod north east into 4a was apparent during Q1 & Q4 with greater occurrence throughout Q2 & Q3. For 7a cod shows some exchange south into 7e – g and north into 6a during Q2 & Q3 was evident. In 7g cod showed a very limited exchange north into 7a during Q4 and south into 7f and 7h during Q2 & Q3. In ICES areas 7e and 7f cod showed a much wider spread exchange of movement between the different ICES management areas. 7e cod showed the most widespread exchange north west and north east across seven different management areas during Q4 & Q1, with majority of recaptures caught outside of 7e. During Q2 & Q3 7e cod were more widely spread to the west within management areas 7f - h of the Celtic Sea and majority of recaptures were again caught outside of 7e. For 7f cod showed a widespread exchange west into neighbouring management areas 7e, 7g and 7h during Q4 & Q1 and Q2 & Q3 with the majority of recaptures caught outside of 7f.

Table 4. Exchange of mark recovery tagged cod between ICES management areas, based on area of recapture. Recapture proportions in area of release are shaded in grey.

Release area	Recapture area									
Q1	5b	4a	6a	7a	7d	7e	7f	7g	7h/7j	4b/4c	Tags
6a		0.10	0.86	0.03	0.00	0.00	0.00	0.00	0.00	0.01	144
7a		0.00	0.02	0.97	0.00	0.00	0.00	0.01	0.00	0.01	404
7e		0.00	0.00	0.00	0.15	0.32	0.21	0.24	0.00	0.08	34
7f		0.00	0.09	0.00	0.00	0.25	0.52	0.09	0.05	0.00	21
7g		0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	27
Q2	5b	4a	6a	7a	7d	7e	7f	7g	7h/7j	4b/4c	Tags
6a	0.01	0.16	0.76	0.05	0.00	0.00	0.00	0.00	0.00	0.02	250
7a	0.00	0.00	0.03	0.91	0.00	0.00	0.01	0.05	0.00	0.00	239
7e	0.00	0.00	0.04	0.00	0.08	0.48	0.16	0.08	0.16	0.00	25
7f	0.00	0.00	0.05	0.05	0.00	0.10	0.60	0.05	0.15	0.00	20
7g	0.00	0.00	0.00	0.00	0.00	0.00	0.07	0.89	0.04	0.00	44

Table 4 (contd.). Exchange of mark recovery tagged cod between ICES management areas, based on area of recapture. Recapture proportions in area of release are shaded in grey.

Release area	Recapture area									
Q3	5b	4a	6a	7a	7d	7e	7f	7g	7h/7j	4b/4c	Tags
6a	0.02	0.28	0.68	0.02	0.00	0.00	0.00	0.00	0.00	0.00	109
7a	0.00	0.01	0.05	0.82	0.00	0.00	0.01	0.08	0.00	0.00	69
7e	0.00	0.00	0.00	0.00	0.00	0.41	0.24	0.06	0.29	0.00	17
7f	0.00	0.00	0.00	0.00	0.00	0.42	0.10	0.16	0.32	0.00	19
7g	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	14
Q4	5b	4a	6a	7a	7d	7e	7f	7g	7h/7j	4b/4c	Tags
6a		0.05	0.95	0.00	0.00	0.00	0.00	0.00	0.00	0.00	59
7a		0.00	0.06	0.76	0.00	0.00	0.00	0.18	0.00	0.00	34
7e		0.00	0.00	0.00	0.00	0.64	0.18	0.00	0.09	0.09	11
7f		0.00	0.00	0.00	0.00	0.45	0.22	0.11	0.22	0.00	9
7g		0.00	0.00	0.011	0.00	0.00	0.00	0.89	0.00	0.00	9

To date, 107 cod (15%) tagged with DSTs have been recaptured, yielding over 11000 days of data: 34 from releases in 7a, 27 from releases in 7e, 8 from releases in 7f and 38 from releases in 7g. Returned cod were at liberty between 1 – 473 days, and grew up to 43 cm in length during the at liberty period. Release and recapture positions of these cod are shown in

Figure 8. Six DSTs were lost in the gutting process of the cod by fishermen. In addition two recovered DSTs failed to download upon return. It was possible to reconstruct (in sufficient detail and with sufficient certainty of location) the daily movements of 81 cod at liberty >10 days (32 from 7a, 17 from 7e, 8 from 7f and 24 from 7g).

2.2.2 Spatial distribution of data storage tags

The daily spatial distributions of DST cod were similar to results of the mark recovery data.

Figure 9 shows the daily spatial distributions of 81 DST cod recaptures by ICES area of release, while

Figure 9 shows all daily spatial distributions of cod by seasonal quarter for each ICES area of release.

Figure 10 to Figure 14 show the daily spatial distributions for each ICES area by month of release and combined season quarters; autumn and winter (Q4 & Q1) and spring and summer (Q2 & Q3). These sub-divisions correspond very broadly to 'spawning' (Q4 & Q1) and 'feeding' (Q2 & Q3) seasons as given by Wright *et al*., (2006) and Righton *et al*., (2007), where the definition of "spawning season" encompasses gonad maturation, spawning migration and the act of spawning itself. Figure 15 to 17 show the overall combined daily position likelihood surfaces of DST cod releases for ICES areas 7a (western Irish Sea), 7a (eastern Irish Sea) and 7g (Celtic Sea), using Hidden Markov model, described by Pedersen *et al*., 2008. Likelihood 'hot spot' surfaces depicted in red (show locations with highest degree of statistical certainty), while 'cold spot' surfaces in blue (show locations with lower degree of statistical certainty).

For 7a DST cod (n=32) spatial distribution was predominantly confined within the Irish Sea primarily in shallower coastal waters throughout December to February off north Wales, Dublin and Liverpool becoming more centrally located within deeper waters of the central Irish Sea and St George's Channel from late February - March. During Q2 spatial distribution was considerably more dispersed throughout the Irish Sea reaching further north into 6a and south into the Celtic Sea within 7g. However cod were much more restricted to the deeper waters of the central Irish Sea, North Channel and St George's Channel and generally remained within depths > 80m. During Q3 cod showed preferences for similar locations off north Wales and within the North Channel during July and September. By Q4 cod began to aggregate in shallower coastal waters off north Wales, Dublin and the North Channel.

For 7e DST cod (n=17) during Q1 a highly widespread distribution across five ICES management areas was observed, very similar to that shown by the mark recovery data. Distribution west into Celtic Sea within 7f-g together with movement east through 7d and into the southern North Sea within 4c was evident throughout January – March. No data however were available for Q4 autumn months October – December. During Q2 & Q3 7e cod showed a more constrained spatial distribution remaining within the English Channel within 7d-e. Some cod showed preferences to certain locations off the French coast in April within 7d, off the south east coast, UK within 7d April – May, yet primarily within 7e close to the Hurd Deep throughout May – July. No spatial data were available for August and September.

For 7f DST cod (n=8), during Q4 & Q1 dispersion occurred out of the Bristol Channel during March together with some limited distribution in October off the far coast of Cornwall, UK. During Q2 & Q3 movement was recorded south through the Celtic Sea in May, and dispersion on the edge of the English Channel around the ICES management boundary between 7e and 7h was particularly evident.

Finally for 7g DST cod (n=24) during Q4 & Q1 and Q2 & Q3 distribution remained fairly constrained within 7g. Some preference to central areas within 7g during January – March and April – June was evident and cod appeared to be more widely dispersed within 7g during Q1 & Q2.

2.2.3 Virtual recaptures from DST cod movements

A total of 453 individual spatial positions were extracted as 'virtual recaptures' from the full DST dataset (81 cod; 11170 data days), to allow for direct comparison between mark recovery data (6a cod predominantly 1960 – 1970's; 7a cod 1970's; 7e & 7f cod 1990's; 7g cod 2000's), with current DST cod movement data (1999 – 2010). Table 5. shows the rate of exchange for DST 'virtual' cod recapture data between ICES management areas. Figure 18 to 19 show the DST ‘virtual’ cod recapture positions by seasonal quarter for cod released in ICES area 7a (Irish Sea) and 7g (Celtic Sea) respectively.

Table 5. Exchange of DST ‘virtual’ cod recapture data between ICES management areas. Recapture proportions in area of release are shaded in grey.

Release area	Recapture area								
Q1	4a	6a	7a	7d	7e	7f	7g	7h/7j	4b/4c	Tags
7a	0.00	0.02	0.88	0.00	0.03	0.03	0.02	0.02	0.00	63
7e	0.00	0.00	0.00	0.37	0.37	0.07	0.13	0.03	0.03	30
7f	0.00	0.00	0.00	0.00	0.00	0.75	0.13	0.12	0.00	8
7g	0.00	0.00	0.00	0.00	0.00	0.00	0.88	0.12	0.00	27
Q2										
7a	0.00	0.02	0.83	0.00	0.0	0.00	0.13	0.03	0.00	107
7e	0.00	0.00	0.00	0.33	0.67	0.00	0.00	0.00	0.00	12
7f	0.00	0.00	0.00	0.00	0.17	0.08	0.25	0.5	0.00	12
7g	0.00	0.00	0.02	0.00	0.00	0.00	0.91	0.07	0.00	10
Q3										
7a	0.00	0.03	0.90	0.00	0.00	0.00	0.02	0.05	0.00	61
7e	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	2
7f	0.00	0.00	0.00	0.00	0.29	0.14	0.14	0.43	0.00	7
7g	0.00	0.00	0.00	0.00	0.00	0.05	0.95	0.00	0.00	21
Q4										
7a	0.00	0.00	0.92	0.00	0.00	0.00	0.00	0.08	0.00	36
7e	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0
7f	0.00	0.00	0.00	0.00	0.00	0.25	0.00	0.75	0.00	4
7g	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	6

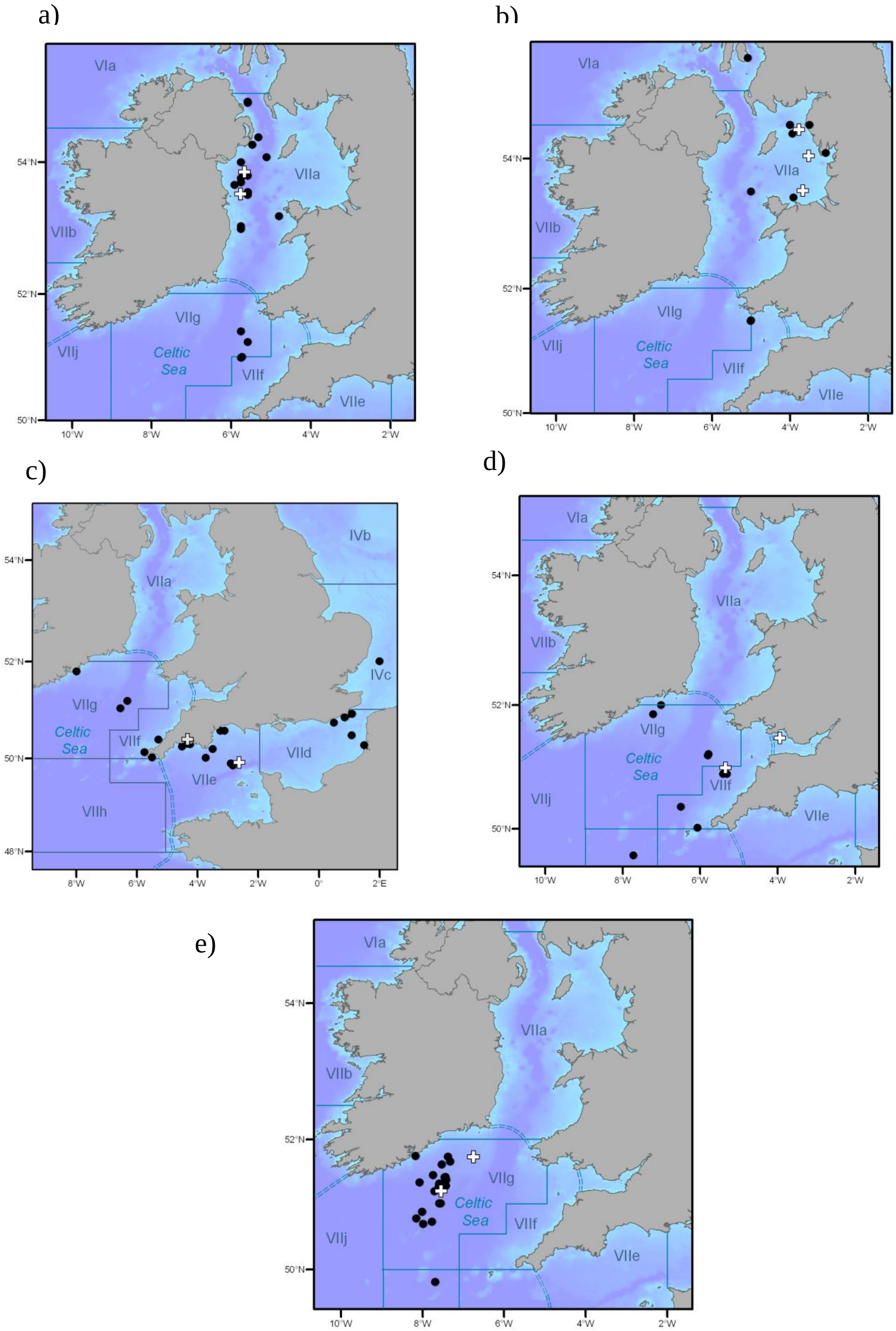

Figure 8. Recapture positions of cod tagged with DSTs in (a) ICES area 7a West (Irish Sea), (b) ICES area 7a East (Irish Sea), (c) ICES area 7e (western English Channel), (d) ICES area 7f (Celtic Sea) and (e) ICES area 7g (Celtic Sea). White cross symbols show the release positions of DST-tagged cod, while solid black circles show the recapture positions of DST-tagged cod.

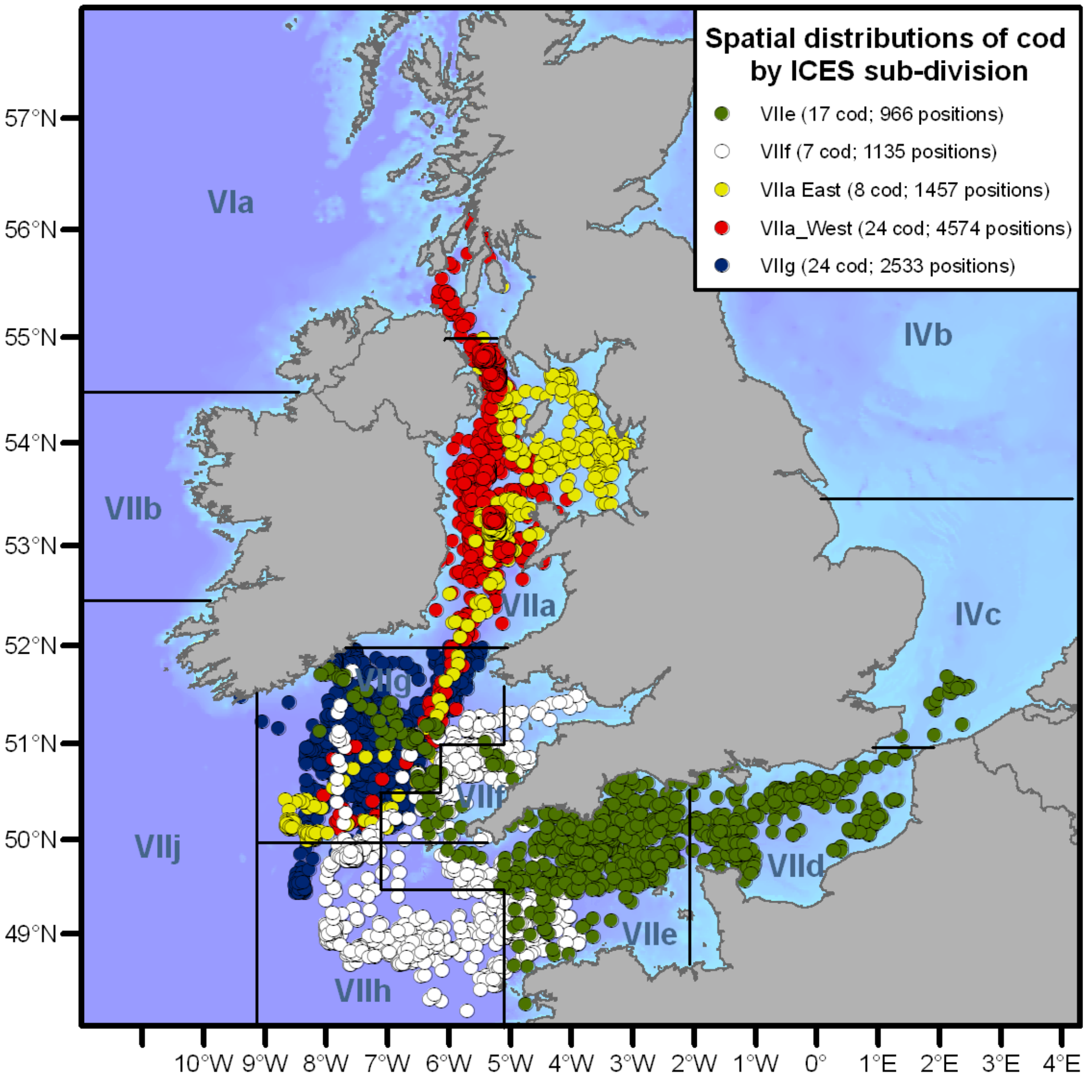

Figure 9. The daily spatial distributions of 81 cod (11,170 days of data) released in the following ICES areas: eastern Irish Sea 7a (yellow; 8 cod = 1457 days of data), western Irish Sea 7a (red; 24 cod = 4574 days of data), eastern Celtic Sea 7f (white; 7 cod = 1135 days of data), western Celtic Sea 7g (dark blue; 24 cod = 2533 days of data), western English Channel 7e (green; 17 cod = 966 days of data). Solid coloured symbols show individual daily geolocated positions reconstructed for each cod at liberty.

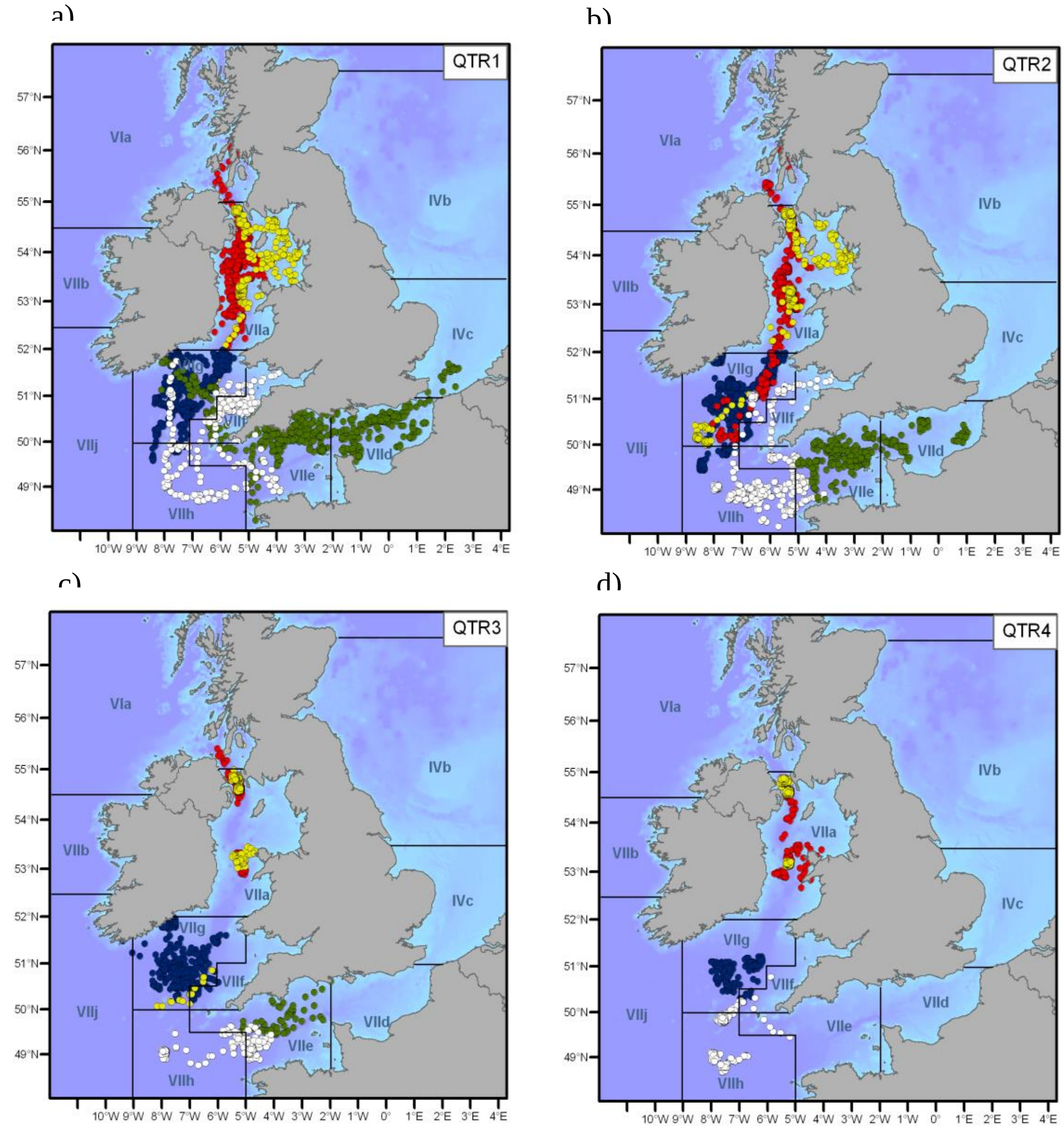

Figure 10. The daily spatial distributions of 81 cod (11,170 days of data) by seasonal quarter; a) quarter 1, b) quarter 2, c) quarter 3 and d) quarter 4 for each ICES area of release; 7a East (yellow), 7a West (red), 7e (green). 7f (white) 7g (dark blue).

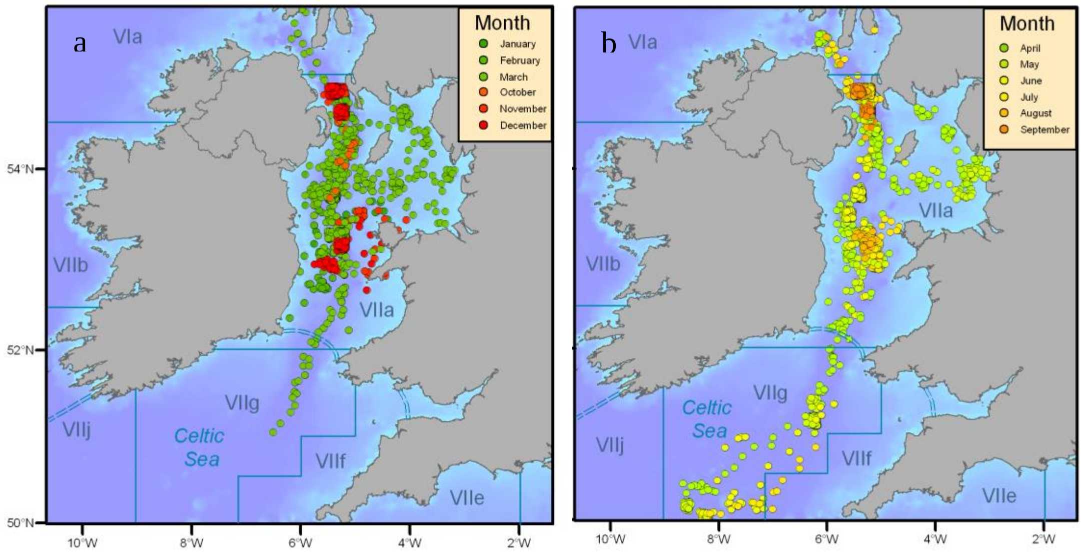

Figure 11. The daily spatial distribution of cod by month, released in ICES area 7a (Irish Sea). Solid symbols show daily geolocated positions reconstructed for 32 cod coloured by month at liberty. Positions shown are for (a) 32 7a cod (2490 days of data) during the Q4 & Q1 autumn and winter quarters; (b) 31 7a cod (4047 days of data) during the Q2 & Q3 spring and summer quarters.

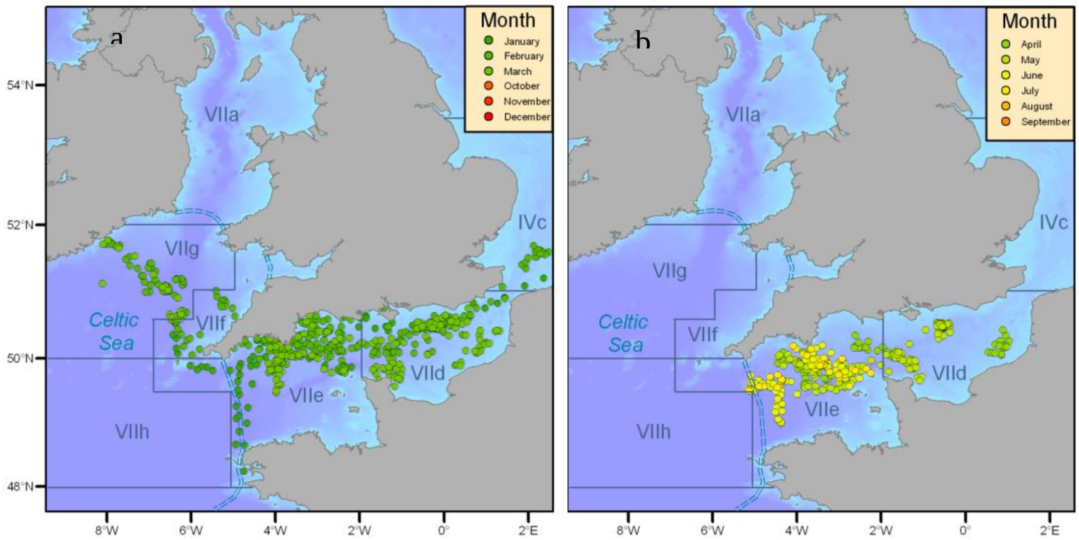

Figure 12. The daily spatial distribution of cod by month, released in ICES area 7e (western English Channel). Solid symbols show daily geolocated positions reconstructed for 17 cod coloured by month at liberty. Positions shown are for (a) 15 7e cod (595 days of data) during the Q4 & Q1 autumn and winter quarters; (b) Six 7e cod (314 days of data) during the Q2 & Q3 spring and summer quarters.

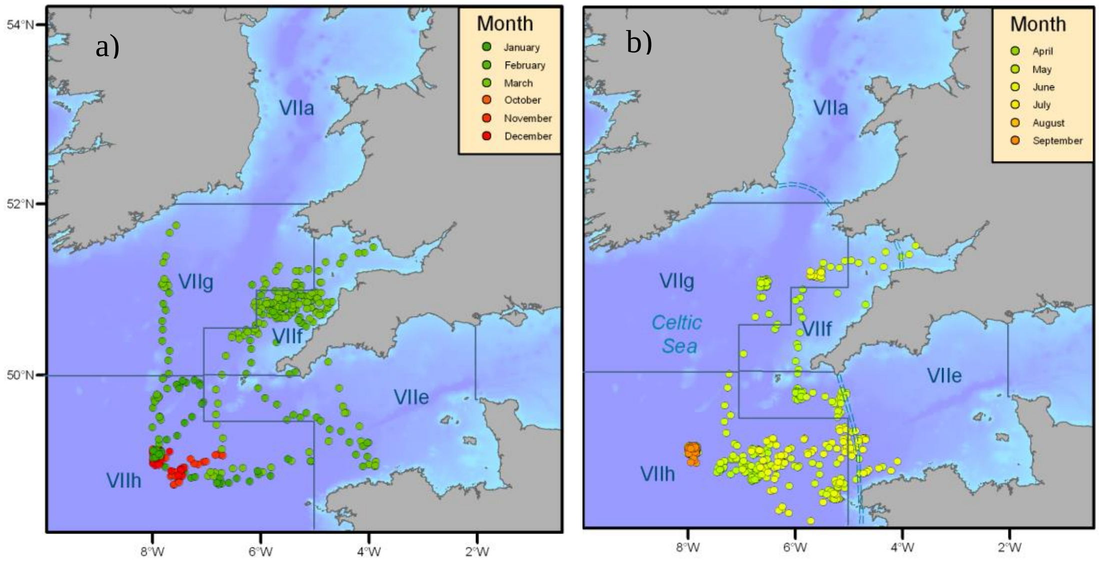

Figure 13. The daily spatial distribution of cod by month, released in ICES area 7f (Celtic Sea). Solid symbols show daily geolocated positions reconstructed for seven cod coloured by month at liberty. (a) Six 7f cod (415 days of data) during the Q4 & Q1 autumn and winter quarters; (b) Five 7f cod (486 days of data) during the Q2 & Q3 spring and summer quarters.

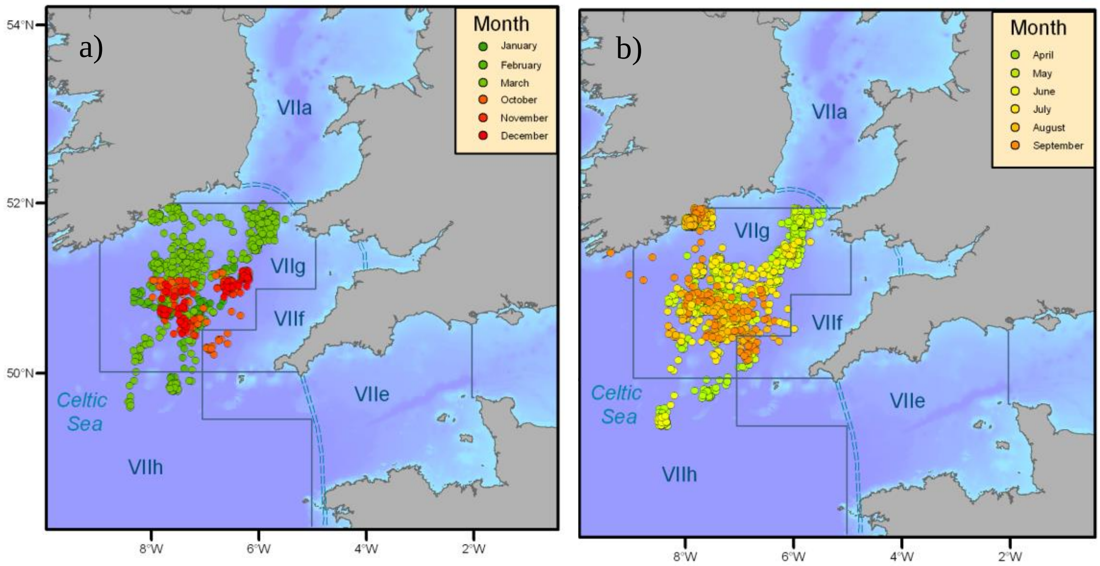

Figure 14. The daily spatial distribution of cod by month, released in ICES area 7g (Celtic Sea). Solid symbols show daily geolocated positions reconstructed for 24 cod coloured by month at liberty. (a) 24 7g cod (839 days of data) during the Q4 & Q1 autumn and winter quarters; (b) 20 7g cod (1694 days of data) during the Q2 & Q3 spring and summer quarters.

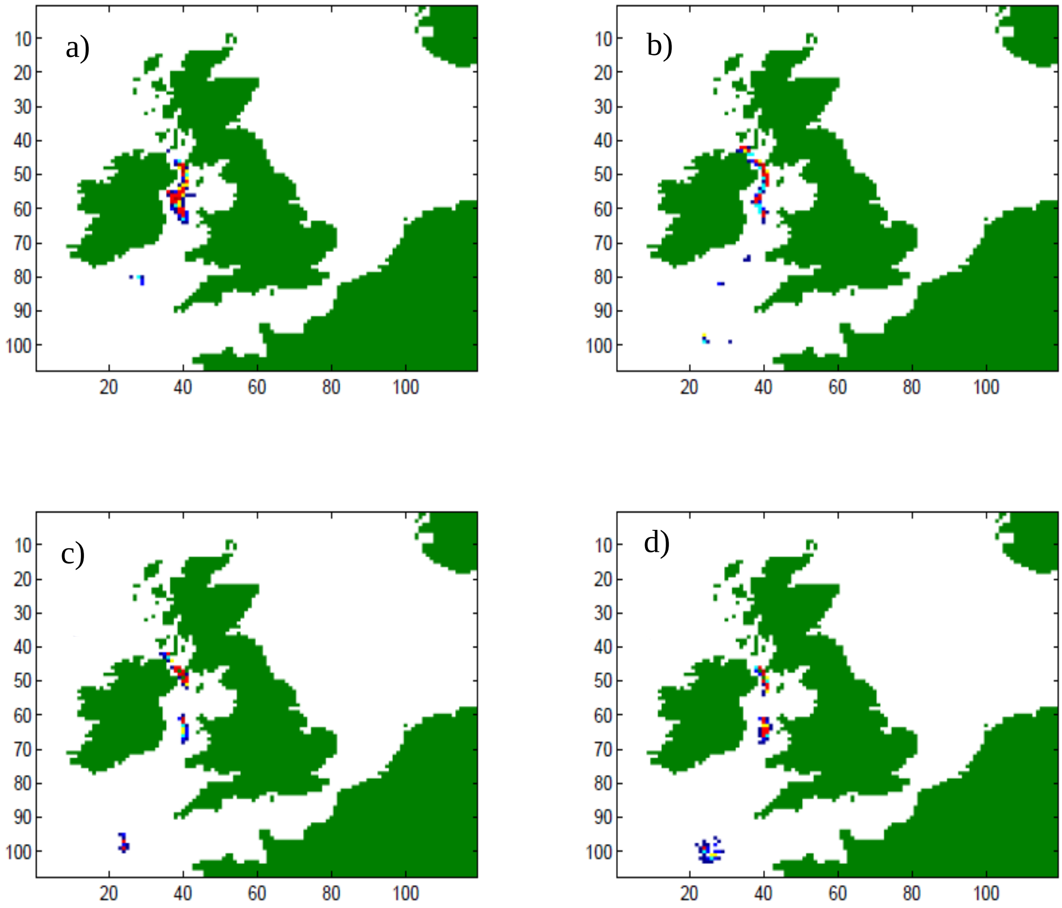

Figure 15. Combined daily position likelihood surfaces (using Hidden Markov model, described by Pedersen et al., 2008) of 7a west (Irish Sea) DST cod releases, showing probable distribution estimates by seasonal quarter ; a) Q1, b)Q2, c) Q3 & d) Q4. Likelihood 'hot spot' surfaces are depicted in red (showing locations with highest degree of statistical certainty), through to 'cold spot' surfaces depicted in blue (showing locations with lower degree of statistical certainty).

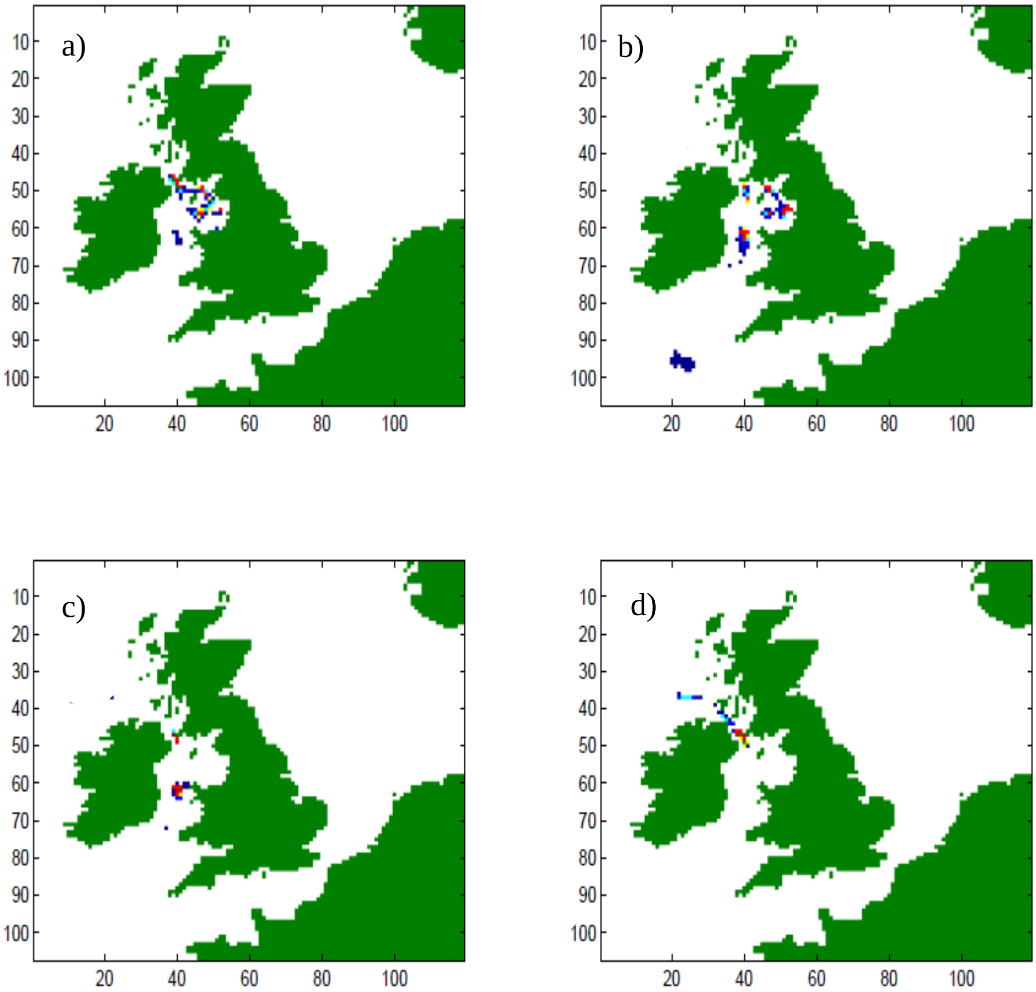

Figure 16. Combined daily position likelihood surfaces (using Hidden Markov model, described by Pedersen et al., 2008) of 7a east (Irish Sea) DST cod releases, showing probable distribution estimates by seasonal quarters; a) Q1, b)Q2, c) Q3 & d) Q4. Likelihood 'hot spot' surfaces are depicted in red (showing locations with highest degree of statistical certainty), through to 'cold spot' surfaces depicted in blue (showing locations with lower degree of statistical certainty).

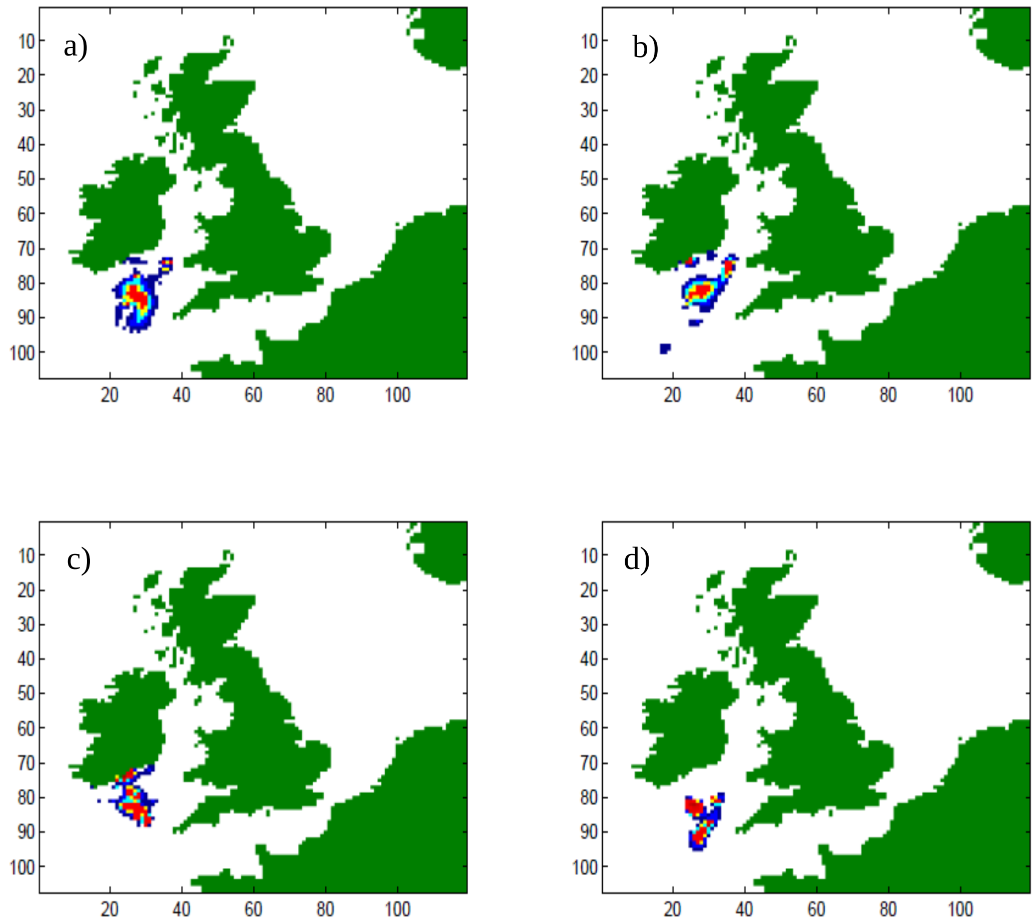

Figure 17. Combined daily position likelihood surfaces (using Hidden Markov model, described by Pedersen et al., 2008) of 7g (Celtic Sea) DST cod releases, showing probable distribution estimates by seasonal quarters; a) Q1, b)Q2, c) Q3 & d) Q4. Likelihood 'hot spot' surfaces are depicted in red (showing locations with highest degree of statistical certainty), through to 'cold spot' surfaces in blue (showing locations with lower degree of statistical certainty).

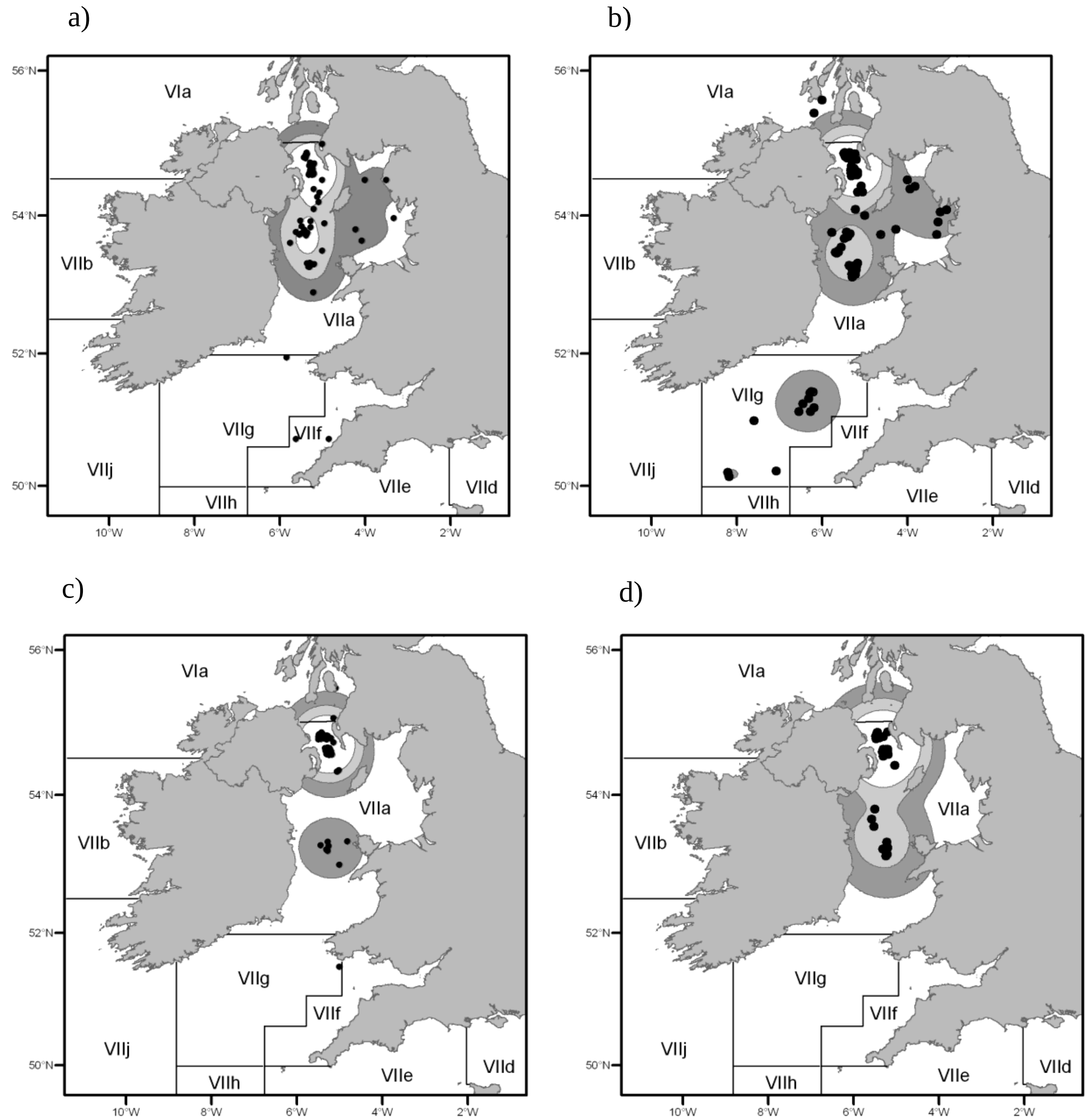

Figure 18. DST 'virtual' cod recapture positions of cod released in ICES area 7a (Irish Sea). Solid symbols show 'virtual' recapture locations, while shading shows the probability density surfaces for 50% (centre white), 75% (mid grey) and 95% (dark grey) of the recaptures. Data shown are for 'adults' recaptured during seasonal quarters (a) Quarter 1; (b) Quarter 2; (c) Quarter 3; and d) Quarter 4.

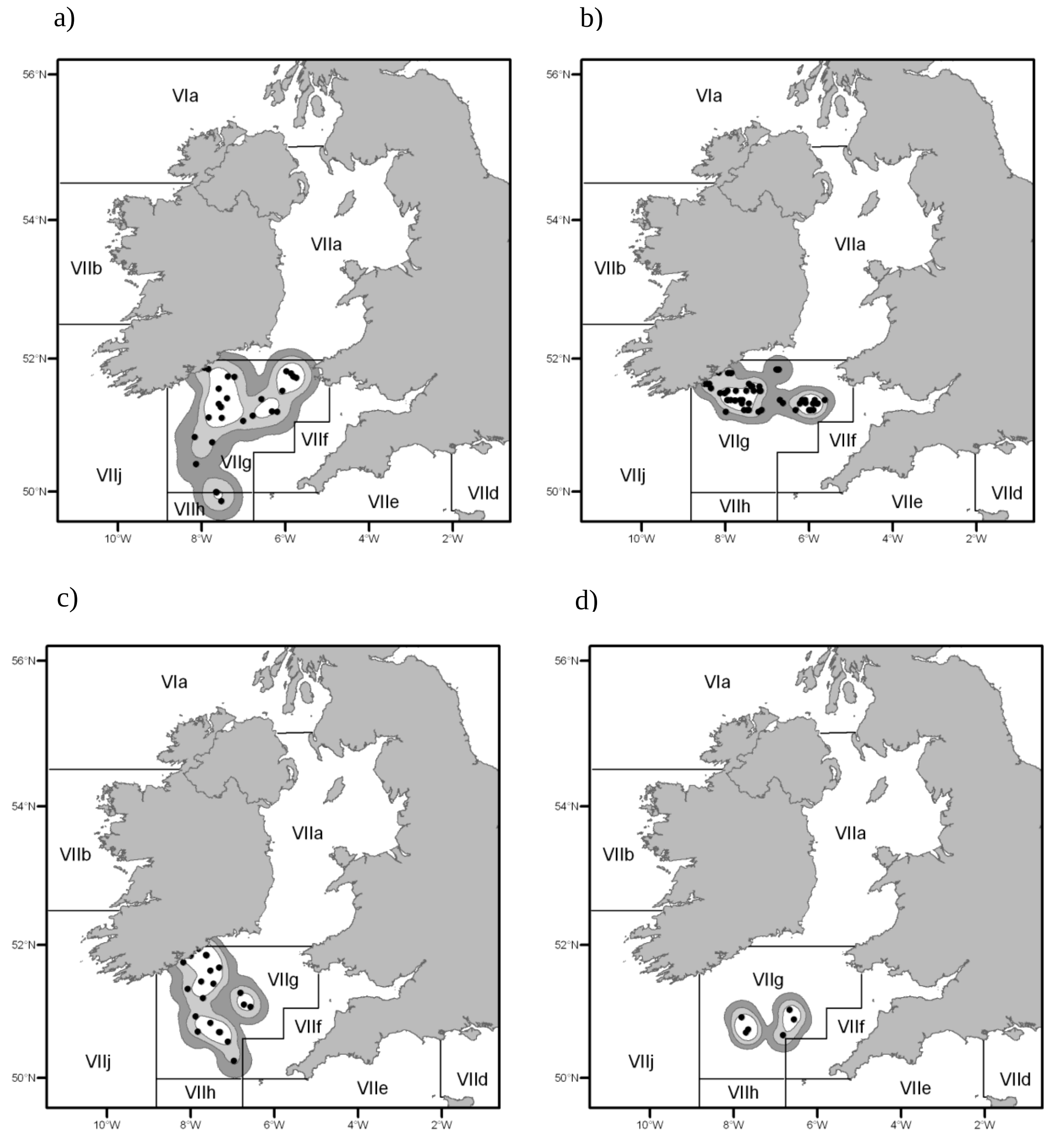

Figure 19. DST 'virtual' cod recapture positions of cod released in ICES area 7g (Irish Sea). Solid symbols show 'virtual' recapture locations, while shading shows the probability density surfaces for 50% (centre white), 75% (mid grey) and 95% (dark grey) of the recaptures. Data shown are for 'adults' recaptured during seasonal quarters (a) Quarter 1; (b) Quarter 2; (c) Quarter 3; and d) Quarter 4.

2.2.4 Development of a tagging study for 2016 - 2018

The tagging study (2016–2018) aim to provide baseline information on the movement rates of cod into adjacent areas and thereby the accessibility / vulnerability of the Irish Sea stock to the fisheries in each area. This required cod to be tagged over the greatest size range possible (including below minimum conservation reference size (MCRS)), over a large spatial area to ensure the tagged fish sample reflected all demographics of the Irish Sea cod population. Tagging opportunities covering a wide range of sources were planned, utilising existing sampling schemes and establish new programmes. The plan was designed to achieve a maximum number of tagged cod, using the experience of operating fishery dependent and independent sampling plans for cod and previous tagging projects by the project partners. Given the existing management measures to reduce cod catches in the Irish Sea, the most proven and effective means to catch and tag cod based on previous sampling schemes are targeted charters using commercial gear specifically developed to target cod in the study area. The plan was developed to have targeted tagging events when the highest catch rates of cod could be achieved during spawning periods and late summer when aggregation in deep water form. This would be augmented by tagging during commercial fishing opportunities throughout the year.

The tagging plan was developed to utilise a range of methods to obtain viable fish for tagging, analysis of known sources of information identified that commercial fishing activity and targeted fishing for cod using semi-pelagic and demersal gear provide the highest catch rates and thus opportunity for tagging.

Historically, Irish Sea fisheries (Figure 20) were predominantly demersal trawling and seining with a high degree of overlap. At present the dominant fishing effort in the area arises from the *Nephrops* fishery, which uses mesh sizes in the range of 70-99 mm. Beam trawls operating within the Irish Sea use mesh sizes in the range of 80-119mm, targeting sole, plaice, and rays. Cod were target by demersal trawl / seine fishers with mesh sizes in the range 100 – 120 mm. Following the cod-recovery plan in 2000, effort of the whitefish fleet using fishing gear with ≥100mm mesh sizes has been declining and reached a historically low (Figure 21) at the start of the study period. This was the dominant fleet targeting cod, with gear specifically designed to catch gadoids, whilst other fisheries had low observed by-catch of cod. At present, there is no directed commercial fishery for cod permitted in the Irish Sea. The known spawning grounds are closed to commercial fishing during February – May, with no vessels using demersal fishing gear allowed during this time. Therefore, to exploit this source of fish for tagging scientific charters are required. These charters would use fishing gear with mesh size in the range 100 – 120mm. To ensure maximised number of viable cod to tag fishing tows would be short (30min – 1 hours) to limit damage and stress to fish.

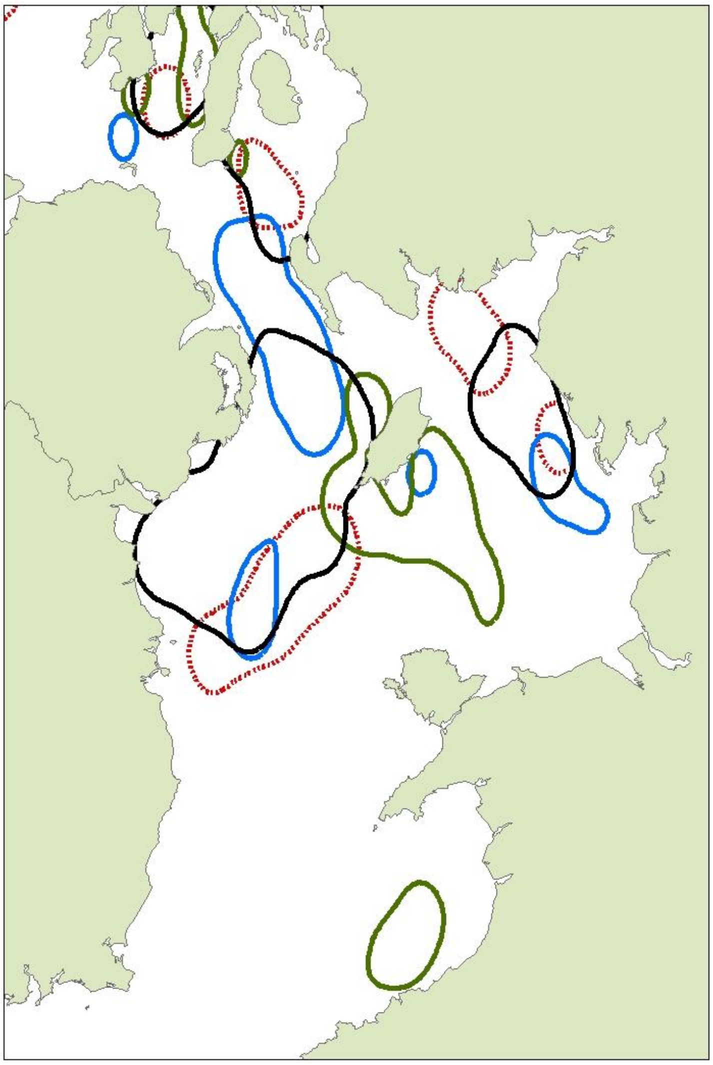

Figure 20. Overview of core fishing areas in the Irish Sea by gear type (Nephrops – black, dredging – green, seine – red dashed & demersal (cod/haddock/hake) – blue. These areas are defined from kernel density analysis of Vessel Monitoring System (VMS) data using gear information from logbooks for the UK fishing fleet (2007 – 2016).

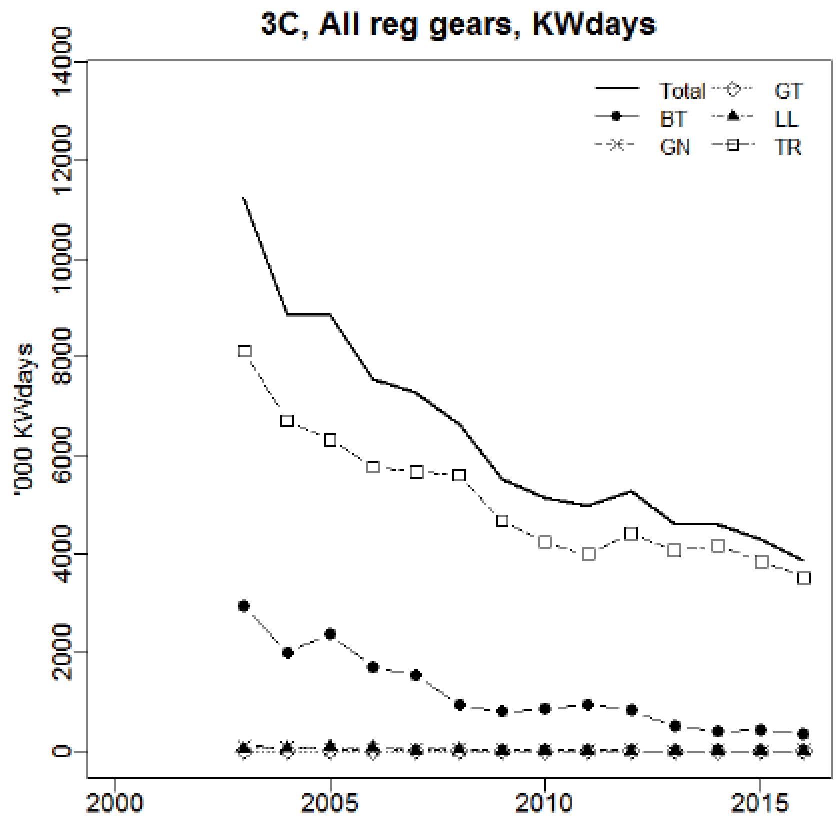

Figure 21. Irish Sea trends in regulated gear nominal effort (kW*days-at-sea) 2003 – 2016 for the international fishing fleet active in the Irish Sea. BT – beam trawls, GN – gill nets, GT – trammel nets, LL – Longlines, TR – trawls. Data are from the STECF (EWG 17-05) Fisheries Dependent Information report.

2.2.5 Tagging Season

A review of seasonal trends in commercial catches of cod was carried out. The review identified an apparent cyclical pattern in the historic landing series. The highest catches occur during the end of quarter 1 and the beginning of quarter 2 (

Figure 22). This coincides with the spawning period of cod when fishers are likely to target pre spawning aggregations. To maximise the catch rates of cod and achieve maximum numbers of tagged cod charters of fishing vessels during quarter 1 and early quarter 2 were planned for March 2016 and March 2017. A shorter charter was also planned to target the summer aggregations in quarter 3.

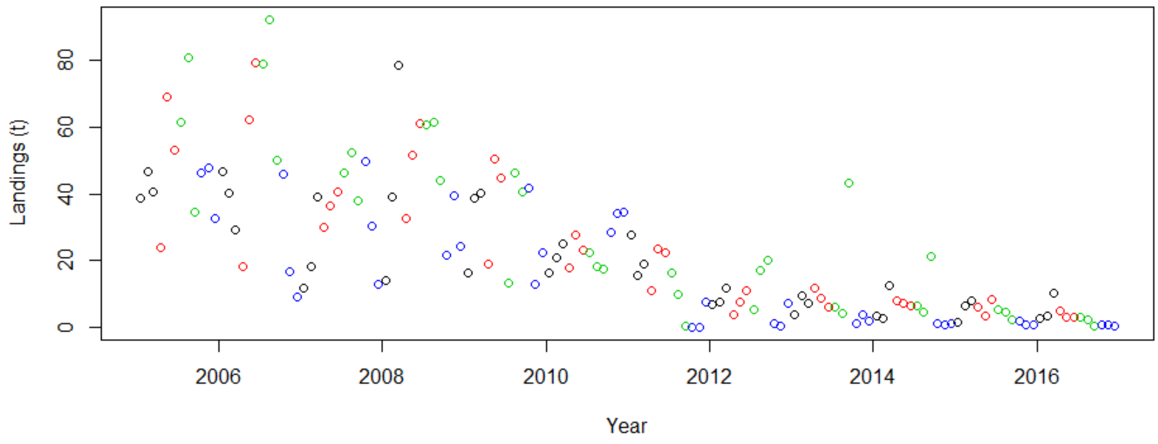

Figure 22. Commercial landings (t) from logbooks of cod in the Irish Sea by the UK fishing fleet. Quarters are coloured; black – quarter 1, red – quarter 2, green – quarter 3 and blue – quarter 4.

2.2.6 Tagging area

Analysis of the spatial distribution of catches (before 2012 when TAC was less restrictive) showed a spatial pattern in the catches of cod. This is considered to be related to cod moving from deep water feeding areas toward spawning grounds. In quarter 1 and early quarter 2 (February – April) cod catches occur across the southern extent and inshore areas of their range (Figure 23). These more shallow areas represent the known spawning and inshore nursery habitats. Following this period, cod move to deeper water regions in the south east of the range and into the Northern Channel. Charter of fishing vessels primarily during this period were planned to be carried out in these regions. The tagging plan was developed using this information, with a primary objective of targeting spawning aggregations during the end of quarter 1 and the beginning of quarter 2.

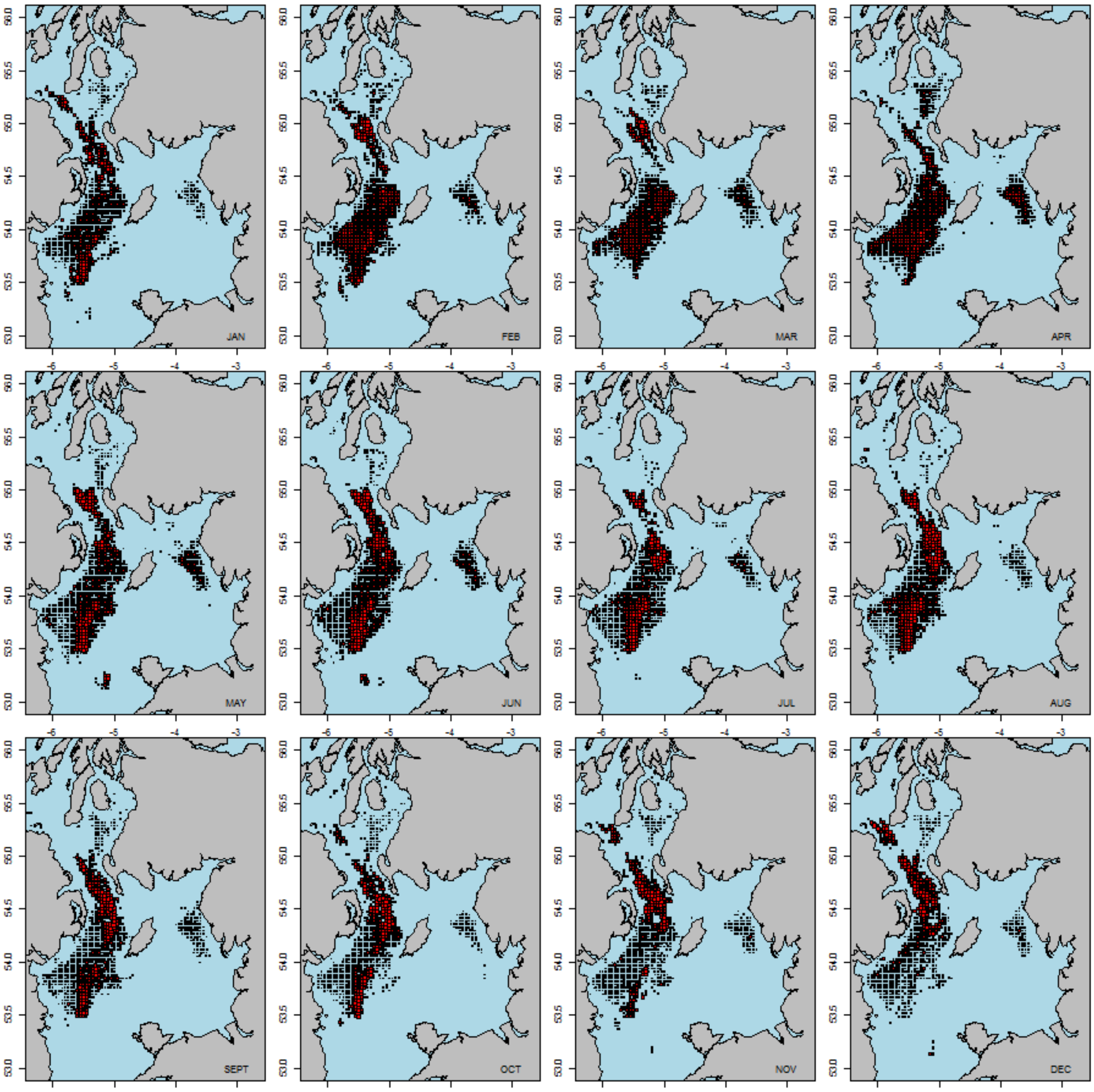

Figure 23. Average month commercial landings of cod taken in the Irish Sea by UK vessels (2006 – 2012). Symbol size is scaled to the landed weight. Data are derived from logbook linked Vessel Monitoring System (VMS) data.

2.2.7 Commercial fishery activity

Data derived from at-sea observations of the *Nephrops* fishery show that whilst no targeted fishing for cod is permitted, the bycatch catch rates reflect the historic commercial catch patterns. Clusters of catches of fish above MCRS are observed in the south-eastern area and northern limit of the *Nephrops* grounds (Figure 24). Cod below MCRS are less frequently caught and are more widespread in their distribution (Figure 26). Catches of cod above and below MCRS shows high levels of internal annual variation, with a decreasing trend over time. At the time of developing the initial tagging plan (2014/2015) and establishing target tag numbers (Table 6), it was unforeseen that the decreasing trend would impact on the availability of cod to tag. Based on estimated catches of cod it was expected that commercial fishing activity would generate annual values of on average 382 t (2007 - 2015). During the study (2016 – 2018) the annual catch estimates have been 127 t, with annual values of 82 t, 84 t and 215 t in 2016, 2017 and 2018 respectively (ICES 2019).

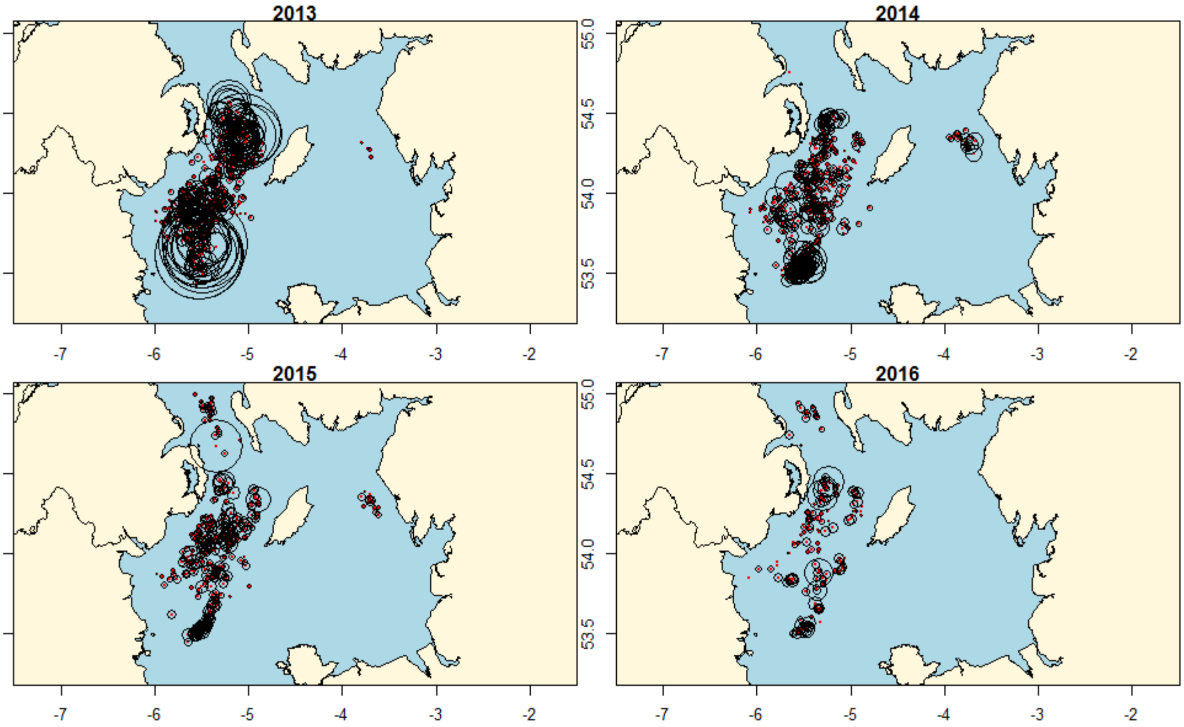

Figure 24. Distribution of commercial catches of cod above the MCRS during 2013 – 2016. The data are derived from AFBI observer at-sea data collection programme sampling catches on-board commercial fishing vessels. The size of open black symbols are scaled to catch rates, red circles indicate sampling location.

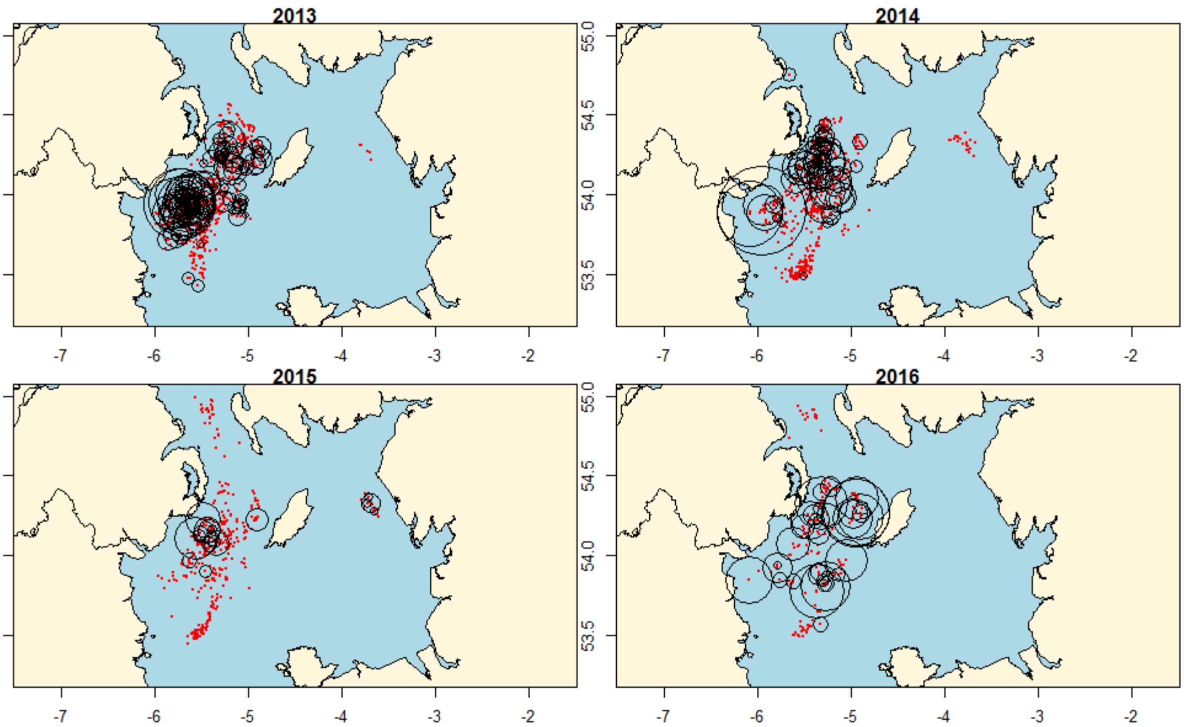

Figure 25. Distribution of commercial catches of cod below MCRS 2013 – 2016. The data are derived from AFBI observer at-sea data collection programme sampling catches on-board commercial fishing vessels. The size of open black symbols are scaled to catch rates, red circles indicate sampling locations.

2.2.8 Reporting recaptures

Information regarding recaptures was obtained from all sources that recaptured cod through 'normal' fishery and recreational activity likely to catch cod. A reward scheme was developed to encourage reporting of recaptures. Carcases could be left in markets / at ports for collection by project staff. Freezer space was provided at ports for fishers to return carcases and contact information. Telephone reporting numbers were on tagged with dedicated staff to receive and log recaptures.

2.2.9 The tagging plan

To achieve the project objectives a number of tagging charters were planned. These charters were intended to target cod of a range of sizes normally encountered in commercial fishing activity, for tagging. Fishing was planned to be undertaken within the western Irish Sea (Area 7a) and North Channel between longitudes 4°50'W and 6°W, south of 55°N and north of 53°20'N. Charters would also be carried out in the Celtic Sea. Scientists were trained to tag and assess the suitability of fish for tagging. It was identified that any opportunity to tag fish in suitable condition should be taken.

In addition to tagging charters, research vessel activities, at-sea observers and recreational fishing events were identified as potential platforms during which cod would be tagged. Tagging activities were carried out through:

- Tagging Charters
- Research vessel time
- At-sea observers
- Recreational angling events

2.2.10 Tagging Charters

Cod spawning aggregations are known in quarter 1. Fishery information supported evidence of aggregations of cod in late July/early August 2017 in deeper areas of the Irish Sea – these would also be targeted by charter tagging trips. Commercial fishing vessels were chartered by both AFBI and the Marine Institute. Initial plans for 6 charter trips were made. These charters would cover the entire distribution of know cod aggregations in the Irish Sea (7a), North channel (7a/6a) and primary cod aggregations in the Celtic sea (7g) and southern Irish Sea (7a). Tagging was carried out in the Irish Sea and adjoining sea areas, at the same time of year. This allowed for movement between areas to analysed, as per section 2.2.1. Failure to tag in adjoining areas would have meant that only one direction movements could be detected. The charter plan:

- March 2016 – Western Irish Sea & North Channel (10 days)
- March 2017 – Western Irish Sea & North Channel (10 days)
- March 2017 – Northern Celtic Sea (5 days)
- August 2017 – Western Irish Sea (5 days)

Good catch rates of semi-pelagic commercial vessels with mesh size in the range 100 – 120mm have been observed to be 80-160 $kg.h^{-1}$. Taking the size of fish, fish condition suitable for tagging and the operational issues on board the vessels into account, the minimum number of fish aimed to be tagged during this charters were 50 per day. These tagging targets were in line with achieved tagging numbers from previous tagging projects in the study area conducted by the project partners.

The deployment of this method was severely restricted by the project budget.

2.2.11 Research Vessel opportunities

AFBI sea-going scientists were trained to carry out tagging of cod encountered during existing research. Time during 5 planned research surveys, to be carried out on the RV *Corystes* in 2018 was identified whereby cod tagging could be carried out through both supplementary time or ad-hoc tows between normal survey operations:

- Ecosystem Survey (February 2017/2018) – RV *Corystes*
- Groundfish survey (March 2017/2018) – RV *Corystes*
- Fishery-Science Partnership (FSP) gadoid survey (March 2017/2018) – Chartered vessel
- Queen Scallop survey (July 2017/2018) – RV *Corystes*
- Groundfish survey (October 2017/2018) – RV *Corystes*

Tagging opportunity on the FSP survey has been significant in the past, but given the need to collect biological information on the other surveys limits tagging opportunities to ad-hoc tows that will be dependent on survey progress. Tagging target from research vessel surveys were based on previous observed catch rates.

2.2.12 At-sea observer programme

All Marine Institute observers would be provided with tagging kits and asked to avail of any tagging opportunities of healthy cod while sampling at sea. AFBI fleet observers would be trained to tag cod and would take tagging kits to sea on all observation trips, including pot fishing vessels, *Nephrops* and whitefish directed fishing vessels, to undertake opportunistic tagging where possible.

At the time of the proposal the majority of cod caught in the commercial fisheries were discarded, so the plan was heavily dependent on using the extensive at-sea observer schemes within the participating laboratories to tag fish. The two dedicated tagging staff employed under the project will further increase the at-sea tagging opportunities presented from by-catch of cod in commercial trawl fisheries, dedicated pot fishing tagging trips and the developing quarter 2 haddock directed fishery in Northern Ireland that deployed semi-pelagic gear. Catch estimates of cod in the Irish Sea vs. the TAC indicated an average operational surplus of 200 tonnes (2012-2015). The observed operational surplus, the anticipated further reduction in the TAC under the cod plan and the observed numbers of cod discarded by the respective at-sea observer programmes, indicated that this method could yield a significant number of tagged fish. The tagging target from commercial fisheries capitalising on the extensive existing observer schemes and the further dedicated effort by the project tagging personnel. It was also recognised that tagging through the routine at-sea observer programme will continue beyond the proposed tagging programme duration of the project.

2.2.13 Recreational angling events

It was planned that both shore angling competitions and at-sea angling ‘recreational’ charter vessels would be used as tagging opportunities. Initially 10 shore angling competition days were identified. Tagging kits would be distributed to recreational anglers and training provided. The kits would contain a tagging gun, 20 standard reward tags, record sheets, a standard operating procedure (SOP) with pictures and a reward poster. It was targeted to have 20 volunteers with kits.

Due to the uncertainty of catch rates and take-up from recreational fishers in the tagging project, tagging targets were conservative using this method.

Table 6. Summary of tagging targets by method, area and season:

Tagging method	Time	Area	Tagging target
Charter – semi-pelagic trawl	Q1/2	Irish Sea/North Channel	1000
Charter – demersal trawl	Q1/2	Northern Celtic Sea	250
Charter – semi-pelagic trawl	Q3	Irish Sea	250
Research surveys	Q1-Q4	Irish Sea/North Channel	600
At sea observer programme	Q1-Q4	Irish Sea/North Channel/northern Celtic Sea – randomised sampling scheme to cover fishing grounds and gears	8500
Recreational fishers	Q1-Q4	Irish Sea/northern Celtic Sea	300

Achievement toward these planned targets is given below in Section 2.3 and was reviewed and update during interim project review (Section 2.3.7 & Section 2.3.8).

2.2.14 Communication and Outreach plan

The project relied on collaboration with the fishing industry to provide the data to develop a better understanding of the current behaviour, biology and stock status of Irish Sea cod. Any recaptured tagged cod can provide useful information. It was recognised that the project should build on existing science and industry partnerships to achieve the project goals. The primary focus of the communication plan was with the main fishers active in the western Irish Sea, Clyde prawn grounds of the northern Celtic Sea. The main fishing nations in the areas are Ireland and Northern Ireland and account for more 90% of the fishing effort in the Irish Sea. The initial plan identified that fishers and fish producing organisations should be prioritised as the target audience of information material.

The planned actions and achievements to meet the communication plan are outlined below.

2.2.15 Commercial fishers:

- Direct contact was made with a proportion of fishermen when planning and executing the tagging plan. Fishermen were appraised of the rationale of the project, and the purpose of the tagging work.

- Direct contact with fishermen was made as part of AFBINI / MI Industry Liaison programme. Industry Liaison Officers raised awareness of the project, and informally discussed fishing practices with to gain a greater understanding of the issues.

- Indirect contact was made through the FPOs and regional fisheries offices. Industry leaders were provided with information about the project, and asked to pass on this information or contact details if they receive any enquiries about the work.

- Media press articles were produced to communicate with stakeholders and the public.

- Posters detailing the tagging programme were produced and sent to fishing ports and FPOs. The posters produced in English, French, Dutch and Welsh and distributed in French, Belgian, Dutch and Welsh ports.

- A short summary of the project was translated into the languages of the majority of the crew working on local fishing vessels; mainly Egyptian, Polish, Filipino and Russian for distribution in ports, and vessel wheelhouses.

2.2.16 Recreational fishers

- Consultation was made with fishermen when planning and executing the tagging plan. Fishermen were appraised of the rationale of the project, and the purpose of the tagging work.

- AFBINI / MI distributed information packs to regional angling groups, including information regarding opportunity and training to become voluntary taggers.

- Posters detailing the tagging programme were sent to recreational fishing organisations throughout Ireland, Isle of Mann and west coast of the UK.

- Attendance by project staff at shore angling competitions provides not only tagging potential but also invaluable opportunity to speak to anglers directly about the project and to tailor the conversation to how they as stakeholders can be affected and/or become involved.

2.2.17 Press

- A Marine Times Article was published detailing the aims of the project, returns process and reward scheme; see March issue of the Marine Times newspaper.

- Off The Scale Article in March 2018: Detailed experience of AFBI and MI taggers with the angling community, some preliminary results and release and recapture maps, details of the returns process and reward scheme – Link:

- http://www.offthescaleangling.ie/issue21/issue21.html#&panel1-13%20

- Irish Angling Update in April 2018: The monthly newsletter published on the Irish Angling Update website which is emailed to their subscribers mentioned the tagging project in conjunction with an angling club competition, showing the involvement with the angling community – Link: http://fishinginireland.info/news/sea-reports/good-fishing-at-ballyhack-for-meapia-sea anglers/?utm_source=Irish+Angling+Update&utm_campaign=b9f6f2fb2b-EMAIL_CAMPAIGN_2018_04_19&utm_medium=email&utm_term=0_9f79bf242a-b9f6f2fb2b-263548273

- Project staff attended and presented at the Swords Angling Expo on 17th February 2018. The presentation was well received and the expo proved to be a good networking event providing contacts for future events.

- The project poster and information was provided to Sea Angler magazine in February 2018 who shared the content on their Facebook page. This was shared further by interested anglers.

- Angling NI published a press release pushed by the AFBI Corporate Communications department in April 2018. Link:http://www.gofishingni.co.uk/tag-a-cod-shore-angling-competition/

- A flyer (Figure 26) was distributed amongst anglers at shore competitions with maps detailing inshore release sites and information on the data collected from a returned fish.

Figure 26. Information leaflet distributed amongst angling community

2.2.18 Engagement with stakeholders

The results of the projects have been communicated to the NI-Gear Trials steering group, which includes representatives from fishery policy, fish producing organisations and fishers. The steering group is involved in a range of fishery selectivity improvement studies. At all quarterly meetings of the steering group scientist involved in the cod tagging study have been present. This allowed continual discussion of the results of the projects with both industry and policy stakeholders. Updates of the project have also been presented to the Seafish Northern Ireland Advisory Committee (SNIAC). The committee has membership form fish producing organization, government policy, scientific institutes and other NGO bodies. The committee meet 3 times a year. At all meeting of SNIAC scientists involved in the cod tagging study have been present to provide formal and informal updates of the project. The schedule meetings provide a regular forum to discussion the progress of the project form inception to delivery. A project update was presented at the ICES Working Group for the Celtic Sea Ecoregion (WGCSE) in May 2018 and in May 2019 (unpublished) at which the assessment scientists for cod in the Celtic Seas Ecoregion were present. The project was also included in the WKIrish 5 workshop, attended by scientists and industry representatives and a presentation given to the ICES data collation workshop (WKCeltic, 2019) which will develop new assessment methods for cod in the Celtic sea, ICES Area 7b-k.

2.3 Work package 2: The tagging campaign

The project proposal was for a 15-month intensive tagging programme to start in quarter 1 2016 and continue through 2017. Although there was a charter during the first quarter of 2016 and tagging carried out during the 'Fishery Science Partnership' (FSP) scientific survey a delay of 12 months in starting the full tagging programme, (e.g. training volunteers, attending recreational events) was caused by delay in recruitment of project staff. During the first phase 38 days-at-sea were carried out on chartered fishing vessels (30 planned), during which 2433 cod were tagged. At-sea commercial fishery observations (552 observed hauls) provided 2 tagged cod, 70 cod were tagged during 44 days of scientific survey days and 70 cod tagged from recreational angling events.

2.3.1 First phase of implementation

The first phase of the programme included training and equipping fishery observers to tag cod, organization of ad-hoc tagging during research vessel operations and engagement of recreational anglers. During the first quarter of 2016 AFBI staff concentrated on setting up initial procedures, tools and communication material to allow the project to be initiated. To take advantage of reports of a good abundance of cod in the area a short dedicated charter was conducted, staffed by existing fishery observers, with experience in previous tagging studies. All charters were completed on commercial fishing vessels with a track record in targeted fishing of whitefish in the Irish Sea or neighbouring sea areas. Short tows are preferred to increase likelihood that captured cod are in good condition and suitable to allow for tagging and release. Large mesh (100 – 120mm) demersal trawls targeting schooling cod in the mid-water (5 – 10m foot rope off bottom) or seine nets were the preferred method to catch cod in viable condition for tagging. Tagging achievement on these is detailed below:

2.3.2 Completed Charters

- Charter 1: Northern Irish Sea – March 2016 (AFBI)

  The charter was conducted in three short trips (influenced by weather conditions) during which 32 short hauls were fished. Catch rates were good and a total of 963 cod were tagged during the exercise. The charter covered the western Irish Sea grounds, including transitional areas, i.e., North Channel. All the cod tagged were above the MCRS. The tagging followed the defined Standard Operating Procedure (SOP) shared with all project partners. The vessel used a mid-water trawl, as used in commercial fishing, to catch cod.

- Charter 2: Northern Irish Sea – February / March 2017 (AFBI)

  The charter targeted cod of a range of sizes normally encountered in commercial fishing activity. Fishing occurred for up to 12 hours per day. The activity allowed for approximately five variable short tows (i.e. from 30 min to several hours) throughout the designated fishing area. Fishing was undertaken within the western Irish Sea (Area 7a) and North Channel between longitudes 4°50'W and 6°W, south of 55°N and north of 53°20'N. Fishing was conducted in a way, which samples across the entire area. Four fishing trips were undertaken over 15 days during which 645 cod were tagged.

- Charter 3: Southern Irish Sea/Celtic Sea – April 2017 (MI)

  The charter was conducted on board a vessel using a seine net. The number of cod tagged was lower than expected owing to low catch rates and damage from other species in the net. The condition of each fish was examined carefully to ensure that only viable fish were tagged and released. 166 cod were tagged. Spatially, the charter covered the southern neighbouring area of the Irish Sea.

- Charter 4: North/mid Irish Sea – April 2017 (MI)

  The charter was conducted over two days, before the MI staff member and skipper agreed to postpone the charter owing to low catch rates of cod. In total 25 cod were tagged out of a total of 39 caught. Using a demersal trawl.

- Charter 5: Southern area of spawning grounds in Western Irish Sea – July 2017 (MI)

  This charter used the method and vessel as described in Charter 4, but fished in the Irish Sea, south of spawning grounds. During the trip 173 cod were tagged.

- Charter 6: Deep water aggregations south east of *Nephrops* grounds – August 2017

  The charter used a mid-water trawl net to target cod of a range of sizes normally encountered in commercial fishing activity. Fishing occurred for up to 12 hours per day. The activity per day should allow for approximately five variable short tows (i.e., from 30 min to several hours). Five days were undertaken across two fishing trips during which 461 cod were tagged. It was noted that a higher pre-tagging mortality rate of cod was observed during the trip; a possible explanation for this was the higher air temperature causing added stress, fishing in deeper water and other biological factors such as parasite load. Intact specimens (15 fish) were retained and for post-mortem but yielded no conclusive results.

2.3.3 At-sea observer programme

Observers aimed to carry out tagging during routine observations. Observers reported that fish were not frequently caught and when caught were rarely in suitable condition. Practicalities with handling holding/recovery tanks during commercial operations also proved problematic on most vessels when vessels are engaged in commercial fishing activity. Due to all these factors, tagging through the observer schemes yielded significantly less tagging than originally anticipated. Although these non-designated tagging charters provide a platform to tag cod throughout the year.

2.3.4 Research vessel activity

Tagging during surveys on-board the *RV Corystes* was conducted although low numbers of suitable fish were encountered. Utilising vessel time within the existing survey programme required identification of time which coincide with suitable fishing conditions. During the on-going survey programme 14 cod were tagged. During the Northern Irish Fishery-Science Partnership survey (NI-FSP) in the both 2016 and 2017 carried out in the western Irish Sea opportunistic tagging of cod was prioritised. In 2016 12 cod were tagged with 44 tagged in 2017. The survey is used to assess the biomass of cod spawning stock biomass in the region. The fishing characteristics are akin to the commercial fishing activity that historically targeted cod with tow duration of 4 – 6 hours.

2.3.5 Recreational fishers:

During the first phase of the project tagging personnel developed a working relationship with the recreational angling community, attending shore competitions and sea angling boat trips in an attempt to tag cod, with four events providing 57 tagged cod. This also provided an opportunity to train and recruit volunteer taggers. Two volunteers tagger successfully tagged 5 cod during the first phase of the tagging programme.

2.3.6 Tagging in practice:

During charters, multiple holding tanks with continuous supply of fresh oxygenated seawater (at times, up to 4) were used. Cod were transferred to holding tanks, as a priority, to ensure the maximum number of cod from the haul were in a healthy condition for tagging. Cod permitted acclimatisation and recovery time within holding tanks before tagged and where possible, held for a time post-tagging in the holding tank before being released back into the sea. Only when a fish was successfully tagged and released alive were they added to the dataset to be reported. Fish in the holding tank with inflated swim bladders, upturned and unable to right themselves, or fish with 'low energy' levels despite excessive scarring or wounds present were not tagged. Some healthy tagged fish were observed being attacked and/eaten by sea birds after release, these fish were not included in the "tagged fish" dataset. Some catches during charters (specifically Charter 6 in 2017) included fish with heavy sea-lice (external parasites) infestations, with observed low energy levels, and so tagging was not performed. Samples were taken to the lab for post-mortem analysis but results proved inconclusive. Some upturned fish were deflated by scientists on board by piercing the swim bladder and allowed time to recover. This proved worth-while as two recaptures to date have been of individuals recorded as having their swim bladder pierced.

Project staff attending shore and sea-angling used a similar protocol during angling events. It was observed that fish caught at angling events tend to be in excellent condition for tagging given their short duration out of the water and small change in pressure owing to fish coming from shallower depths. Fish were rejected for tagging if injury had been caused by unhooking (even if the fish was still viable), to further reduce the possibility of post tagging mortality. This was to provide quality assurance and reporting accuracy.

In preparation for tagging, a tagging work-station was set-up and the available deck tanks filled with seawater, ready for the reception of live cod. The deck tank set-up would ultimately vary between vessels. Cod were manually removed from the trawl catch, gill nets or hooks and placed in deck tanks. If possible the codend of the trawl was lowered into a filled deck tank and emptied. The deck tanks received a regular and frequent exchange of clean seawater.

The expectation was that all cod considered to be lively and in good condition would be tagged with an external mark ID tag. Individuals suitable for tagging were measured before being placed onto a suitable surface such as a V-shaped foam block, where their gills and head were be covered with a wet towel (kept wet with fresh seawater). If possible, tissue samples were taken for future genetic analysis. Training of vessel crew in good cod handling methods, recording and tagging and release procedures was emphasized to maximize the chances of future live commercial discarding and survival of cod.

2.3.7 Interim review of tagging programme – November 2017

At a project meeting attended by all project partners in November 2017, the tagging approach and methods were reviewed. In the initial proposal, it had been anticipated that tagging could be carried out during at-sea observations within the existing fleet observer programme by national fisheries laboratories on both white-fish directed boats and the *Nephrops* fishery. Owing to long haul durations and practical constraints with limited space for holding tanks on board, extensive tagging during commercial operations proved prohibitively challenging. It was identified that commercial charters proved extremely successful. After an extensive and necessary review by all project partners, the tagging programme was redesigned and the focus placed on extending the commercial charters, with maximum budget committed to this tagging activity.

An analysis to evaluate the level of confidence in the current programme's ability to derive robust conclusions was applied. This analysis provided an assessment of the level of confidence that could be attributed to the observed patterns of recaptures and potential sources of cod mortality. The analysis used a time series of tag release events, recapture reports and simulated fishery removals. The results of the Lincoln-Petersen mark-recapture method (Pollock 1982) for estimating population size were examined. The analysis was applied using numbers of fish and converted to a biomass estimate. The catches by fishers were calculated from at-sea observed catch rates of cod. These rates were applied to the reported fishery activity, from logbooks, over the course of the tagging study.

The analysis diagnostics were used to review the confidence in the project and tagging plan to deliver fundamental population level insights in the cod population in the study. The results of the analysis were initially discussed with the EASME at the review meeting in December 2017, with further detailed discussion in January 2018. These diagnostics support that the implemented tagging programme could provide robust information about the Irish Sea cod population. Simulations of tagging effort in 2018 support that increased tagging effort in 2018 would continue to improve confidence in the population parameters derived from the study. Following an initial analysis of the recapture data collected at that stage and qualitative evaluation of tagging success, a tagging plan for 2018 was developed.

The results of post mortem examination of recaptured fish were discussed with regard to evidence to support the appropriateness of the tagging procedure to ensure viability of the method. All recaptures throughout the project were examined to ensure quality was maintained. For all recaptured tagged fish there was no evidence of mal-effect of tagging. Re-growth of skin around tagging sites, absence of abscess, blood spots and no evidence of necrosis was observed. This evidence supported the view that the tagging protocol was effective and all staff taking part in tagging activities were properly trained. Tagging equipment was taken on all AFBI fishing surveys on the research vessel *RV Corystes* by trained staff during in 2017, to allow for opportunistic tagging of cod. The 'ground fish surveys' in March and October and the Queen Scallop survey in June were identified as surveys with a high likelihood to yield most tagging opportunity.

2.3.8 Redesign actions

As commercial charters proved extremely successful and had provided the main source of tagged cod (963 tagged fish from the first charter alone), further charters were planned by both AFBI and the Marine Institute in Q1 of 2018 to coincide with the spawning season of Irish Sea cod. During the AFBI charter in late July/early August 2017, observers reported increased numbers of cod being unsuitable for tagging. Some cod were landed in order to carry out biopsies and lab tests to determine the cause of poor suitability. It was considered that March provided greater numbers of suitable fish for tagging, therefore all available budget was committed to charter days in Q1, with August/September charters being second choice should any budget be left over.

Additional charters:

- March 2018 – Western Irish Sea & North Channel (5 days)
- March 2018 – Northern Celtic Sea (5 days)
- August 2018 - Western Irish Sea (5 days)

It was planned that the charter programme would be extended until August 2018. In March 2018 AFBI would target cod in the North Channel and the Marine Institute in the Celtic Sea, with an overlap of tagging by AFBI and the MI on the Irish Sea cod spawning grounds. This spatial overlap was to ensure that the majority of effort was targeted on the largest aggregation of cod in the Irish Sea. All charters would be staffed by two experienced observers. In August 2018 AFBI would carry out a further charter to target cod in deep water aggregation in the Western Irish Sea.

Furthermore, that all charters would be staffed by two members of personnel, using contract observers where necessary, to ensure that the largest possible number of healthy cod were processed and tagged. During year one of the tagging programme it quickly became apparent that space for and logistics of deck tanks on board the

Nephrops fleet specifically proved challenging. This however, worked well on charter trips, where deck space for multiple holding tanks and a suitable workstation set-up was taken into consideration during vessel selection. The redesigned plan of November 2017 this was communicated to the contracting authority in December 2017 and January 2018. It was paramount to ensure that only viable cod with a high probability of survival should be tagged and released.

2.3.9 Research surveys:

A dedicated cod tagging trip was planned on the AFBI research vessel *RV Corystes* in late January 2018. It was intended that the AFBI project scientist would lead a 3 day cruise from January 31st to February 3rd 2018, along with trained personnel. Any ship time available for cod tagging whilst the *RV Corystes* was at sea, was committed to be utilised where possible. It was anticipated that any time available on other research cruises would have cod tagging added to the sailing orders as an additional duty of the cruise plan, either by way of a supplementary day or ad-hoc tows in between sampling stations of the relative survey. Where time and resources allowed on the AFBI survey schedule, fishing for cod and subsequent tagging was planned to be carried out. Tagging equipment and trained personnel were to be present on every cruise where potential cod tagging may occur.

The Northern Ireland Fisheries Science Partnership survey, conducted in March, provided some opportunistic tagging in 2016 and 2017, with some survey stations located at the cod spawning grounds. Tagging was, however, an additional task to be carried out where possible on top of the main survey tasks. To allow for more fish to be tagged more efficiently and maintain them in better condition, it was proposed that a dedicated tagger, most likely a contracted observer would also staff the NI FSP in March 2018, with the aim to improve on the previous year’s numbers of tagged cod.

2.3.10 Recreational tagging volunteers

A recreational tagging programme was also proposed for interested stakeholders to get involved in the tagging project. Tagging kits containing a tagging gun, 20 standard reward tags, record sheets, a SOP with pictures and a reward poster were put together to be distributed amongst suitable stakeholders in a plan to establish a voluntary tagger initiative.

2.3.11 Ad-hoc tagging

The Marine Institute has a well-established observer programme in the Irish Sea and Celtic Sea for offshore and inshore vessels. Trained observers were provided with tagging kits and asked to avail of any tagging opportunities of healthy cod while sampling at sea, with the permission of the skipper. AFBI fleet observers were trained and continued to take tagging kits to sea on all observation trips, including pot fishing vessels, *Nephrops* and whitefish directed fishing vessels, to undertake opportunistic tagging where possible.

Opportunities to tag during the commercial inshore fishery were investigated. Project staff contacted pot-fishermen to carry out observation trips on their vessels in a bid to tag any cod caught. The Marine Institute’s inshore team were enlisted to provide contacts and possible tagging trips alongside their regular sampling trips.

The tagging programme review also identified the need to allocate more effort towards generating tagging opportunities targeting cod below MCRS, to ensure the sample of cod tagged was reflective of the Irish Sea cod population. Project staff attended national angling competitions, which provided some cod for tagging and received reports of good inshore fishing during the winter months. An extensive schedule was developed for project staff to attend shore competitions and sea angling boat trips in an attempt to increase tagging numbers and target fish below the MCRS.

2.3.12 Update to reward scheme

After review of initial data the rate of recaptures was lower than expected < 3% compared to rates exceeding 27% (Burt *et al*., 2006). It was discussed that a potential reason for this was that while the commercial fishing skippers are locals, the majority of crew are foreign, often with limited English language skills, therefore the posters may have been having only a limited impact. Skippers had been contacted directly by project staff, but this did not guarantee that the information was passed on to crew. There had also been some feedback from the industry that the EUR 25 reward was not viewed as sufficient incentive to encourage crew to look for tags. To increase the likelihood of crew actively looking for tags, as well as the likelihood of skippers passing on project information to crew, the decision was made to increase the tagged return incentive. Previously there had been a EUR 25 reward for red tags and EUR 75 for pink, blue or yellow tags. An increased incentive of EUR 1000 for every 20th tagged cod returned to the project (for a period of time at project staff's discretion) was added in December 2017. It was expected that this would increase the incentive to check for tags and for skippers to pass on project information to their crew. Furthermore, the opportunity was taken to increase additional media coverage published when a EUR 1000 reward was received in the relevant fishing news press, social media, AFBI and MI websites.

2.3.13 Second phase of tagging programme; January 2018

- Following the interim review of the project, by project partners in November 2017, an updated tagging plan for 2018 was adopted. The focus of intensive charter tagging trips was considered to be best applied in quarter one, focused in the western Irish Sea but exploring other areas also. Extensive tagging using other methods, at lower intensity would still be applied outside quarter one and some shorter charters were planned for quarter three when fish concentrate in deep water. Every opportunity to tag cod was taken and extensive resources and staff were provided to the project in-kind.
- Charter 7: Irish Sea spawning grounds and Celtic Sea – February/March 2018 (MI)
- The first trip was carried out at the end of February in the Celtic Sea Conservation area (statistical rectangle 32-E3). The charter was conducted using a demersal trawl to target schooling cod. After 12 hours of searching for cod within the closed area, the vessel moved outside the conservation area to finding cod at low densities. The vessel returned to normal fishing activity (non-chartered time) and allowed any cod that came on-board to be tagged. The vessel was out for a total of three days – two days of which were dedicated to cod tagging – and tagged a total of 41 cod in the Celtic Sea over 13 hauls.
- In mid-March this charter was re-commenced following reports of cod catch by the vessel. Four days were spent fishing in the Irish Sea where 225 cod were tagged and released over 28 hauls. Weather disrupted the trip and the vessel returned to port until conditions improved. During the 3rd trip, three days fishing resulted in 170 tagged cod over 17 hauls, weather was again the cause of return to port. The vessel was contracted for one further day of tagging and the vessel owner committed to providing a further day of dedicated cod tagging and accommodating MI staff member(s) on-board during regular fishing trips later in the summer to tag any viable cod caught. The remaining two days of tagging on-board the charter vessel were to be arranged with the vessel owner.
- Both phases observed that dense cod aggregations were scarce in the western Irish Sea during the first quarter of 2018. 46% of the cod tagged during the charter programme were tagged over four days of fishing effort in the North Channel where cod were observed in dense aggregations and were ideal for tagging (in good condition when caught). Every effort was made to tag as many viable fish as possible.

- Charter 8: North Channel and Western Irish Sea – February / March 2018 (AFBI)
- A total of 975 cod were successfully tagged and released over four dedicated commercial charter trips in February and March 2018. Four days were spent in the North Channel where 647 cod were tagged over 18 hauls. 10 days were spent in the Western Irish Sea where 328 cod where tagged over 39 hauls. During the four trips over 89 % of the cod caught were tagged, mortality rates were considered low. Two dedicated cod tagging staff were present on each of the trips and the vessel provided plenty of deck space, allowing for four holding tanks when needed. Tagging was carried out from 25/02/2018 - 21/03/2018 when progress was impacted by poor weather conditions. Trips were ended prematurely on two occasions due to storms and cod gradually dispersed, resulting in few cod caught per haul towards the end of March. 14 days were completed before catch rates decreased to a point where continuing with the charter was no longer deemed to be providing sufficient catch rates. The remaining six days were reserved for use in August/September to carry out further tagging.
- Charter 9: Western Irish Sea – August 2018 (MI)
- Dedicated cod tagging was carried out by the Marine Institute from 28/08/2018 – 30/08/2018, where 85 cod were tagged over 13 hauls. The vessel used demersal trawl fishing gear. Fishing was concentrated in the Western Irish Sea but cod catches were deemed to be low. In total, 85 cod were tagged.
- Charter 10: Northern Irish Sea – September 2018 (AFBI)
- A further 203 cod were tagged and released in early September 2018 during a dedicated commercial trip. Two dedicated cod tagging staff tagged fish over 16 hauls in the northern Irish Sea. The vessel was used previously on dedicated tagging charter on the current project and so crew were experienced in survey operations and aiding the scientific staff in preparing the deck tanks as before. Finclip samples were taken from tagged fish. Cod were in good condition to be tagged and mortalities were retained for biological analysis.

2.3.14 Research Vessel Activity

A biological survey during which all viable cod was planned for tagging was conducted on AFBI’s *RV Corystes* from 31/01/2018 - 02/02/2018. Both AFBI’s cod tagging project manager and the MI cod tagging technician were present as well as two additional AFBI scientists. After review of historical cod landings data and consultation with local skippers, six hauls were fished over two days on cod grounds, however, low catch rates were observed. The survey experienced adverse weather conditions resulting in one survey day being lost. Other whitefish vessels were also operating in the fishing areas and yielded similar low catch rates of cod. This aided the decision to delay dedicated commercial charter days until the end of February as cod aggregations had not begun to show at this time.

- During the project review in November 2017, four research surveys planned for the *RV Corystes* and chartered survey vessels in 2018 were identified where cod tagging could be carried out through either supplementary time or ad-hoc tows between normal survey operations:
- Ecosystem Survey (February 2018) *RV Corystes*: This survey coincided with the first few dedicated charter dates and therefore cod tagging staff were unavailable for the Ecosystem survey. Time on the commercial vessel rather than the Ecosystem survey would provide more opportunity for tagging cod.
- Groundfish Survey (March 2018) *RV Corystes*: Three dedicated cod tagging days were conducted within the time allocated for this survey, since the survey objectives were met on time. The groundfish survey was completed in good time, allowing for the vessel to return to port to pick up cod tagging personnel and carry out three more days of semi-pelagic fishing from 23/03/18 - 26/03/18. Five hauls were fished in the Western Irish Sea and two hauls in the North Channel where 18 cod were tagged. Cod aggregations had dispersed.

- Despite providing some tagging opportunity in previous years, the Queen Scallop Survey on board the *RV Corystes* in July 2018 and the Groundfish Survey in October 2018 did not catch any suitable cod for tagging.
- Fishery-Science Partnership Gadoid Survey (March 2018) – *MFV Sparkling Sea*: The *MFV Sparkling Sea* was charted to carry out this survey, accompanied by a member of the fleet observation staff as a dedicated tagger to maximise on tagging opportunity. Fishing tow durations averaged of six hours and therefore not all cod were in suitable condition for tagging, however, 113 healthy cod were tagged.

2.3.15 At-sea Observer Programme

A target of 20 pot sampling trips from January 2018 to August 2018 were planned. Progress was reviewed on an ongoing basis. Fish hauled in pots are normally in excellent conditions for tagging. Despite conversation with pot fishing skippers to gain more understanding of numbers caught in pots, these fishing trips did not yield much success. When time allowed, project staff continued to carry out pot fishing trips for opportunistic tagging, however the target of 20 days was lowered in priority. In total 13 pot fishing observation days were carried out, yielding 4 tagged cod.

One pot vessel skipper showed an interest in contributing to the project by utilizing a tagging kit so after a tagging demonstration onshore, the vessel utilized the kit when opportunities arose, resulting in 16 voluntary tagged cod during pot fishing activities. Various other methods were trialled and tested to capitalise on all tagging opportunities, including using a vivier to hold cod caught in fishing pots and purchase of cod traps. Every effort to tag cod at any given opportunity was seized during the duration of the tagging scheme.

AFBI fleet observers continued to take tagging kits to sea on all observation trips (584 hauls observed) including pot fishing vessels, *Nephrops* and whitefish directed fishing vessels to undertake opportunistic tagging where possible. Tagging opportunity on commercial fishing vessels remained low due to the long towing duration and the inability to use holding tanks of adequate size (deck space restrictions) yielding only a single cod for tagging in the second phase. The Irish Sea was ‘closed’ to targeted whitefish activity during February to April. The targeted haddock fishery which can yield cod began on May 1st, however an increased cod TAC for the Irish Sea further limited fish available for tagging. In total 15 cod were tagged on commercial trips of this nature.

2.3.16 Recreational fishers - Shore & Sea angling competitions

The tagging programme review also identified the need to allocate more effort towards generating tagging opportunities targeting cod below MCRS, to ensure the sample of cod tagged was reflective of the Irish Sea cod population. Cod tagging personnel developed a working relationship with the recreational angling community, attending shore competitions and sea angling boat trips in an attempt to tag cod. This proved the second most successful tagging activity after commercial charters in terms of numbers as well as suitable fish condition. Significant effort was directed towards capitalising on this opportunity, particularly in the last year of the project.

During phase 2 a total of 29 angling competitions were attended with 267 cod tagged. The recreational angling clubs were engaged to assist in the project. Whilst project staff attended shore competitions on beaches along the East Antrim coastline, feedback from anglers was that historically good cod catches were seen off the more exposed coastlines, rocky outcrops, near deeper ledges and piers along this particular stretch of coastline, in winter and during the April/May “spring run” of cod. Cod are not frequently targeted in these competitions. To test the ability of this approach to provide opportunity, a "Tag a cod" competition was organised by project staff and co-hosted Sea Angling Club. This competition took place on 28th April 2018. The competition was attended by 47 anglers, fishing for 5 hours from rocky outcrops and piers using methods targeted at catching gadoids. In total 3 cod were caught and tagged. During the summer months in 2018, 16 trips, through a combination of angling boat charters and individual trips were accompanied by tagging staff.

2.3.17 Voluntary Taggers

Fourteen tagging kits were provided to interested anglers and one potting fisherman tagging 66 cod during phase two of the tagging programme. The Ulster Wildlife Trust (UWT) secured funding for an elasmobranch tagging study to be commenced in the summer/autumn of 2018. The AFBI and the UWT project coordinator planned to run tagging training in a collaborative capacity to multiple anglers at various training sessions around the country.

2.3.18 Overview

During the second phase 32 days-at-sea were carried out on chartered fishing vessels (15 planned), during which 1699 cod were tagged. Charters for this phase were originally planning for 15 tagging days, but were increased to 32 – the maximum that could be achieved with maximum budget committed. This was increased to attempt to increase tagging numbers, since other methods yielded low numbers despite significant effort. Achieve of at-sea commercial fishery observations (584 observed hauls) provided 1 tagged cod, 131 cod were tagged during 16 days of scientific survey days and 333 cod tagged from recreational angling events, including 66 by voluntary taggers.

2.3.19 Review of the tagging programme

Conceptually this project was initiated as a large scale tagging programme attempting to tag both juvenile and adult cod. The project proposal therefore considered all possible opportunities for tagging to maximise tag opportunities from existing sampling programmes as well as funding a number of charters through the project (focusing on cod closure periods, for example). Tag numbers were originally estimated based on catch rates observed at that time during the entire suite of sampling activities and was informed by tagging achievement in previous projects. The aim was to maximise all tagging opportunities with assumptions made on catch rates on commercial vessels, potential charter vessels and research surveys. The availability of fish to tag is, of course, completely dependent on the stock abundance, commercial gear selectivity and effort. The significant uncertainties associated with this was a known entity at the time of project commissioning.

The project proposal was for a 15-month intensive tagging programme to be conducted during year one of the project and the first quarter of the second year. Although there was a charter and tagging during on-going surveys during the first quarter of the 2016, the delay in the recruitment of the dedicated tagging personnel resulted in delay of intensive tagging programme by 12 months, but when initiated this continued for 20 months. Dedicated tagging personnel remained in post for the duration proposed in the project plan.

Lower than expected recapture rates were observed during the initial stage of the project. The project was initiated and resources campaigned for by the fishing involved, therefore, buy-in and awareness was thus high from the onset of the tagging activities and industry cooperation was considered unlikely to have a negative impact on return rates. Given the significant implication of low return rates within the context of high total mortality for the stock, focus was shifted completely for fish condition to mitigate the possible influence of post tag mortality on the results. This change in emphasis was supported by feedback received on review of the initial project reports by EASME. The result of the focus on quality and fish condition, rather than quantity clearly effected the absolute numbers tagged.

As a result, some tagging activities, e.g. at-sea observer tagging during commercial operations, did not yield the tag numbers estimated. The tagging effort increased on less intrusive capturing techniques, such as pot and recreational fisheries, but this resulted in low tag numbers (<10) in relation to tagging effort. Chartering commercial vessels proved to be the most effective method and produced the highest proportion of fish in good condition. Being a costly part of the tagging programme, the initial project plan allowed for 30 charter days. Despite the budgetary implications, the project plan had to be amended to ensure robust delivery of the scientific objectives of the project. Completed charter days more than doubled to 69 days over the duration of the project.

At the review stage an analysis was applied to examine the ability of the project to deliver robust population level parameters. The analysis was carried out at the interim project review stage to inform the plan for tagging in the second stage of the tagging program. The purpose therefore was to use expected tagging rates based on lessons learnt during the initial stage.

An absolute assumption of direct proportionality between tag numbers and tagging effort would be incorrect. In the first instance there is no consideration given to tagging quality or success. For example, tagging all cod by-catch from the commercial fishery regardless of fish conditions would have resulted in a larger number of tagged fish, however even within a fisheries management context the assumption would be for zero survival of these fish. Alternatively effort could have been biased toward nursery areas to generate high catch numbers, however, this may have impacted the ability of the project to meet its objectives, in particular, with regard to elucidating the steep age structure of Irish Sea cod. Similarly, in a scenario where the population abundance declines during a tagging project, an increase in tagging effort will yield less tags compared to a scenario of stable population. Tagging effort, in fact, exceeded that initially planned over the duration of the project. Whilst lower tagging numbers were achieved compared to the original estimate, this is a reflection of the changing behaviour within the fishery, management and control, and natural variability of the population beyond the control of the project.

2.4 Work package 3: Results & Data analysis

2.4.1 *Review of mark-recapture analysis methods*

Typically tagging studies create, by marking them, a subset of animals within their population that are known and can be identified by their tags or marks. Following a period of time allowing this marked subset of animals to mix with the rest of the population, their progress is then followed by means of their recapture and reporting, in both space and time to provide information that can be associated with the entire population. Tagging studies have historically utilised an array of methodologies to provide information on aspects of fish biology and behaviour. These methods rely on marking and recapture events and have become common since the mid-17th century with a mark-recapture method first used for ecological study in 1896 by Petersen to estimate plaice (*Platichthys platessa*) populations (Petersen 1896). Over time the methods and application of mark-recapture studies have evolved. Initially the technique was used to estimate abundance, developing into a method to assess survivability and sources of mortality and more recently explore species behaviour. The ability to achieve these applications is linked to advances in tagging technology, with available tagging now ranging from passive non-permanent ink-marks, non-digital plastic tags, micro coded wire tags, to radio-frequency identification (RFID) tags and electronic tags recording storing environmental and positional data such as data storage tags (DSTs) and satellite tags, providing real time behavioural data. In some instances chemical markers using methods such as radiochemical dating or marking with calcium-binding chemical oxytetracycline, alizarin, or calcein are appropriate, where large numbers of individuals can be tagged and ageing and growth is a focus of the study, as such techniques laydown a marker in the skeletal component used in ageing (Wilson *et al*., 2011).

Conventional mark-recapture methods can inform biologists about the two specific time points in the life of a fish – when caught and tagged, and when recaptured – in some cases multiple recapture events on the same individual can occur. In addition to collecting spatiotemporal data regarding the location of tagging and recapture the condition, age, body mass, length and other biological parameters can be collected at both the initial and re-capture events, and information inferred as to the behaviour and biology of the fish during the period at liberty.

Within any tagging study there are assumptions which under pin the analysis. These must be recognised to ensure valid interpretation of results:

- Marked animals are not affected (either in behaviour or life expectancy) by being marked, and the marked individuals can always be attributed to a marking event.
- Marked animals are representative of the entire population.
- The probability of capturing a marked animal is the same as that of capturing any member of the population.

Mark and recapture is a method commonly used in ecology to estimate an animal population's size. The principle used to calculate the population size is based on the theory that when a sample from a population are caught, marked, returned to the population, allowed to completely re-mixing and are re-sampled, the number of marked individuals in the second sample will have the same ratio, as the total number of marked fish in the population. From this, the population size can be estimated. This is the most basic form of the analysis. Other intricacies and assumptions are however, made within a range of analytical techniques.

Populations can be classified as either open or closed. A closed population remains unchanged over the period of study whereas an open population changes because of some combination of birth, death and emigration. Closed models include the Lincoln–

Petersen model and are most appropriate for short-term studies (Otis *et al*., 1978; Seber 1982).

In its simplest form the population estimate for a mark-recapture study is derived:

$$M/N = x/n$$

Rearranged to:

$$N = nM/x$$

Where *N* is the population size, *M* is the number of marked individuals in the first catch, *x* the number of marked individuals in the second catch and *n* the total number of observed individuals in the second catch.

These methods assume that the population does not change over the period of study – no immigration or emigration, births or deaths – which is termed a closed population. It is therefore essential that this period is short compared to life expectancy. Further, individuals must not be able to enter or leave the study area. Methods in which the probability of capture is not assumed constant require a series of occasions (at least two) on which animals previously marked are recaptured, marked again, and released.

A number of methods have been developed to estimate population parameters for open populations, of which the most general is the Jolly-Seber method (Williams *et al*., 2002). Simply tagging offers both a full Jolly-Seber analysis and a reduced model in which probability of capture and survival are assumed to be constant over the period of the experiment. Before either of these methods is attempted, it is important to note that they are unlikely to produce good estimates unless a high proportion of the population is tagged. If only a small proportion of the population are captured, then closed methods should be used and effort is best expended in ensuring that the population can be assumed closed for the duration of the experiment. Pollock (1982) detailed 'the robust design', a combined analysis design using aspects of both closed and open models. Within this method a series of discrete, closed population studies are linked to provide an estimate population of abundance with an open-population model to estimate survival (analysis of mark-recapture data to estimate aspects of survivability are dealt with below). The main advantages of the robust design is that it allows for unequal capture probabilities and also temporary emigration of fish (Williams *et al*., 2002).

The present study used the 'robust design' (Pollock 1982), with multiple tagging events and continuous reporting of recaptures to inform the tagging study and ensure validity of the results. A population assessment was applied using the Lincoln-Petersen mark-recapture method for estimating population size was applied. This method allows an estimate of population size to be derived from the current tagging programme, whilst making an assumption about losses from the population due to natural processes. The method was used to assess the power of the tagging study as a diagnostic comparison with the ICES assessment of Irish Sea cod SSB.

One of the objects of tagging experiments is to estimate the survival rate of the individuals in the tagged population. The final estimate may be expressed in terms of the proportion of individuals that survive for one time step (e.g. a year) or as an instantaneous coefficient of total mortality. Typically, methods for estimating survival rates are divided into two groups (Jones 1979):

Methods for estimating survival rate when tagging have been done on one occasion only. If tagging is carried out at single event the survival rate can be determined from the rate of decline of the tagged individuals. Recaptures can be made during a number of focused recapture attempts to record the tagged individuals surviving in the population. This method is considered appropriate when a large proportion of the population can be tagged and recapture rates are expected to be high. These methods are more often applied in focused, small-scale studies on discrete subunits of a population (e.g. Weber *et al*., 2016).

If the expectation of obtaining tagged fish in subsequent samples is small, continuous monitoring of recaptures over an extended period is appropriate. This is frequently the study design applied with mark-recapture experiments on commercially exploited, widely distributed fish stocks (Fabrizio *et al*., 1999).

Both scenarios rely on the ability to calculate the proportion of the total numbers of tagged individuals remaining in the population at successive times. Additionally, regression estimates, assuming a constant mortality rate with the decline in the numbers of tagged individuals can be expected to approximate to an exponential curve (Beverton and Holt 1956, Paulik 1963, Gulland I969).

In the case that populations are large and/or widely distributed or where non-permanent methods of marking are used, multiple tagging events are often required to ensure a sufficiently large proportion of the population is marked at a given point in time. In this case the data analysis must classify the marked-recaptured individuals suitably. Often this classification relates to the probability of recapture. When the probability of encountering an individual on a number of occasions is high, a decision on data analysis should reference:

- All occasions of marking & recaptured
- The last occasion of marking
- The occasion on of first released.

Within the current project it was expected that multiple recaptures of the same individual would be rare with release of recaptured fish unlikely. The key objective of the current study was to establish sources of mortality – this predicated that the analysis of the recapture (and mortality) would be limited to the cause of the non-natural mortality.

Tagging studies can provide valuable data for measuring growth under the assumption that the marking process does not affect growth. The individual growth trajectories from tagging data aid in identifying the key sources of variation. This can be especially important for species that cannot be aged or that can only be aged with difficulty. In this case multiple repeated sampling at regular time intervals are used to establish length (or weight) with age, where age is inferred from the cumulative time since marking. A growth curve can be fitted to these data using methods such as the Von Bertalanffy curve. In cases where sampling is carried out over unequal time intervals, Gulland and Holt (1959) described a graphical estimation method with conversion to a linear equation.

In situations where individuals can be easily aged, the growth increments from tagging studies, irrespective of sampling interval, provide a means to validate existing growth models (Hamel *et al*., 2014). Alternately, mark–recapture techniques to estimate growth rates (and ages) are particular well-suited for long-lived species. These methods can be used to validate both the periodicity of growth increments and the absolute age. An integrated analysis of these complementary data sources provides the most reliable approach for understanding growth (Pine *et al*., 2012). When fish age is known at marking, either directly or inferred (i.e. young fish), absolute age validation can be performed when fish are recaptured. In the case that the age is unknown at the time of marking, multiple recapture events (a minimum of 2) will be needed to inform on growth rates. It is unlikely that conventional markers, such as implanted tags, will be a viable method in these cases and other methods will be needed – these experiments often rely on chemical markers using methods such as radiochemical dating or marking with calcium-binding chemical oxytetracycline, alizarin, or calcein.

To inform knowledge of Irish Sea cod biology it was planned that recaptured cod would be sampled biologically in order to determine sexual maturity, stomach content, age (by obtaining otoliths for future age determination studies) and stock identity (by obtaining a finclip for future genetic studies). During tagging activities only lively cod were tagged and recorded in the dataset, finclips were taken for ongoing genetic studies, while biological sampling was carried out on all remaining cod captured. The length of cod at the time of marking and recapture was recorded. Age and length change would be used to validate and refine existing growth models of Irish Sea cod derived through traditional sampling. Additionally to improve knowledge and understanding of cod catches it was planned that the characteristic of the catches continuing tagged of cod by a vessel would be recorded and submitted with each fish when a tagged cod was recaptured. In practice, this was rarely the case, most recaptured tagged cod were returned with the recapture location, date and vessel details only.

Information derived from mark-recapture studies is essential in developing spatial management programs such as marine protected areas or defining the spatial limits and management areas of a stock. Within the analysis suite of mark-recapture records, a number of parameters can be derived describing the movement of marked individuals. These parameters can explore aspects of animal behaviour, such as speed and direction of movement. The simplest way of demonstrating the pattern of movement of a group of recaptured marked fish is pictorially. The position of recapture of each fish can be plotted on a chart in relation to its position of liberation and its mean direction and distance of travel can be indicated. To achieve accurate derivation of quantitative parameters it is necessary to have a recapture method with sufficient interval, which will be determined by directionality and speed of movement, to ensure the marking and recapture locations, represented by a straight line, give a reliable indication of the overall direction and distance of movement (Figure 27). For highly mobile species, this can dictate that conventional marking methods are not appropriate and data storage tags (DSTs), which log locational information at a higher rate than directional change occurs, should be used as these can show all movements between the time of marking and tag recovery.

Movement information from DSTs can provide in-depth data of animal behaviour, such as vertical daily movements within the water column in relation to feeding behaviour or predator avoidance. It must be noted however, that these are non-independent, auto-correlated observations, and must be balanced in comparison to the independent observations of recaptures from conventional tags. This is particularly the case when analysing selectivity behaviour, such as habitat selection, when assessment of choice is the aim of the study (Boyce, 2010). Alternatively the use of isotopic and elemental markers may be used as forms of ‘natural tagging’, to determine natal origins and to assess large-scale movement patterns of larvae, juveniles and adult fish over large areas (Elsdon *et al*., 2008).

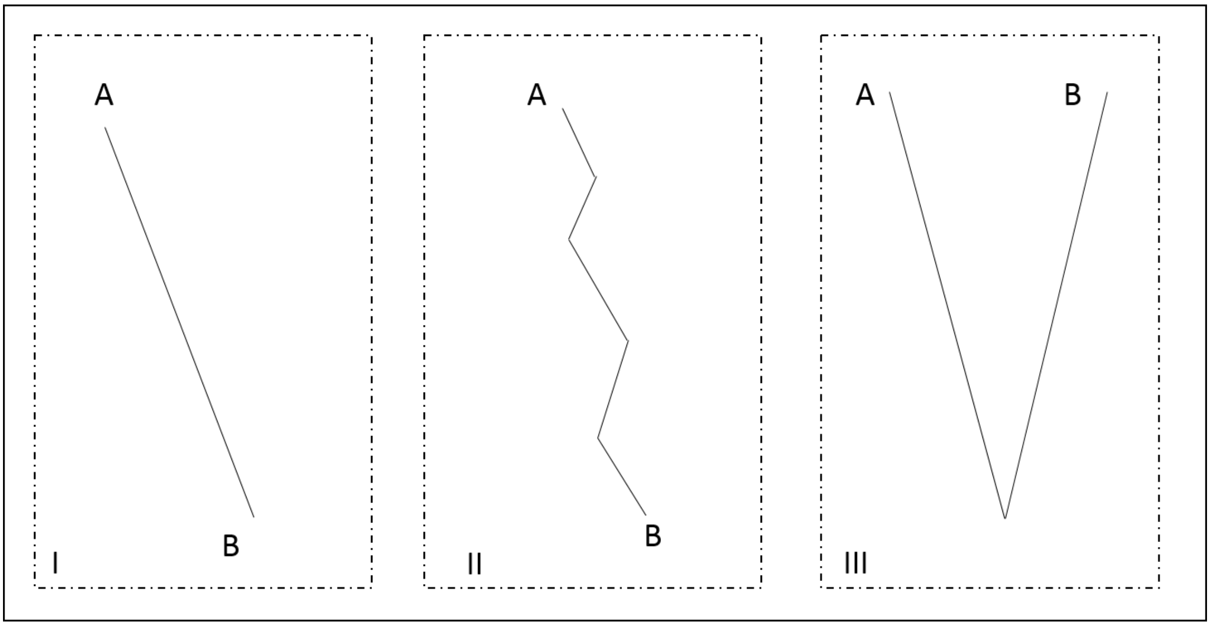

Figure 27. Hypothetical movement paths between marking location 'A' and recapture location 'B'. Panel I. shows a scenario where the marking and recapture interval is sufficient to define both direction and speed of movement. Panel II. shows a scenario where the marking and recapture interval is sufficient to define direction but insufficient to accurately represent fine detail and speed of movement. Panel III. shows a scenario where the marking and recapture interval is insufficient to define either direction or speed of movement.

Tagging and analysis of recapture data provides a method to inform population ranges. Population-level estimates of species' distributions can reveal fundamental ecological processes, facilitate conservation and assist in the appropriate definition of management units. Data from DSTs may also be applied to explore individual animals ranging or movement patterns. This information can be useful when defining local level conservation or exploring the potential impact of an activity at a site scale. Methods for the analysis of this data can be both non-statistical and statistically derived. Non-statistical methods can include mapping location information and provide limits of the distribution, such as observed range boundaries in terms of latitudinal or longitudinal ranges – a Minimum Convex Polygon (MCP), bounding 100% of all recapture and marking location. Alternatively, analytical methods can quantify the probability of utilisation distribution (UD) – the probability that an animal spends time in given areas.

Within the UD there are distinct areas which are defined by the 'characteristic' of their usage. These are defined by the frequency, or density of use (Burt 1943):

- The home range or core of an animal or group of animals is the area that is inhabited while engaging in daily activities.
- Geographic range is the geographic extent of the distribution of a species.

These areas are frequently estimated using kernel density analysis. The geographic range is often defined as the 95% or 90% kernel densities (Borger *et al*., 2006). Use of 50% of locations is considered as a core area of the range, as the area most frequently used by an animal or population within its whole home range.

The use of mark-recapture data can elucidate a wide array of information ranging from population estimates to species behaviour. The design of any study and the question of interest will dictate the appropriate analysis methods but must be interpreted with respect to the assumptions of the marking study to accurately reflect individual or population level parameters. The use of UD was applied in the current study to determine the distributional range of Irish Sea cod and compared with the spatial overlap of stocks in adjoin areas.

2.4.2 Data analysis of recapture data

Multiple tagging opportunities were utilised during this study including: chartered commercial fishing vessels, research survey vessels, at-sea observer programmes and recreational fisher events. Charters proved to have provided by far the most effective method to maximise tagging rates (fish tagged and released per day). Charters focused on the known spawning aggregations during Q1 in the study region and mid to late summer and utilised semi-pelagic trawling, bottom otter trawling and purse seine fishing. The second most successful tagging activity was through recreational angling events. Project staff attended shore competitions, angling boat trips and charters, as well as recruiting voluntary taggers from the angling community who could continue tagging *ad-hoc* outside of competitions. The project also organised a cod tagging shore competition. Tagging at angling events targeted fish below the minimum conservation reference size (MCRS), in inshore waters, to further strengthen the range of spatial coverage and size distribution of Irish Sea cod included in the tagging programme (Figure 28).

In total, 4743 cod have been tagged (Table 7.) details of the capture events are provided in Appendix 1. The coverage of the tagging scheme was more comprehensive spatially, temporally and by fishing method, than any previous tagging study of the region (Figure 29 & Figure 30).

Table 7. Number of fish tagged each year by each tagging source.

Year	Charter	Shore Angling	Sea Angling	Scientific Survey	Commercial	Voluntary
2016	963	0	0	0	12	0
2017	1470	95	8	58	6	5
2018	1699	77	152	131	1	66
Total	4132	172	160	189	19	71

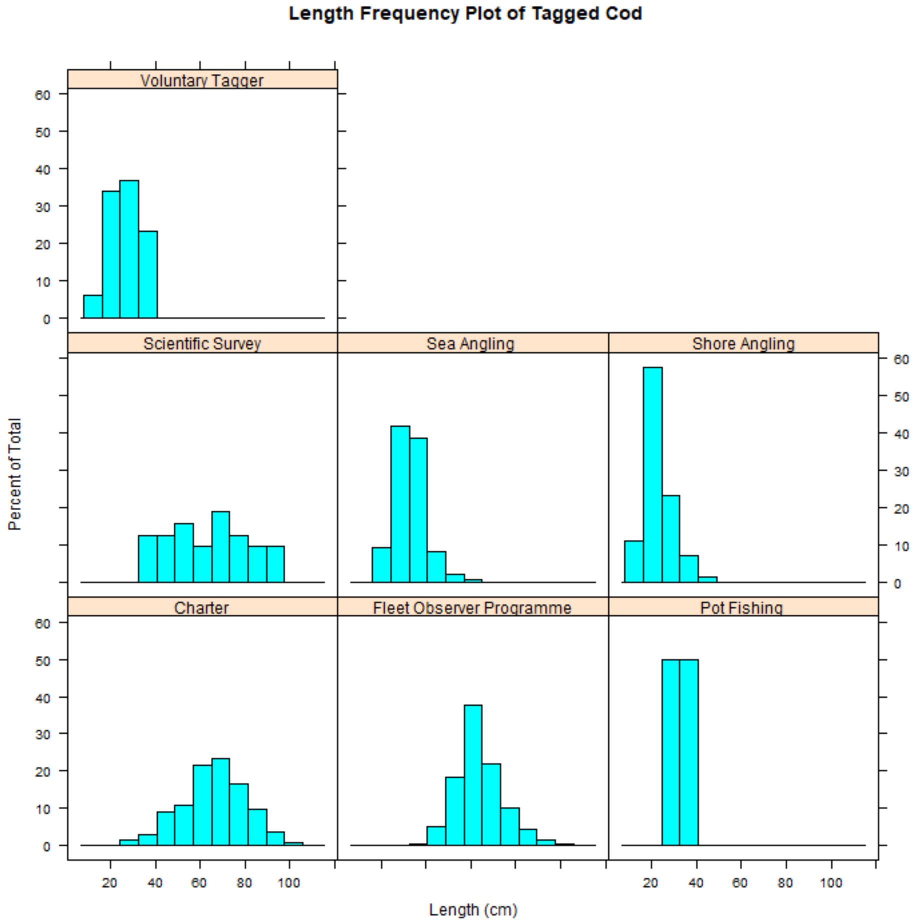

Figure 28. Length frequency distribution of tagged cod by tagging activity. Data is aggregated across all sampling events for separate sources.

Planned cod tagging charters focused on the known cod spawning aggregations in the Western Irish Sea (7a), with an intentional overlap by AFBI and the MI's charter vessels to obtain good coverage in this area. The North Channel (6a) and Northern Celtic Sea (7g) were also targeted as "spill over areas" but to a lesser extent. There are no known cod aggregations in the North Channel outside of the Firth of Clyde cod box, which exhibits fishing restrictions in Q1 is a recognised spawning region. There is also significantly less fishing effort from whitefish directed fishing vessels. The time spent at various locations reflected all these factors, while ensuring fishing was conducted in a way which sampled across the entire area and targeted cod of a range of sizes normally encountered in commercial fishing activity. The coverage of tagging release locations achieved complete coverage of the known fishery data as reviewed in section 2.2.7.

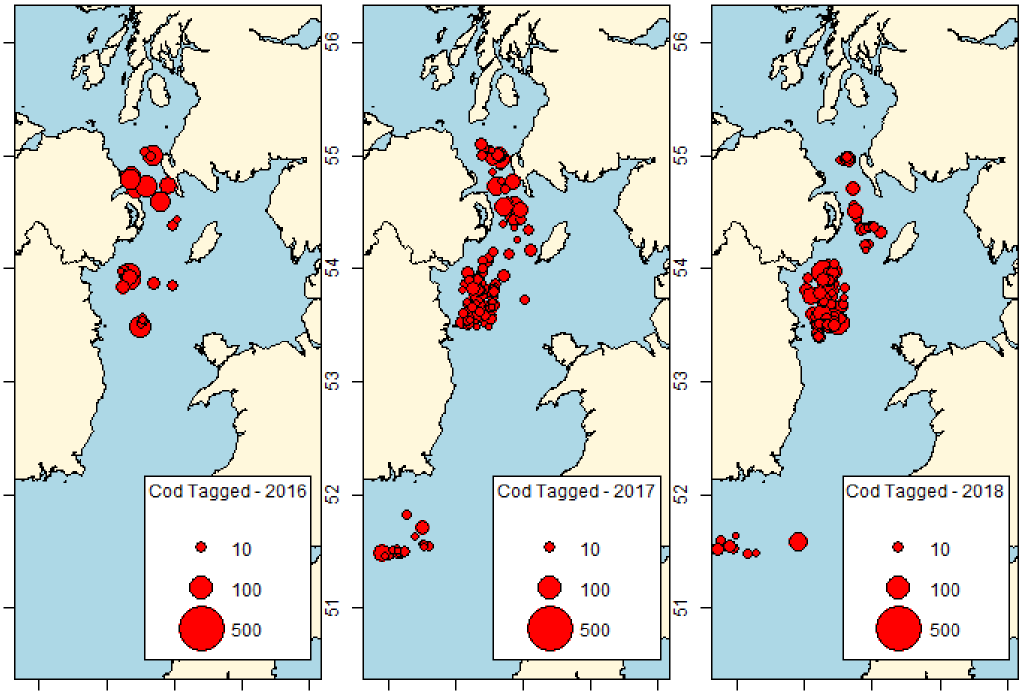

Figure 29. Map of showing haul/release positions and the number of tagged cod released in each years of the project 2016 - 2018. Symbols are scaled to the number of fish tagged in each fishing haul or event in the case of recreational angling.

To date 187 recaptures have been reported (3.92% return rate), with 172 of these with complete datasets sufficient for data analysis (3.61% return rate). Recapture rates remain lower than anticipated – a recapture rate of 10% may be expected based on previous studies – despite increased reward incentives and full implementation of the extensive communication plan. The recapture of 172, with 161 used in the analysis suggests the study has the ability to detect a medium size effect with high power based on the applied power analysis.

The current spatial analysis records supports that the range of Irish Sea cod extends as far south as 50.5° N, overlapping with Celtic Sea cod and extending beyond the southern boundary of the Irish Sea. Within the current tagging project no movements of cod from the Celtic Sea to the Irish Sea have been observed. Recapture records are providing further insights into the behaviour, biology and range of Irish Sea cod (Figure 30). This supports the historic review of tagging data, although shows a more extensive distribution in the Celtic Sea than previously observed.

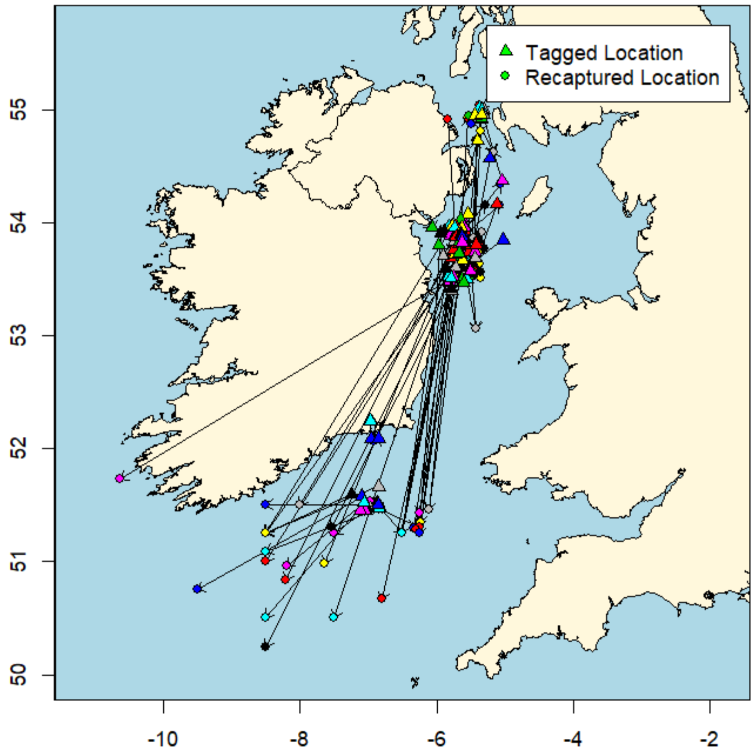

Figure 30. Release and recapture positions of all recaptured cod reported until November 2018. Triangle symbols denote tagging location with circles indicating recapture sites.

Recaptured tagged cod were predominantly caught by the 'TR1' fleet (fishing vessels targeting demersal fish with a mesh size in the range of 100 – 120mm) in the Irish Sea in 2016 (Figure 31), however, the total number of recaptures was low. The number of recaptures increased in 2017, as did the gear types contributing to the data set. Recapture numbers increased significantly throughout 2018, the vast majority being returned to the project by the small number of whitefish directed fishing vessels operating as TR1s in the Irish Sea (Figure 31). The proportion of recapture records by gear type was; gillnet: 0.6%, rod and line: 4.5%, otter trawl targeting *Nephrops* 14.0%, demersal trawl targeting fish 69.2% , seine netting 6.7% and 9% by beam trawl.

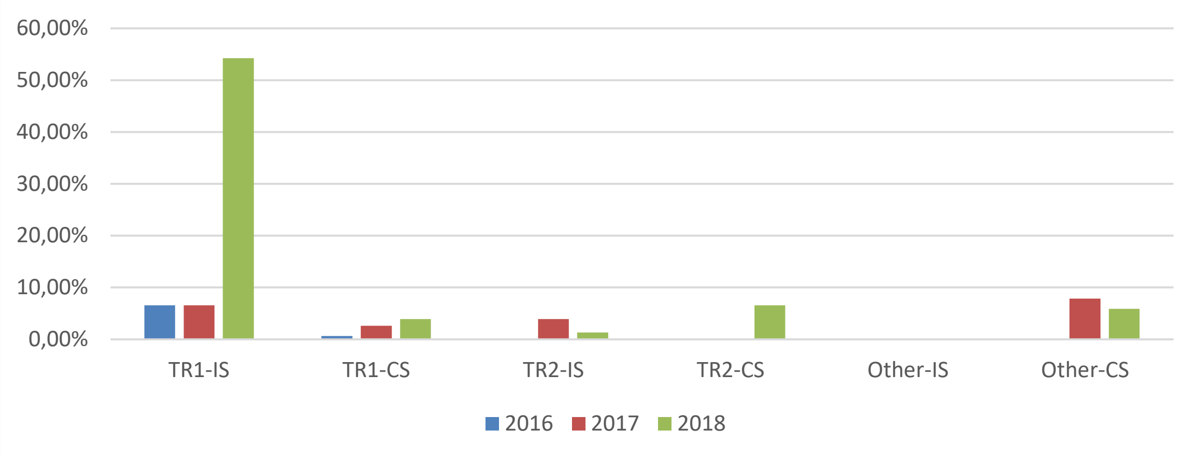

Figure 31. Recaptures of tagged cod in the Irish Sea (IS) and Celtic Sea (CS) in 2016, 2017 and 2018. By regulated gears bottom trawls and seines with mesh: TR1 ≥ 100 mm; TR2 ≥ 70 mm and < 100 mm; TR3 ≥ 16 mm and < 32 mm; other = primarily gills nets and beam trawls. Not include recaptured tagged fish caught by anglers, where rod and reel fishing making up a small number of the total recaptures.

Initial tag return rates were expected to be in line with other studies at around 10%. This expected rate was also informed by the high fishing effort indicate by the scientific assessment available at the time. Within the project a tag return rate of 3.92% was observed. Discussion with stakeholders and an adapted communication plan was put in place to ensure continued support from industry and awareness of reporting tagged fish caught. Other contributing factors were assessed to include tagging during closed season and area, limiting tag returns in the immediate period after tagging and observed reduction in fishing effort and bycatch of cod in the main fisheries active in the region. The combination of low fishing mortality and tagging occurring when fishing activity is prohibited, within the immediate area, could have contributed to lower than expected recaptures. Rates of tag loss were monitored. Approximately 17.5% of recaptures during the current study were returned with only one tag. From this loss of both dorsal tags is estimated to occur in 2.8% of study animals. Tagged fish returned with only one tag intact had an average time at liberty of 224 days, with some exceeding 550 days. It is likely that tag loss occurs immediately after release, before the tag has become securely embedded into the dorsal tissue.

To address the ability of the tagging campaign to support fishery management and provide insight into species biology, simulations of tagging effort informed by the initial results were used to plan tagging events and demonstrate the potential power of the study. A Lincoln-Petersen mark-recapture method (Seber, 2002) for estimating population size was applied. The method allowed an estimate of population size to be derived from the tagging programme, whilst making an assumption about losses from the population owing to natural processes. The analysis was applied using numbers of fish and converted to biomass estimates. Applying the method to a time series of tagging events and recaptures allowed for improvement and changes in uncertainty to be evaluated. The analysis, diagnostics and comparison with the current ICES assessment (ICES, 2018) of the size of the spawning stock biomass (SSB) suggested that the current tagging programme was able to provide robust information about the Irish Sea cod population. To forecast the potential effect of planned tagging scenarios, the analysis was extended to simulate marking and recaptures in 2018. Three scenarios were simulated:

- Cessation of tagging and no further recapture reporting.
- Continued tagging with continued reporting.
- Increased tagging effort with continued reporting.

The simulation results supported continuing the tagging effort in 2018, indicating that confidence in the population parameters derived from the study would be increased.

Results of the projects have been communicated to the Northern Ireland Gear Trials steering group, which includes representatives from fishery policy, fish producing organisations and fishers, and to the Irish Fisheries Science Research Partnership (IFSRP) in the Republic of Ireland, a collaboration between representatives from fish producing organisations and fishers, and scientists of the Marine Institute and BIM. A project update was presented at the ICES Working Group for the Celtic Sea Ecoregion (WGCSE) in May 2018 and in May 2019 at which the assessment scientists for cod and gadoids in the Celtic Seas Ecoregion were present. The project was also included in the ICES WKIrish 5 workshop, attended by scientists and industry representatives.

2.4.3 Fishing mortality sources of Irish Sea Cod

An increased in the number of recaptured tagged cod returned to the project was seen in 2018 (Figure 32). This may in part be explained by an increased TAC in the Irish Sea for cod in 2018, the first year since 1999 that ICES advice was for a catch greater than zero tonnes. Commercial skippers reported fishing on marks showing mixes of cod and haddock, which they would have previously avoided due to minimize cod bycatch. Statistical analysis of recaptures by gear type showed a significant difference in causes of mortality within the recapture data (The *chi*-square statistic: 21.21 $p < 0.0001$) with the Irish whitefish directed TR1 fleet in the Irish Sea providing the biggest contribution to cod mortality.

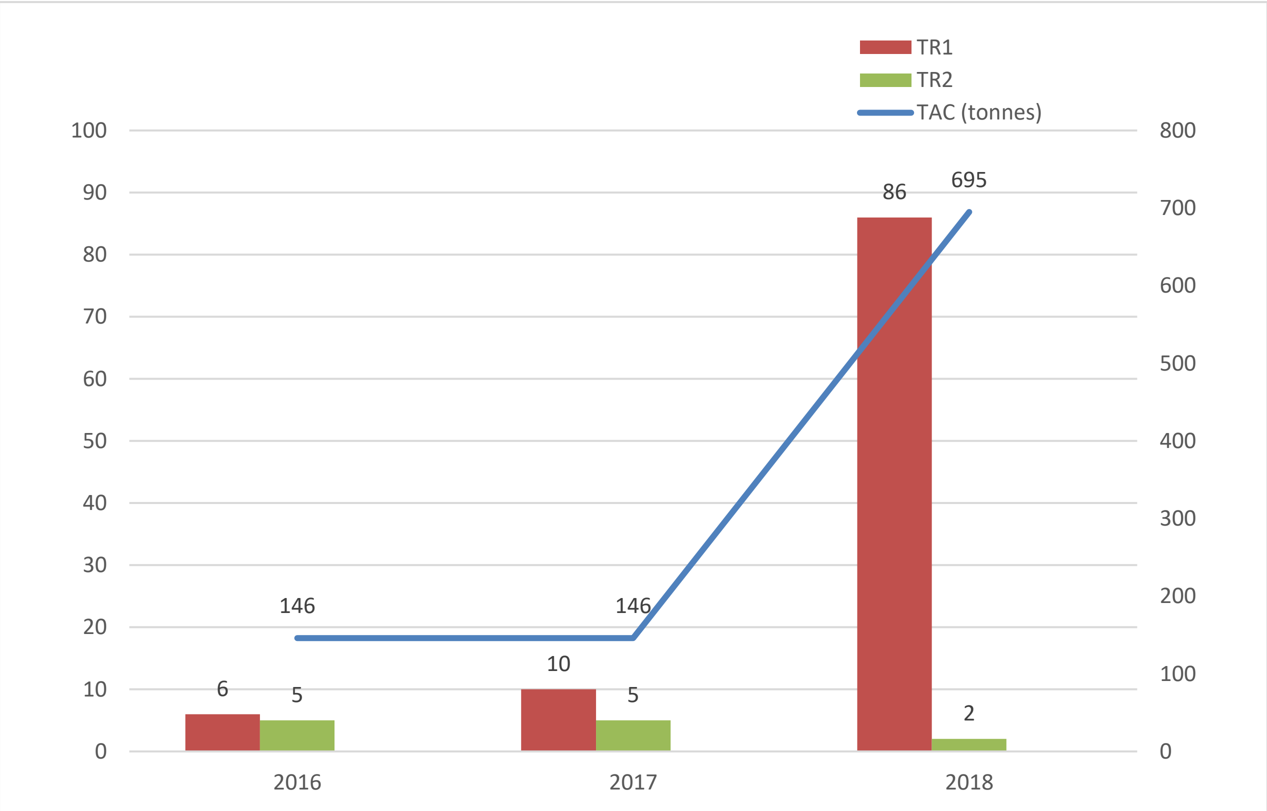

Figure 32. Number of recaptures by regulated gear type and agreed Total Allowable Catch (TAC) in the Irish Sea (ICES 7a) in 2016, 2017 and 2018.

2.4.4 Migration, mixing and spatial range

The recapture records used in the analysis include 140 fish which were tagged and released within the Irish Sea (ICES management division 7a) and 21 fish which were tagged and released within the Celtic Sea (ICES management division 7g). Summary statistics by release year (2016, 2017 and 2018) and release area are reported in

Year	Total n	Release area n	Release length (cm)	Time at liberty (days)	Remain in IRE	Remain in CEL	IRE to CEL	IRE to WSC	Other (notes)	Distance travelled (km)	Mean velocity (km day^{-1})
2016	16	IRE = 16	IRE = 62.0 (± 5.9)	IRE = 219.8 (± 285.7)	11 fish (68.8 %)	-	3 fish (18.8%)	2 fish (12.4%)	-	IRE = 99.1 (± 121.0)	IRE = 0.9 (± 0.9)
2017	65	IRE = 50 CEL = 15	IRE = 67.4 (± 20.0) CEL = 48.0 (± 7.3)	IRE = 235.8 (± 156.6) CEL = 106.7 (± 158.8)	44 fish (88.0 %)	15 fish (100.0 %)	5 fish (10.0%)	1 fish (2.0 %)	-	IRE = 55.9 (± 97.2) CEL = 25.1 (± 39.7)	IRE = 0.9 (± 2.7) CEL = 0.4 (± 0.4)
2018	80	IRE = 74 CEL = 6	IRE = 70.3 (± 13.5) CEL = 67.0 (± 10.5)	IRE = 122.9 (± 61.9) CEL = 133.5 (± 58.7)	58 fish (78.4 %)	5 fish (83.3%)	15 fish (20.2%)	-	1 fish released in CEL moves west into ICES management division 7j 1 fish released in IRE moves south through the CEL and is recaptured in ICES management division 7k	IRE = 93.4 (± 116.3) CEL = 120.7 (± 45.8)	IRE = 1.0 (± 1.2) CEL = 1.1 (± 0.6)

7. Given the markedly different management measures that have been in place during the study period for individual years, in particular for Irish Sea cod, the distributional analysis of recapture (see Table 8 and Figure 33 / Figure 34). A time at liberty threshold was not imposed (min/ max number of days since release) on the recapture data. Given annual management of stocks and different management between

the two divisions (7a and 7g) the study period provides an opportunity to explore how management may effect recapture rates between the two divisions.

The extent of geographical range for cod in Irish and Celtic Sea is described using utilisation distributions (UDs) (Figure 33 & Figure 34). UDs are defined as the probability of locating a tagged individual within an area (Worton 1987). The UDs are calculated for each release area and each release year. All UDs are calculated using the kernel probability density function (KPDF) approach using the adehabitatHR package in R. As in previous studies the 95%, 70% and 50% probability contours are extracted (see Bendall *et al*., 2009) described as the range (95%) and the core area (50%) of cod. Range provides a spatial representation of all broad scale area utilised by tagged cod (Downs & Horner 2008; Dean *et al*., 2014). Whereas, core area is assumed to reflect the areas where individuals spend the most time conditional on our observations (Downs & Horner 2008; Dean *et al*., 2014). The KPDE method is more typically used in studies of territoriality and home ranges (Righton & Mills 2008). However, because tag recapture locations are analogous to the density and distribution of the locations of single individuals over time, the technique is applicable to population-level mark-recapture data (Righton *et al*., 2007; Bendall *et al*., 2009).

Values of distance travelled (km; *d*) were calculated as the straight-line distance between release and recapture locations, along the surface of a sphere, using the Great Circle equation in R. Mean velocity was calculated by dividing *d* by the time spent at liberty (number of days) (

Year	Total n	Release area n	Release length (cm)	Time at liberty (days)	Remain in IRE	Remain in CEL	IRE to CEL	IRE to WSC	Other (notes)	Distance travelled d (km)	Mean velocity (km day^{-1})
2016	16	IRE = 16	IRE = 62.0 (± 5.9)	IRE = 219.8 (± 285.7)	11 fish (68.8%)	-	3 fish (18.8%)	2 fish (12.4%)	-	IRE = 99.1 (± 121.0)	IRE = 0.9 (± 0.9)
2017	65	IRE = 50 CEL = 15	IRE = 67.4 (± 20.0) CEL = 48.0 (± 7.3)	IRE = 235.8 (± 156.6) CEL = 106.7 (± 158.8)	44 fish (88.0%)	15 fish (100.0%)	5 fish (10.0%)	1 fish (2.0%)	-	IRE = 55.9 (± 97.2) CEL = 25.1 (± 39.7)	IRE = 0.9 (± 2.7) CEL = 0.4 (± 0.4)

2018	80	IRE = 74 CEL = 6	IRE = 70.3 (± 13.5) CEL = 67.0 (± 10.5)	IRE = 122.9 (± 61.9) CEL = 133.5 (± 58.7)	58 fish (78.4%)	5 fish (83.3%)	15 fish (20.2%)	-	1 fish released in CEL moves west into ICES management division 7j 1 fish released in IRE moves south through the CEL and is recaptured in ICES management division 7k	IRE = 93.4 (± 116.3) CEL = 120.7 (± 45.8)	IRE = 1.0 (± 1.2) CEL = 1.1 (± 0.6)

).

Table 8. Summary statistics by of tagged and released cod by year (2016, 2017 and 2018) and release area (ICES management division). All reported values are means. Uncertainty is reported as ± 1 standard de6ation. n= sample size. 7a, Irish Sea (ICES management division 7a). 7g, Celtic Sea (ICES management division 7g). 6a, West of Scotland (ICES management division 6a).

Year	Total n	Release area n	Release length (cm)	Time at liberty (days)	Remain in IRE	Remain in CEL	IRE to CEL	IRE to WSC	Other (notes)	Distance travelled (km)	Mean velocity (km day^{-1})
All	161	IRE = 140 CEL = 21	IRE = 68.3 (± 15.7) CEL = 53.4 (± 11.9)	IRE = 174.3 (± 149.9) CEL = 114.4 (± 136.6)	113 fish (80.7%)	20 fish (95.0%)	23 fish (16.4%)	3 fish (2.1%)	1 fish released in CEL moves west into ICES management division 7j 1 fish released in IRE moves south through the CEL and is recaptured in ICES management division 7k	IRE = 80.6 (± 111.2) CEL = 52.4 (± 59.8)	IRE = 0.9 (± 1.9) CEL = 0.6 (± 0.6)

Table 8 (contd). Summary statistics by of tagged and released cod by year (2016, 2017 and 2018) and release area (ICES management division). All reported values are means. Uncertainty is reported as ± 1 standard de6ation. n= sample size. 7a, Irish Sea (ICES management division 7a). 7g, Celtic Sea (ICES management division 7g). 6a, West of Scotland (ICES management division 6a).

Year	Total n	Release area n	Release length (cm)	Time at liberty (days)	Remain in IRE	Remain in CEL	IRE to CEL	IRE to WSC	Other (notes)	Distance travelled (km)	Mean velocity (km day^{-1})
2016	16	IRE = 16	IRE = 62.0 (± 5.9)	IRE = 219.8 (± 285.7)	11 fish (68.8%)	-	3 fish (18.8%)	2 fish (12.4%)	-	IRE = 99.1 (± 121.0)	IRE = 0.9 (± 0.9)
2017	65	IRE = 50 CEL = 15	IRE = 67.4 (± 20.0) CEL = 48.0 (± 7.3)	IRE = 235.8 (± 156.6) CEL = 106.7 (± 158.8)	44 fish (88.0%)	15 fish (100.0 %)	5 fish (10.0%)	1 fish (2.0%)	-	IRE = 55.9 (± 97.2) CEL = 25.1 (± 39.7)	IRE = 0.9 (± 2.7) CEL = 0.4 (± 0.4)
2018	80	IRE = 74 CEL = 6	IRE = 70.3 (± 13.5) CEL = 67.0 (± 10.5)	IRE = 122.9 (± 61.9) CEL = 133.5 (± 58.7)	58 fish (78.4%)	5 fish (83.3%)	15 fish (20.2%)	-	1 fish released in CEL moves west into ICES management division 7j 1 fish released in IRE moves south through the CEL and is recaptured in ICES management division 7k	IRE = 93.4 (± 116.3) CEL = 120.7 (± 45.8)	IRE = 1.0 (± 1.2) CEL = 1.1 (± 0.6)

Cod remained at liberty on average for approximately five months (166.5 days ± 149.2 days;

Year	Total n	Release area n	Release length (cm)	Time at liberty (days)	Remain in IRE	Remain in CEL	IRE to CEL	IRE to WSC	Other (notes)	Distance travelled (km)	Mean velocity (km day^{-1})
2016	16	IRE = 16	IRE = 62.0 (± 5.9)	IRE = 219.8 (± 285.7)	11 fish (68.8%)	-	3 fish (18.8%)	2 fish (12.4%)	-	IRE = 99.1 (± 121.0)	IRE = 0.9 (± 0.9)
2017	65	IRE = 50 CEL = 15	IRE = 67.4 (± 20.0) CEL = 48.0 (± 7.3)	IRE = 235.8 (± 156.6) CEL = 106.7 (± 158.8)	44 fish (88.0%)	15 fish (100.0%)	5 fish (10.0%)	1 fish (2.0%)	-	IRE = 55.9 (± 97.2) CEL = 25.1 (± 39.7)	IRE = 0.9 (± 2.7) CEL = 0.4 (± 0.4)
2018	80	IRE = 74 CEL = 6	IRE = 70.3 (± 13.5) CEL = 67.0 (± 10.5)	IRE = 122.9 (± 61.9) CEL = 133.5 (± 58.7)	58 fish (78.4%)	5 fish (83.3%)	15 fish (20.2%)	-	1 fish released in CEL moves west into ICES management division 7j 1 fish released in IRE moves south through the CEL and is recaptured in ICES management division 7k	IRE = 93.4 (± 116.3) CEL = 120.7 (± 45.8)	IRE = 1.0 (± 1.2) CEL = 1.1 (± 0.6)

), travelling an average distance from release to recapture of 77.0 km (± 106.2 km) at a mean velocity of 0.89 km per day (± 1.7 km day^{-1}). The longest time at liberty was a little over 30 months (939 days), by a cod recaptured only 6.0 km away from its original release site in the Irish Sea. The greatest distance travelled was by a cod at liberty for 150 days, recaptured within the Celtic Sea, 403.6 km from its original release site in the central Irish Sea.

The following four broad-scale movement patterns were observed (

Year	Tot	Release	Release leng	Time at libert	Remain	Remai	IRE to CEL	IRE to WSC	Other (notes)	Distance	Mean velocity

	al n	ar ea n	th (cm)	y (day s)	in IRE	n in CEL				trav elle d (km)	(km day^{-1})
2016	16	IRE = 16	IRE = 62.0 (± 5.9)	IRE = 219.8 (± 285.7)	11 fish (68.8%)	-	3 fish (18.8%)	2 fish (12.4%)	-	IRE = 99.1 (± 121.0)	IRE = 0.9 (± 0.9)
2017	65	IRE = 50 CEL = 15	IRE = 67.4 (± 20.0) CEL = 48.0 (± 7.3)	IRE = 235.8 (± 156.6) CEL = 106.7 (± 158.8)	44 fish (88.0%)	15 fish (100.0%)	5 fish (10.0%)	1 fish (2.0%)	-	IRE = 55.9 (± 97.2) CEL = 25.1 (± 39.7)	IRE = 0.9 (± 2.7) CEL = 0.4 (± 0.4)
2018	80	IRE = 74 CEL = 6	IRE = 70.3 (± 13.5) CEL = 67.0 (± 10.5)	IRE = 122.9 (± 61.9) CEL = 133.5 (± 58.7)	58 fish (78.4%)	5 fish (83.3%)	15 fish (20.2%)	-	1 fish released in CEL moves west into ICES management division 7j 1 fish released in IRE moves south through the CEL and is recaptured in ICES management division 7k	IRE = 93.4 (± 116.3) CEL = 120.7 (± 45.8)	IRE = 1.0 (± 1.2) CEL = 1.1 (± 0.6)

):

- Cod released in the Irish Sea and recaptured within the Irish Sea (80.7% - 113 out of 140 fish).
- Cod released in the Irish Sea and recaptured in the waters off the west coast of Scotland (2.1% - 3 out of 140 fish).
- Cod released in the Irish Sea and recaptured in the Celtic Sea (16.4% - 23 out of 140 fish).
- Cod released in the Celtic Sea and recaptured within the Celtic Sea (95.0% - 20 out of 21 fish).

The rate of recapture of cod released in 7a and recaptured in 7g is much higher than observed in the review of existing data 16.4% in the current study compared to 3.7% in the review. However, the historic review and current study both support the spatial distribution and range overlap of Irish Sea and Celtic Sea cod (Figure 34).

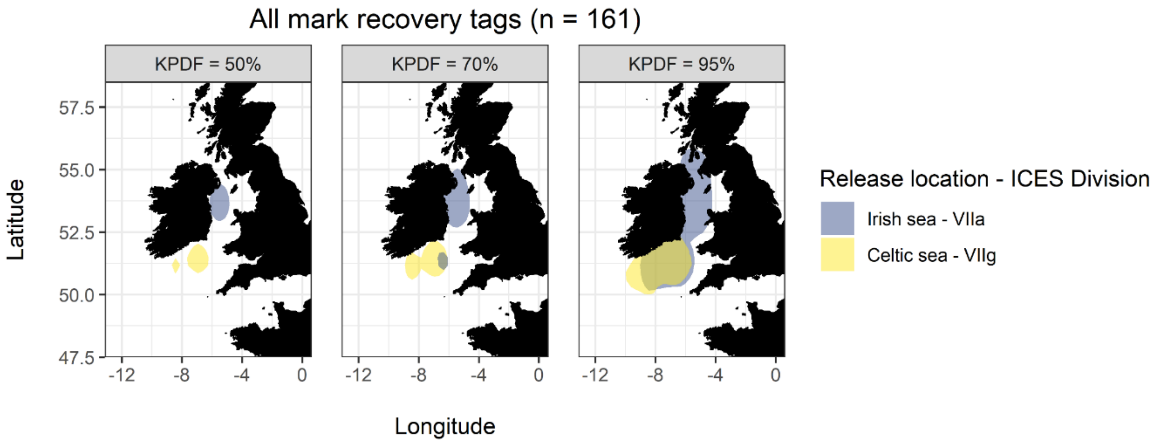

Figure 33. Summary Utilisation Distributions (UD) for tagged mark-recovery cod in 7a (Irish Sea) and 7g (Celtic Sea) in 2016 - 2018. Probability kernel density contours (KPDF) are stated. Core areas of the stocks are indicated by the 50% kernel contour and species range by the 95% contour.

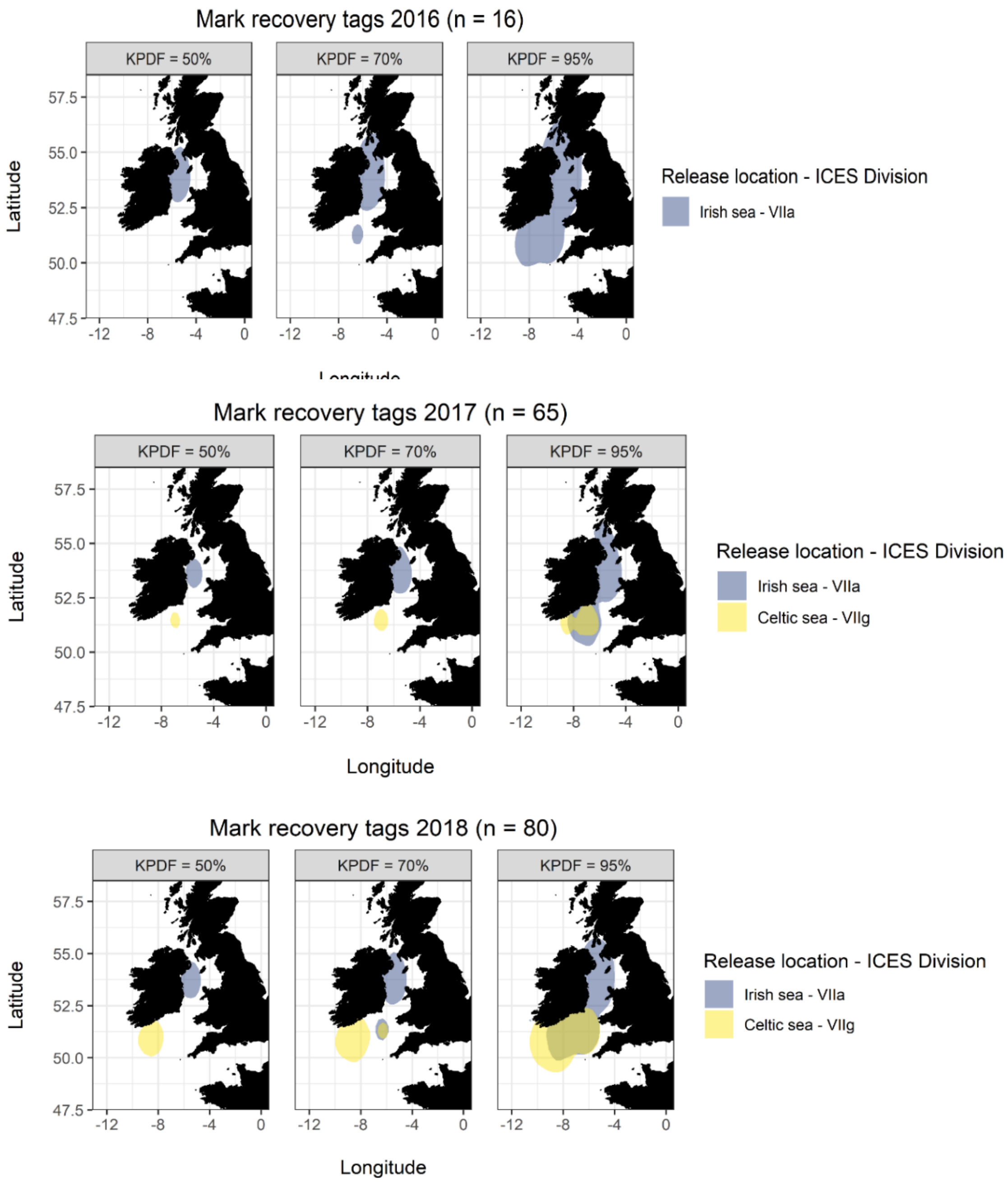

Figure 34. Summary Utilisation Distributions (UD) for tagged mark-recovery cod in 7a (Irish Sea) and 7g (Celtic Sea) in 2016 - 2018. Probability contours are stated. Core areas of the stocks are indicated by the 50% kernel contour and species range by the 95% contour.

2.4.5 Influence of environmental factors

Cod in the Irish Sea are considered to be at the upper thermal boundary of the species, and their growth and surplus production (i.e. including the reproductive component) are among the highest found throughout the range. Cod stocks are not observed much above annual mean bottom temperatures of 12°C (Drinkwater, 2005).

Analysis was applied to explore the thermal habitat suitability of the Irish Sea and adjoining sea regions based on assumptions of thermal limits. Literature has been used to identify optimal sea bottom temperatures for different ages of cod, developing a baseline habitat suitability model for cod in the Irish Sea and neighbouring areas. The model demonstrates the continual thermal link between the Irish Sea and adjoining areas. The theoretical model of habitat suitably was tested for predictive capacity with the empirical results of the current recapture study. The spatial pattern of this optimal habitat and overlap with the observed recapture results validates the habitat suitability (Figure 35). At present the study identifies a small area in 7a of suitable thermal habitat which mirrors the core area of the 7a recapture data and clearly identifies a much larger area of suitable habitat in the Celtic Sea within which the recapture data is recorded. Additionally the analysis of monthly habitat suitability supports the hypothesis this environmental driver would have strongest effect in late quarter 3 and early quarter 4 (Figure 36).

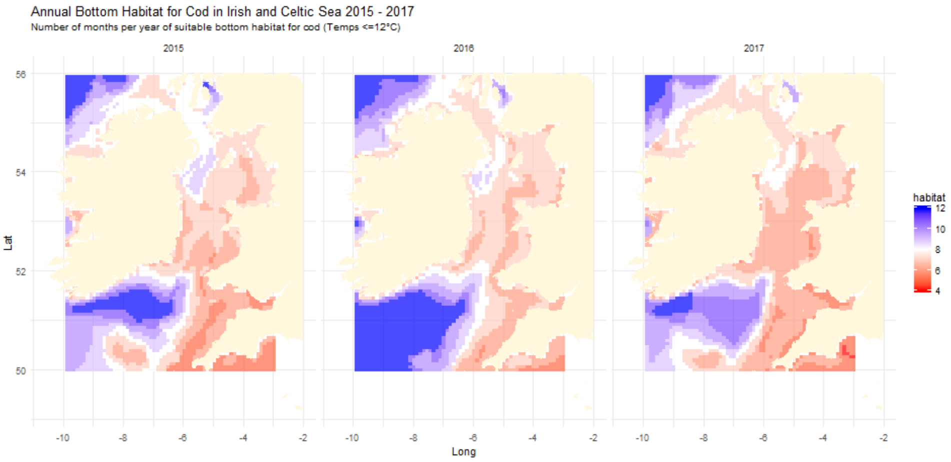

Figure 35. Annual variation in mean monthly thermal habitat (bottom temperatures <=12°C) of study area 2015-2017. Habitat scale represents sum of months where thermal habitat was <=12°C.

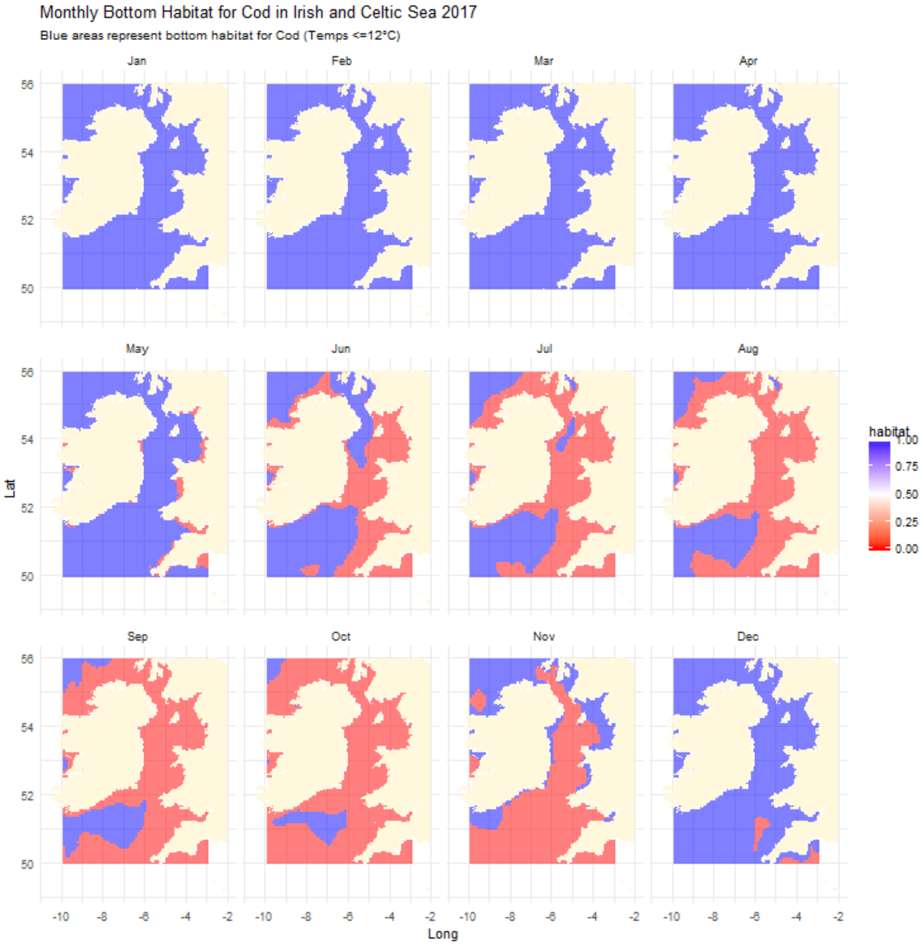

Figure 36. Monthly variation in thermal habitat (bottom temperatures <=12°C) of study area calculated in 2017. Blue areas represents thermal habitat <=12°C, whereas red areas represent bottom temperatures >12°C.

2.4.6 Irish Sea cod biology

It was critical that tagging was applied to fish across the size distribution reflective of what is being caught from the stock. By tagging over a broad spatial area, using various gear types and tagging activities throughout the year, a large range of cod lengths and ages were tagged (Figure 37).

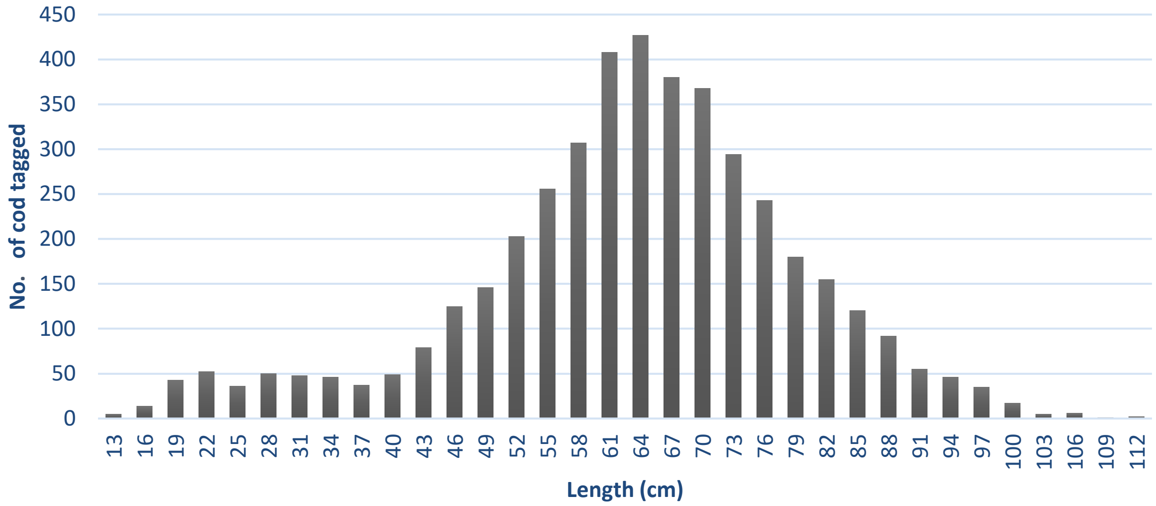

Figure 37. Combined length frequency of tagged cod showing tagged individuals from all sources.

Otolith age analysis was carried on fish returned with intact carcasses. All fish that moved between ICES Divisions ‘transient fish’ were aged as 3+ years. 23 cod were tagged and released in the Irish Sea and recaptured in the Celtic Sea (16.4% of cod released in the Irish Sea). Of those aged, all were 4+ years old cod. There were 4 fish (2.9% of cod tagged and released in the Irish Sea) displaying movement from the Irish Sea to management area 38-E4/North Channel. Otolith age analysis showed all these fish were 3+ years old.

The body length of cod at the time of release ranged from 18 cm to 103 cm with an average value of 66.3 cm (± 16.6 cm;

Year	Total n	Release area n	Release length (cm)	Time at liberty (days)	Remain in IRE	Remain in CEL	IRE to CEL	IRE to WSC	Other (notes)	Distance travelled (km)	Mean velocity (km day^{-1})
2016	16	IRE = 16	IRE = 62.0 (± 5.9)	IRE = 219.8 (± 285.7)	11 fish (68.8%)	-	3 fish (18.8%)	2 fish (12.4%)	-	IRE = 99.1 (± 121.0)	IRE = 0.9 (± 0.9)
2017	65	IRE = 50 CEL = 15	IRE = 67.4 (± 20.0) CEL = 48.0 (± 7.3)	IRE = 235.8 (± 156.6) CEL = 106.7 (± 158.8)	44 fish (88.0%)	15 fish (100.0%)	5 fish (10.0%)	1 fish (2.0%)	-	IRE = 55.9 (± 97.2) CEL = 25.1 (± 39.7)	IRE = 0.9 (± 2.7) CEL = 0.4 (± 0.4)

2018	80	IRE = 74 CEL = 6	IRE = 70.3 (± 13.5) CEL = 67.0 (± 10.5)	IRE = 122.9 (± 61.9) CEL = 133.5 (± 58.7)	58 fish (78.4%)	5 fish (83.3%)	15 fish (20.2%)	-	1 fish released in CEL moves west into ICES management division 7j 1 fish released in IRE moves south through the CEL and is recaptured in ICES management division 7k	IRE = 93.4 (± 116.3) CEL = 120.7 (± 45.8)	IRE = 1.0 (± 1.2) CEL = 1.1 (± 0.6)

). Time spent at liberty is found to be similar across stocks (t = 1.8, df = 27.7, p value = 0.08), whereas body length at the time of release is significantly larger in those cod released in the Irish Sea compared to those released in the Celtic Sea (t = 5.1, df = 31.6, p value < 0.0001;). That said, sample size is skewed towards the Irish Sea.

Recaptured cod were dissected to collect stomachs and further biological data including sex and maturity. Otoliths were extracted, mounted and ages read. Stomach content analysis was performed to identify prey items and create a database of cod diet. Within the project it has been noted that a number of recaptured carcasses are of smaller length than at the time of tagging. This is a known effect of carcass freezing and storage. Fishers often freeze tagged cod prior to reporting the fish and freezing is the recommended preservation method prior to scientific analysis. A species and area specific shrinkage factor is required to account for this phenomenon.

An up-to date growth model was derived for Irish Sea cod for 2017 (Figure 38). This model has been updated with data from the current project and other sampling sources including fishery independent and fishery dependent sources. This was applied using the methods as performed in the annual ICES stock assessment (ICES 2017a). The growth parameters for 2017 were: $L_{inf\ 2017}$ = 174.51 cm, K_{2017} = 0.126 and $t0_{2017}$ = -0.568

In comparison, Table 9 shows growth parameters estimated for the years 2012 to 2016. These and the most recent cod growth parameters suggest that cod growth rate has been reducing (K value) with individuals expected to reach a larger asymptotic length (L_{inf}). It is likely that this results from the presence of older, larger, fish in the population as a result of the maturation of the 2013 cohort, which was relatively strong compared to previous cohorts of cod in the Irish Sea.

Table 9. Von Bertalanffly plot growth curve parameters for cod the data are derived from commercial sampling of Irish Sea cod, fishery independent surveys and the current tagging for years 2012-2016.

	Year				
Parameter	**2012**	**2013**	**2014**	**2015**	**2016**
K	0.409	0.356	0.402	0.211	0.202
L_{inf}	102.04	108.476	115.61	134.27	147.25
t0	0.041	-0.038	0.393	-0.146	0.232

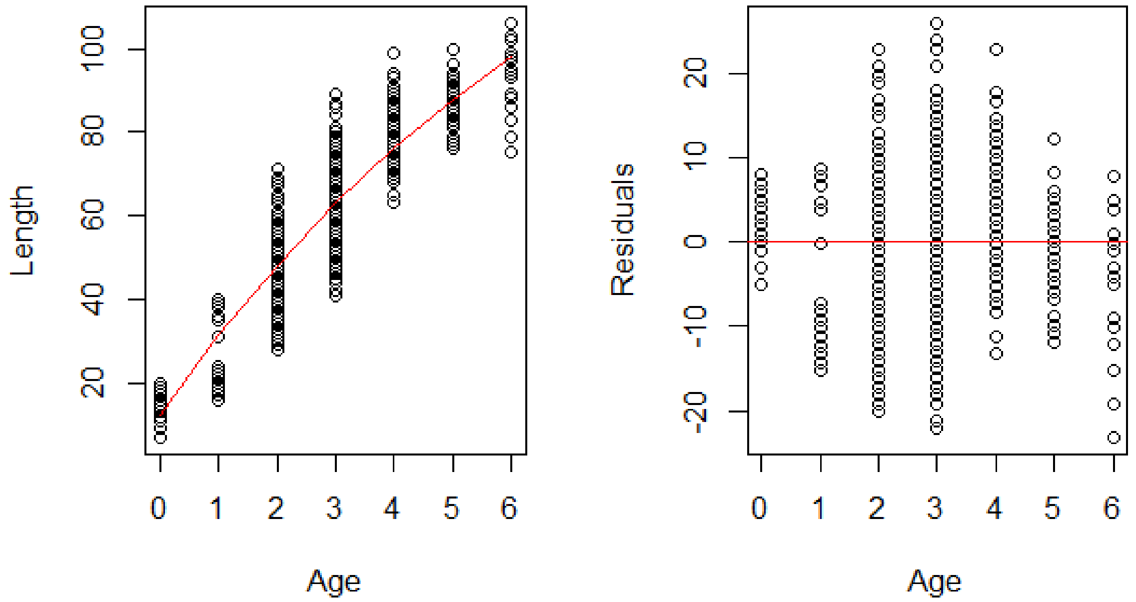

Figure 38. Von Bertalanffly plot (growth curve) for cod the data is derived from commercial sampling of Irish Sea cod, fishery independent surveys and the current tagging project from 2017.

An experiment to examine shrinkage due to freeze of cod carcasses revealed an on average 2.42% (s.d. 1.26) decline in length due to freezing. This factor was used to correct the lengths of recaptured cod stored or returned frozen. Using the days at liberty, annual growth increments were estimated for aged recaptured cod. Comparison of tagging study derived growth rates (converted form daily increments to yearly growth) with the age based Von Bertalanffy model show similar rates of growth at age (Figure 39). From the tagging study, annual growth of cod aged two was 26.8 cm per annum, decreasing to 6.5 cm per annum at age 6.

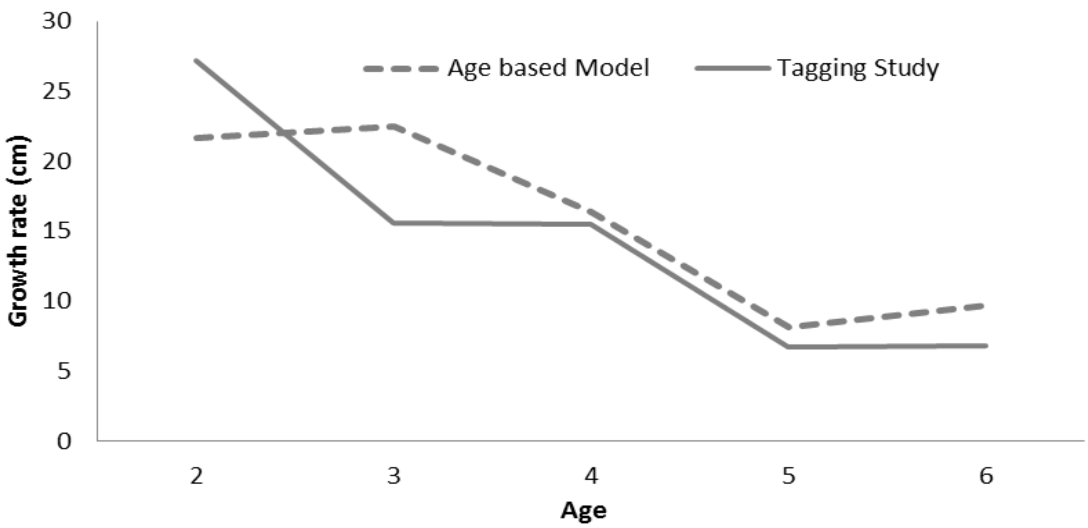

Figure 39. Comparison of tagging study derived growth rates to Von Bertalanffy modelled change in length at age (quarter 1 mean length). The growth rate per year for

cod at age 2 – 6 was calculated as the change in length within year from the Von Bertalanffy method and by growth since tagging or recaptured tagged cod.

Stomach content analysis was carried out along with the field work activities and dissection of returned cod carcases. Full analysis of these is ongoing, with 577 cod stomachs processed and 1069 prey items identified, this data is being incorporated with the foodweb ecosystems models being developed through the ICES WKIrish process. There have been 92 individual prey items recorded in cod stomachs. Of the cod stomachs processed from the cod tagging project, 8 were empty. 5 prey items comprised almost 75% of the diet by weight *Pasiphaea sivado* (19.6%), *Nephrops norvegicus* (17.8%), *Melanogrammus aeglefinus* (15.7%), *Merlangius merlangus* (13.3%) and *Clupea harengus* (7.9%).

The stomach contents data will be included in an ongoing project looking at trophic interactions of Celtic and Irish Sea fish stocks in an attempt to improve fisheries management advice. A breakdown of the percentage abundance of prey groups encountered in this analysis is given in Figure 40, showing that fish are the most common prey group taken in terms of numbers followed by shrimps. The most common fish species taken were sand eel sp., sprat, whiting and herring. *Nephrops* was the third most common prey item by number. Whilst, outside the scope of the current project this analysis will contribute to the overall project objectives and regional management objectives towards the ongoing development to the ecosystem understanding to the region.

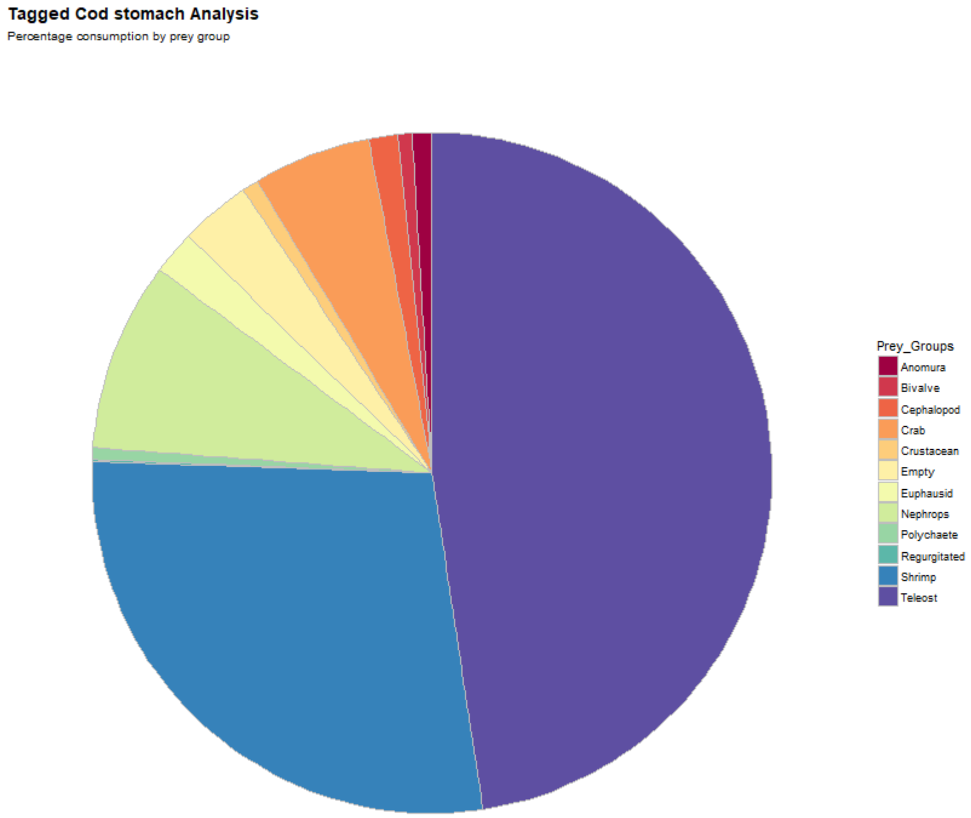

Figure 40. Composition of prey groups by number in cod stomach contents

2.4.7 Implication for assessment of stock status

The quality of the Irish Sea cod assessment and the lack of a short term forecast have severely impacted the ability to provide sound management advice and maximise yield of the stock since the mid 2000s. This was primarily due to the uncertainty in the mortality estimates for the stock. Total mortality rates for the stock have been high throughout the time period for which information is available for the assessment (since the 1960s) and the stock is characterised by the paucity of older fish in the population. As the information that inform the stock assessment increased and quality improved, the high mortality rate translated into an unallocated removals estimate form the assessment model (essentially due to a mismatch in the mortality signal for the surveys and catch over time). Unallocated removals could potentially include components due to increased levels of emigration, discarding, survey catchability, natural mortality, changes in fishery selectivity, as well as misreported landings.

The 2017 ICES benchmark accounted for most of the sources that could result in the unallocated mortality estimates, but lacked updated information on emigration. The resulting assessments (ICES 2017b, ICES 2018a) have changed the perception of fishing mortality showing a marked decrease since 2010 to a current F <0.10. The assessment also indicates an increase in the Irish Sea cod population and spawning stock biomass (SSB). This increase is greatly reliant on the 2013 year-class, which had relatively strong recruitment compared to recent years. The 2013 cohort accounted for approximately 60% of the SSB in 2017 (ICES 2017b, ICES 2018a). There is still some uncertainty and bias in the assessment with a year on year downward revision of SSB and a change in the magnitude of mortality over the assessment period (Figure 41; ICES 2018a). The downward revision in SSB is apparent in retrospective comparisons between modelled and observed SSB (Figure 41).

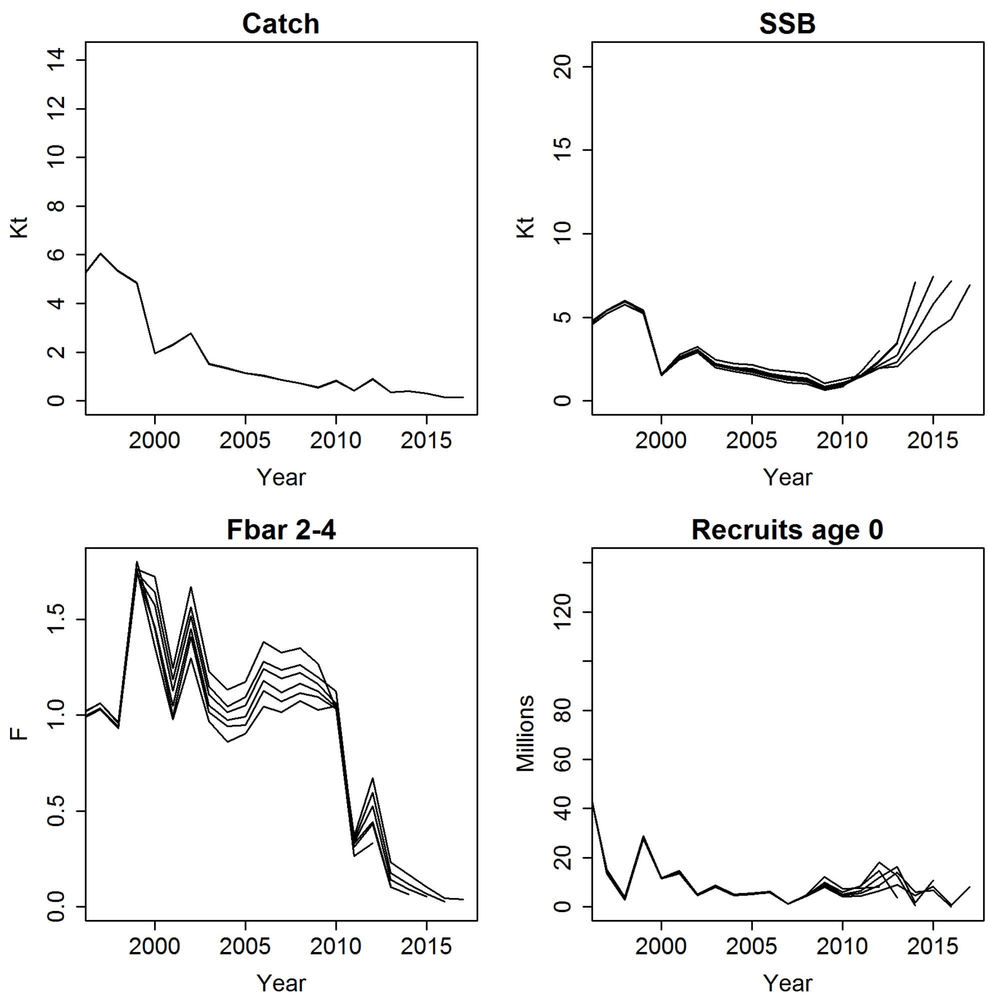

Figure 41. Retrospective analysis of stock status, as applied in the ICES annual assessment of cod in the division 7a in 2018 (ICES 2018a). Each panel shows comparison of the assessment model output for catch, spawning stock biomass (SSB), average fishing mortality for cod aged 2 – 4 (Fbar 2-4) and recruitment. The retrospective is applied for with the same model removing the final year for 5 years to compare the model predictions with subsequent model runs.

Stock identification and the biological containment of a stock within a defined geographical area is clearly important for stock assessment and the sustainable management of the stock within a spatially matched management area. ICES (2012) reviewed historical tagging studies to evaluate the stock identity of Irish Sea cod and concluded that although there is evidence for limited seasonal migrations into neighbouring regions, most fish will stay within their management area and there is no need to change the assessment units. Genetic evidence, however, indicated that cod spawning in the Firth of Clyde, Irish Sea, Celtic Sea, and western Channel form a single breeding unit (Heath *et al*., 2014). Such larger meta-population structures are often the outcome of genetic studies, where the data do not allow for differentiation if there are any mixing between stock units (even at a very low rate as suggested by historic tagging studies). The migration rate of mature fish from the Irish Sea to the Celtic Sea observed in this study is an order of magnitude larger than anything previously observed. The tagging study suggests a 'migration' of approximately 15% to 20% of mature fish from the Irish to the Celtic Sea. The review of historic tag records shows that this can be variable over time but with a comparable result (18%) observed in quarter 4.

The observed movement supports two hypotheses:

1. There is a migratory part of the Irish Sea stock which returns to the spawning grounds in the Irish Sea. Cod show considerable spawning ground fidelity, however, within the current tagging project no movements of cod from the Celtic Sea to the Irish Sea have been observed.
2. A proportion of mature fish emigrate permanently out of the Irish Sea, due to environmental conditions, carrying capacity or re-homing, to spawning areas in the Celtic Sea. This might be Celtic Sea fish that spent their juvenile years in the warmer Irish Sea, which enhances fast growth and they then return to the Celtic Sea at a later stage, or Irish Sea fish which migrate into the Celtic Sea owing to the carrying capacity and or environmental factors in the Irish Sea.

Neither hypothesis can be truly be rejected, but provide potential scenarios which should be included in management considerations and sensitivity analysis for both Irish Sea and Celtic Sea cod. To initially assess the impact of both hypotheses on stock assessment and management both options are being investigated. The tagging results support that:

- Only fish aged 4+ are migrating from the Irish to the Celtic Sea.
- 23% of 4+ cod caught in ICES area 7g are cod that have migrated from the Irish Sea.
- 19% of 4+ year old fish are migrating from the Irish Sea, i.e. fish tagged in Irish Sea re-captured in Celtic Sea.
- No fish have been observed to migrate from the Celtic Sea to the Irish Sea.

An age structured population model was applied following the peer reviewed ICES Irish Sea cod stock assessment model (ICES 2017a, ICES stock annex). The implications of current management have been incorporated into the analysis by applying short term forecasts. Forecasts are using TAC for catches in 2018 (intermediate year) and catches under F_{MSY} in the Irish Sea for 2019 and 2020.

The assumptions applied within the assessment model to describe mortality were:

- **Catch reallocation** - 23% of catches of cod >60cm in area 7g were re-assigned to area 7a, following the assessment methods for plaice in 7d (ICES).
- **Increased natural mortality M** - Permanent migration out of the Irish Sea was simulated as an increase in natural mortality M of individuals age 4+ (fish 4+ contribute the majority to length >60cm).

Here migration is included from 2015 onwards to reflect the current project estimates of movement out of Division 7a. Landing and discard data for ICES area 7g for 2015 and 2016 were taken from the STECF report on Fishery Dependent Data 2017. Landings and discards for 2017 were the average of 2015 and 2016 as data were not available at time of report (STECF Fishery Dependent data report 2018).

Results of Irish Sea cod Spawning Stock Biomass (SSB) and Fishing mortality (F) under the two different hypotheses were compared with the model used at WGCSE 2018 (ICES 2018) (Figure 42). The annual downward revision of the SSB and continued truncated age structure in Irish Sea cod remains unexplained despite low fishing pressure experienced by cod in the Irish Sea. The results of the current tagging study incorporated into the assessment framework provides an explanation for this, given the observed movements in particular for larger cod (>60cm).

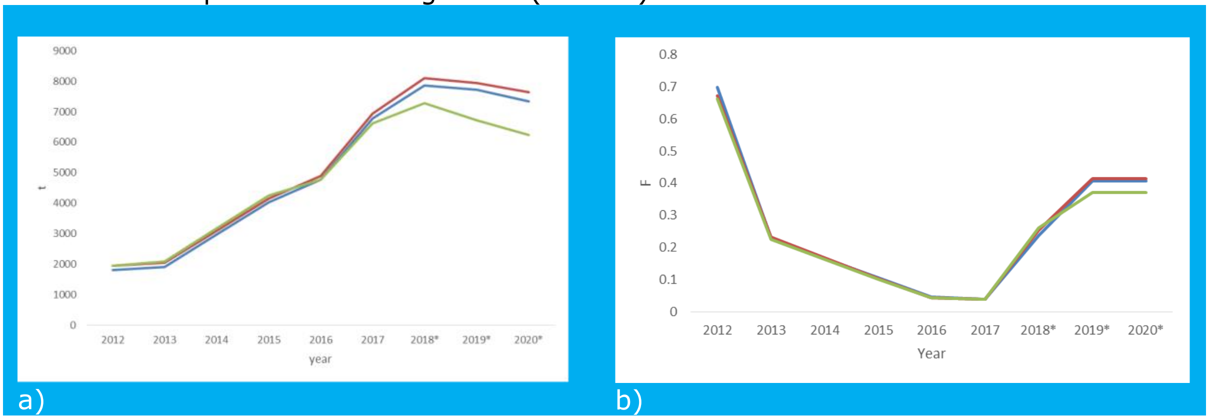

Figure 42. Time series and forecast of Irish Sea cod a) Spawning Stock Biomass (SSB) and b) Fishing mortality (F) under the two different hypotheses compared with the model used at WGCSE 2018 (ICES 2018). Migration was only included in the 3 most recent years (2015-2017). Hypothesis 1 - Blue: Migratory stock that returns to spawning sites in 7a (taking into account catches of 4+ year old fish in area 7g), Hypothesis 2 - Green: Emigration out of 7a (adjusted M) and Red: WGCSE baseline (stock assessment without considering migration).

While all three scenarios (i.e. the original one used to produce the ICES advice, and the two scenarios including migration) show a downward trend in future SSB owing to low recruitment in years following 2013, the downward trend in SSB is considerably faster under the assumption that cod migrate permanently out of the Irish Sea. This supports observed retrospective annual downward revision of SSB as shown in the current annual assessment of the stock abundance and adjusts the observed uncertainty in the forecast.

Management Strategy Evaluation

To investigate the impact of permanent migratory behaviour of Irish Sea cod out of the Irish Sea, a MSE (management strategy evaluation) was conducted. The MSE was used to evaluate possible future management scenarios from a starting point where the status of the stock is assumed to be known (i.e. the assessment for a given year). This scenarios allow a comparison of management based on the current assessment model and assuming stock mixing and migration as observed. Three starting years are chosen for the MSE, 2015, 2016 and 2017. The management scenarios are a range of F values, from 0.01 to 0.36 (the current F_{MSY} lower range). SSB, catches and F are projected up to 2025 and a number of statistics are applied to compare between assessments including migration or not. Those statistics are:

- Risk 1: Mean probability for the second half of the projection that SSB falls below B_{lim} Mean(P(SSB<B_{lim}))
- Risk 3: Maximum probability for the second half of the projection that SSB falls below B_{lim} MAX(P(SSB<B_{lim}))
- Risk 4: Mean probability for years 2019 - 2025 of the projection that SSB falls below B_{lim} Mean(P(SSB<B_{lim}))
- Average catch in years 2019-2025

All risks should be below 0.05 to assure sustainability; risk 3 < 0.05 is seen as a conservative measure.

In the simulations migration is accounted for by an additional 20% natural mortality for cod aged 4-6 years. Figures 1 to 3 show the differences in recruitment, SSB, catch and F for starting years 2015 to 2017 setting the TAC at the lower F_{MSY} range (0.36). Both scenarios (original and migration) have large confidence intervals, however, SSB is projected to be slightly larger without migration. While the projections have a strong year-effect, originating from random recruitment events, including migratory behaviour in the assessment makes the projections more stable and less dependent on occurrence of those events. The maximum sustainable F becomes more centred between 0.11 and 0.21 without taking in the migratory behaviour it has a much larger range between 0 and 0.3. Estimated average catches for the period 2019-2025 taking into account the migratory behaviour of fish is below the estimated average catches without migration due to the more stable estimation of F. Both simulations scenarios support that the current F reference points, estimated from historic patterns of SSB and recruitment, exceed those that based on the MSE with a starting position of the stock in its current state whilst minimising the risk of stock biomass falling below reference points.

2.5 Work package 4: Management advice

2.5.1 Current management

The first management agreements date back to the 1600's allowing access to fish in the Irish Sea. Reliable records of landings date from the late 1960s. Landings have fluctuated markedly and diminished since the late 1980s. Following advice in 1999 from the International Council for the Exploration of the Sea (ICES), in 2000 the European Commission implemented a series of iterative management policies in the form of a recovery plan. These initially closed two areas in the Irish Sea to protect spawning over their known grounds between mid-February and the end of April each year, and subsequently detailed specifications of banned fishing gears (Kelly *et al*., 2006). The specifications aimed to protect spawning cod while allowing the continuation of other fisheries. The closed areas and gear specifications were subsequently redefined in early 2001. In 2004 the "cod recovery plan" defined a target biomass at B_{pa} = 10,000 tonnes, along with a plan to achieve a 30% annual increase in stock biomass and limit TAC changes by 15% (Kelly *et al*., 2006).

The 2017 ICES assessment showed that the stock had increased to be above B_{lim} (6,000 t) but remained below the current B_{pa} value of 8616 t (ICES 2017c). In 2018 the assessment again above B_{lim} but remained below the current B_{pa} and noting "The current assessment shows a significant downward revision of SSB" (ICES 2018d). In 2019 the annual assessment was changed to a different framework, largely based on the "strong tendency for the assessment to overestimate SSB" (ICES 2019).

A number of paths are available for future management of the Irish Sea cod stock. Under current management the stock appears to have responded favourably in particular with regard to reduction of fishing pressure which, all-be-it that they have taken almost two decades to affect an observed response.

Since the inception of the Irish Sea Cod Tagging Project, the cod stock in the Irish Sea has seen some recovery (Figure 43; ICES, 2018a) with catch advice, following the MSY approach, of 1073 t for 2018 and 807 t for 2019. These represent the first ICES advised catches above zero tonnes since 1999. Within the assessment model of Irish Sea cod there is uncertainty of the assessment to reliably inform SSB. An increase in the stock biomass has been driven by slightly improved recruitment in isolated years, but it also implies that the implemented management measures, by reducing effort generally and especially during spawning aggregations, have given space for the stock to recover from the high exploitation levels experienced during the 1980s and 1990s - notably the reduction in F in 2010 (Figure 43) following the implementation of Cod Long Term Management plan under Council Regulation (EC) No. 1342/2008. The observed retrospective downgrading of cod SSB within the Irish Sea assessment model highlights aspects of unknown behaviour and biology for the stock and its current management.

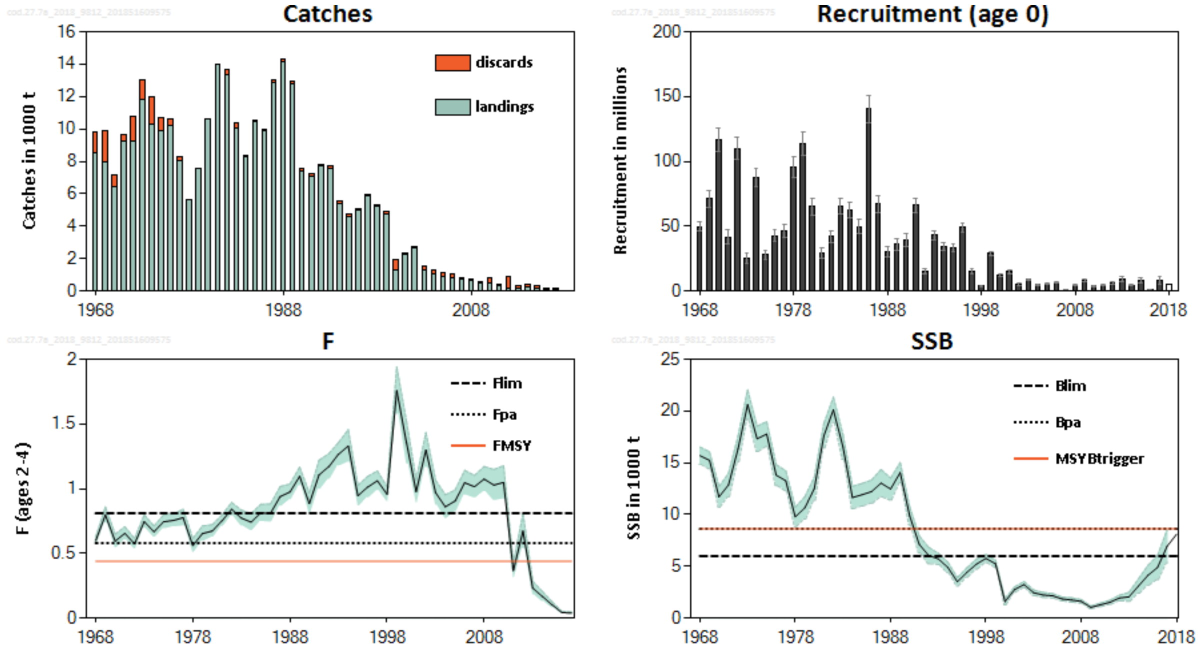

Figure 43. Cod in Division 7a. Summary of the stock assessment (weights in thousand tonnes). The assumed 2018 recruitment value is not shaded. Shaded areas in F and SSB plots and error bars in the recruitment plot represent 1 × standard de6ation. Uncertainty boundaries are not available for 2018 (ICES, 2018a).

Within the 2013 reformed Common Fisheries Policy (CFP), multiannual plans became a priority to form the framework for management of fish stocks by fishery and sea basin. A regional approach was introduced taking into account the specific features of each sea basin. The overall objective of the multiannual plans (MAP) is to restore and maintain fish stocks above levels capable of producing the maximum sustainable yield (MSY). The Basic Regulation also defines the content of the plans, which must include quantifiable targets (such as fishing mortality rates and spawning stock biomass), and safeguards to ensure that quantifiable targets are met.

Multi-annual plans have been developing as a means of safeguarding the state of stocks by setting catch opportunities in line with sustainability targets. In August 2016 the Commission proposed a multi-annual plan for demersal fish stocks in the North Sea, in February 2017 a multi-annual plan for small pelagic stocks in the Adriatic Sea, in March 2018 a multi-annual plan for demersal stocks in the western Mediterranean and a Multiannual plan for fish stocks in the western waters and adjacent waters, and for fisheries exploiting those stocks (2018/0074 (COD)). It is this proposal which incorporates cod in the Irish Sea, under Article 1.1 (5). Article 3 sets the objectives, to achieve the objectives of the CFP applying the precautionary approach to fisheries, aiming to ensure exploitation of living marine above levels which can produce MSY, implementing the ecosystem-based approach to fisheries management. Article 4 details targets, aiming to achieve fishing mortality in line with the ranges of F_{MSY} as soon as possible on a progressive incremental basis by 2020. A multiannual plan for demersal fish stocks in the Western Waters and adjacent waters is at an advanced stage to be adopted in EU regulation. While this plan has yet to be adopted, its intentions in line with sustainability goals.

The plan incorporates a number of principles and objectives of relevance to this study:

- Restore and maintain fish stocks above levels capable of producing MSY
- Ensure fishing is environmentally sustainable in the long term
- Establishment of appropriate reference points for management (scientific advice should particularly include ranges of F_{MSY} and biomass reference points, i.e. MSY $B_{trigger}$ and B_{lim})
- Reference to mixed fisheries considerations
- Should be based on multi-species considerations
- Implement the ecosystem approach to fishery management
- Consistence with geographical distribution in biology and fishery terms
- Measures shall be taken in accordance with the best available scientific advice.

Results from this study support these objectives, both directly and indirectly. The observed linkage and mixed stock area in area VIIg have implications for the stock assessment of both Irish Sea and Celtic Sea stocks. In turn this will impact on known reference points (no longer accepted by ICES (ICES 2019)) for the Irish Sea and potentially adjacent stocks. In particular, the results questions the appropriateness of the current management areas and their independence.

Mixed fishery and multispecies models are not as developed for the Irish Sea as for the North Sea or Celtic Sea. The timely completion of the study will greatly informed the development of these models. A mixed fishery model of the Irish Sea is in development through the ICES MixedFish-Methods group and there is significant movement towards ecosystem based management for the Irish Sea through the ICES workshops. The results from this study has been presented to the ICES community and are already partly integrated into the development of an ecosystem based approach to management (ICES 2018c) by informing the likely energy movement out of the Irish Sea food web ecosystem model. The project results have been presented in the initial work toward the 2019 benchmark process of the Celtic Sea gadoid stocks. The mixed fishery model development, the ecosystem modelling process and the Celtic Sea benchmark are ongoing processes which can use the information from the current project. Here we outline a road map for this and detailed elements to improve the management of the Irish Sea cod stock in the multiannual plan.

2.5.2 Irish Sea cod tagging findings and future management

The results and findings of the 2016 – 2018 Irish Sea cod tagging project are clearly important to the development of future management of the stock through development of the stock assessment and management controls. Recommendations will influence management through a number of routes, integral to these is the current framework for scientific advice. In 2000 the STECF reviewed tagging programmes in the Irish sea and concluded that while some cod moved from the Irish Sea into the Celtic Sea they constituted a very small proportion of the Celtic Sea stock and furthermore that no cod tagged in the Celtic Sea were recovered in the Irish Sea (Anon., 2000). Results of the current study suggest that the proportion of cod migrating from the Irish Sea into the Celtic sea is of importance in terms of removal from the Irish Sea stock:

Management recommendation: *Stock assessment as currently undertaken by ICES must to account for the proportion of the stock leaving the Irish Sea stock and entering the Celtic Sea stock. Model development must explore the sensitivity of the model and advice to stock mixing in VIIg. Through this advice to the European Commission, on the structure and content of management regulations pertinent to fisheries exploiting the Irish Sea cod stock. Management Strategy Evaluation should be used to define appropriate reference points taking into consideration mixing and the current stock status.*

In relation to regulatory controls, the current system of defining Total Allowable Catches is the most direct way of controlling the fishing mortality on cod. For the immediate future this will continue to take the form of single stock catch advice, though may move in the medium term to multi-species or ecosystem based assessments. Development of multi-species assessments should continue to be encouraged through ICES. In 2019 the ICES working group WKCELTIC will review the findings of the current tagging study into account at the benchmarking process for the cod stock in the Celtic Sea.

Biomass estimates form the tagging project support annually assessed SSB estimates. The whilst the stock is considered to be above B_{lim} its size below B_{pa} suggest that currently (2018-2019) the Irish Sea stock remains in a delicate state. All management measures to limit cod mortality outside sustainable limits should be taken:

Management recommendation: *The TAC should be maintained as exclusively for by-catch. This should aim at preventing a resumption of an unsustainable cod targeted fishery until the stock recovery is confirmed.*

An increase in fishing pressure is probable given that fishing opportunities increased in 2018 and 2019, although the uptake of TAC in 2018 was low. The Landings Obligation, which in 2019 will require all TAC species that are caught in the Irish Sea to be landed may also result in increased reporting of cod catches, however, current estimates of discards are considered to be sufficient to assess catch. The increased fishing opportunities and landing obligation may result in enhanced port sampling, by giving opportunity to sample the entire size distribution of the stock in ports.

With a bycatch only fishery significant catch proportion is generated by the *Nephrops* fishery. The experience of tagging staff during the project indicate that whilst cod catch rates within the predominant *Nephrops* fishery is low the viability of cod for release was insufficient due to low vitality levels. This was considered to be due to long tow duration.

Management recommendation: *Discard survivability of cod within the Nephrops fishery is low and must be included / discounted against TACs and landed. Technical measures are regarded to have contributed to low catch rates. Given low survivability of bycatch, monitoring of catch rates must ensure that bycatch is maintained at a minimum level.*

The most successful method to obtain cod to tag during the current project was through target demersal and midwater trawling using trawls with mesh 100 – 120mm. Furthermore, during quarter one / early quarter two when cod were form spawning aggregations tagging rates were highest.

Management recommendation: *Management of mortality on cod should be continued through gear restrictions. Current gear specific technical measures should be maintained and further developed.*

Development of multi-species assessments is likely in the next decade. The ICES Working Group on Multispecies Assessment Methods (WGSAM) carry out a multi-species assessment in the North Sea and will now consider the a model for the Irish Sea in 2019. An Irish Sea mixed fishery model will be developed by ICES Mixed-Fish Methods group in 2019. This will help develop understanding of predator-prey interactions and advise on the ecosystem approach to fisheries management. There has been significant recent progress in understanding multi-species dynamics and interactions using Ecopath with

Ecosim (ICES, 2018) through the WKIrish workshop series at which the current work has been presented and initial results reported. Progress on the development of true multi-species stock assessments and advice has yet to mature. Managers through the CFP have identified a need for multispecies management but this will require dedicated resources and clear guidance from managers and stakeholders to develop properly.

Ongoing modelling studies at AFBI of cod habitat suitability and the recapture results from this study support a thermal linkage and driver to cod distribution. More likely to provide the next advisory assessments are ecosystem based assessments. These comprise multiple trophic levels, incorporating abiotic and biotic impacts across the food web from primary production through primary, secondary and tertiary consumers, incorporating state of the environment in combination with the concept of a carrying capacity of the ecosystem for the resource of interest, be they targeted fisheries or conservation interests such as cetaceans, elasmobranchs and birds. Coupled with impacts of fishing pressure, spawning stocks biomass, recruitment estimates and estimated reference points, these models are likely to be developed further and may provide an implementable ecosystems basis for resource management.

Management recommendation: *The ecosystem approach being development with predator-prey linkage and food-web dynamics must include appropriate environmental drivers to allow change dynamics to be addressed.*

Through the diffuse distribution of the projects findings. These may include the incorporation of the results of the study into development of Spatial Resource Management Plans for the Irish Sea; through public bodies and resource managers such as national governments, county and local councils. Whilst these are diffuse influences may arise from project publicity, project reporting, scientific and natural resource management networking (including science-government advisory processes, collaborative industry-science partnerships and science eNGO partnerships), and through the research network of scientific peer reviewed literature, conferences and meetings.

The actions required to achieve these management measures for the Irish Sea cod stock are:

- Review of the ICES cod 7a stock assessment and consideration of the need to account for mixing with the Celtic Sea stock based on the results of this project. Both assessments have very significant retrospective bias revisions and associated uncertainties. Further focused analysis using alternative methods, such as otolith microchemistry to resolve stock origins and quantify inter-annual variation in seasonal migration patterns.
- TAC management needs to take account of assessment uncertainties. A more cautious management regime is appropriate where by-catch only fisheries are allowed and cod avoidance measures are maintained, until the stocks are rebuilt for several years.
- Realignment of the spatial coverage of management measures to incorporate the spatial extent of aggregations of cod found in the project over the spawning period and catch and sampling data.
- Develop a time series under the changing landscape of the Landings Obligation, the increased fishing opportunities for cod and the Western Waters MAP assuming it is implemented.
- Realignment of the time period of closures, to coincide with the observed timing of spawning aggregations.
- Extension of the time of the restrictions, in line with the ranges of timing of spawning. It is currently extremely difficult to accurately model times of spawning, with enough lead time to translate into legislation/ regulation, and with possible changes in the temperature and current regime in the Irish Sea. It may therefore be better to extend the period to ensure the spawning events are covered within the time frame.
- Introduction of more selective gears will be needed in the Irish Sea. The selectivity objective will need definition but should fundamentally aim to reduce the catch of cod below MCRS.
- Review of data collection under the Landings Obligation, non-zero TAC and Western Waters MAP and benchmarking of the ICES cod 7a stock assessment in light of the data.

3 DISCUSSION

The aim of the current study was to explore sources of mortality for Irish Sea cod. Through the project we establish a new baseline understanding of the current movements and distribution of Irish Sea cod. Previous movement studies have relied on recapture data sampled pre-2011 (Brander 1975; Connolly & Officer 2001; Bendall *et al*. 2009; Neat *et al*., 2014). Migration of Atlantic cod has been reported in other cod stocks around Britain and to a greater extent in the North Atlantic. Incorporation of these movement patterns into the assessment process is of fundamental importance to define the population structure of the stock and to allow forecast of stock abundance and derive management options.

The results of the study indicate that inter-annual movement of cod from Division 7a to Division 7g is 16.4% sd = 4.5%. Recaptured cod remained at liberty on average for approximately five months (166.5 days ± 149.2 days;

Year	Total n	Release area n	Release length (cm)	Time at liberty (days)	Remain in IRE	Remain in CEL	IRE to CEL	IRE to WSC	Other (notes)	Distance travelled (km)	Mean velocity (km day^{-1})
2016	16	IRE = 16	IRE = 62.0 (± 5.9)	IRE = 219.8 (± 285.7)	11 fish (68.8%)	-	3 fish (18.8%)	2 fish (12.4%)	-	IRE = 99.1 (± 121.0)	IRE = 0.9 (± 0.9)
2017	65	IRE = 50 CEL = 15	IRE = 67.4 (± 20.0) CEL = 48.0 (± 7.3)	IRE = 235.8 (± 156.6) CEL = 106.7 (± 158.8)	44 fish (88.0%)	15 fish (100.0%)	5 fish (10.0%)	1 fish (2.0%)	-	IRE = 55.9 (± 97.2) CEL = 25.1 (± 39.7)	IRE = 0.9 (± 2.7) CEL = 0.4 (± 0.4)
2018	80	IRE = 74 CEL = 6	IRE = 70.3 (± 13.5) CEL = 67.0 (±	IRE = 122.9 (± 61.9) CEL = 133.5 (± 58.7)	58 fish (78.4%)	5 fish (83.3%)	15 fish (20.2%)	-	1 fish released in CEL moves west into ICES management division 7j 1 fish released in IRE moves south through the CEL and is recaptured in ICES	IRE = 93.4 (± 116.3) CEL = 120.7 (±	IRE = 1.0 (± 1.2) CEL = 1.1 (± 0.6)

			10.5)						management division 7k	45.8)	

), travelling an average distance from release to recapture of 77.0 km (± 106.2 km). An up-to date growth model was derived for Irish Sea cod for 2017 (Figure 38). This model has been updated with data from the current project and other sampling sources including fishery independent and fishery dependent sources. The growth parameters were: $L_{inf\ 2017}$= 174.51 cm, K_{2017} = 0.126 and t^{0}_{2017} = -0.568. These and the most recent cod growth from published sources (ICES 2018a) parameters suggest that cod growth rate has been reducing (K value) with individuals expected to reach a larger asymptotic length (L_{inf}). This was considered to be linked to maturation of the 2013 cohort, which was relatively strong compared to previous cohorts of cod in the Irish Sea. The annual assessment of Irish Sea cod to provide advice has identified a retrospective bias – with an over estimation of the spawning stock biomass. The results of the current tagging study were incorporated into the assessment framework and show a reduced retrospective bias therefore providing an explanation for the annual downward revision of the SSB, given the observed movements in particular for larger cod (>60cm) outside the limits of the current assessment area.

A review of historic tagging study data has been conducted by Bendall *et al*., (2009) and Neat *et al*., (2014) who found that fish tagged in the Celtic Sea remain exclusively in ICES management divisions 7f, 7h and 7g and display no evidence of northwards migration into the Irish Sea (ICES management division 7a). Conversely, cod tagged in the Irish Sea have been shown to migrate both southwards into the Celtic Sea (Connolly & Officer 2001; Bendall *et al*., 2009; Neat *et al*., 2014) and northwards into the waters off the west coast of Scotland, most notable the North Channel and the Firth of Clyde (Brander 1975; Neat *et al*., 2014). This is supported in by the recapture results of the current study (Figure 30). The reasons why Irish Sea cod undertake such migrations were previously largely unknown. From the current project the a corroborative environmental / habitat suitability driver is thought to define the distribution and movements of Irish Sea cod based on habitat suitability modelling of thermal habitat (Section 3.1.4). At present the study identifies a small area in 7a of suitable thermal habitat which mirrors the core area of the 7a recapture data and clearly identifies a much larger area of suitable habitat in the Celtic Sea, within which the recapture data are recorded. Additionally the analysis of monthly habitat suitability supports the hypothesis this environmental driver would have strongest effect in late quarter 3 and early quarter 4 (Figure 36), as shown from the historic tagging review.

It cannot be discounted that there are two distinct, sedentary stocks in the Irish and Celtic Seas, which might be complemented by a third, migratory component, as seen in Skaggerak and Kattegat cod (Svedang *et al*., 2007). Comparative to the Irish Sea, adult cod abundance in the eastern Skagerrak and Kattegat has dramatically declined since the 1980s (Andre *et al*., 2016). For the first time we now have robust estimate of the contribution of this stock component to the Irish Sea cod stock – by combining the ICES stock assessment model with the observed movement data. A hypothesis that cod populations in the Skagerrak and Kattegat comprise a mixture of resident and migratory stocks was supported by a tagging study (Svedang *et al*., 2007). Kattegat and Gullmar Fjord showed an abundance of cod displayed resident behaviour, whereas fish tagged and released off the eastern Skagerrak coast predominantly migrated during the spawning season towards the North Sea. The study observed the majority of these fish returning to the tagging site by late spring. In the eastern Skagerrak region, small spawning aggregations of cod have resulted in observed low adult cod abundance coinciding with high juvenile abundance (Svedang 2003). It is thought that the majority of these juvenile cod result from passive movement from spawning grounds further offshore. The observed low abundance of adult cod resulted from juvenile and/or maturing fish of a certain size exhibiting return migration behaviour to the North Sea. This raises questions regarding the degree of connectivity between marine fish populations should both a migratory and resident cod stock exist in the Irish Sea and to what degree they may fluctuate over time.

A significant change in TAC for 2018 and 2019 has already seen a higher amount of cod landings. This had a marked effect on the recapture rates observed in the project which were lower in the first two years but increased as the targeted whitefish 'TR1' vessel began to catch increasing amounts on cod in 2018 in response to TAC increase. The source of recapture records between years demonstrate how changes in management and in particular catch advice can result in markedly different sources of mortality (Figure 32).

Within the current ICES assessment catches are summarised for 'otter trawls' targeting *Nephrops* and demersal fish, 'Scottish Seines', 'Mid-water trawl', 'Beam trawls' and 'others' (ICES 2019). Results of the current project support that these categories include the main sources of cod mortality with all reported recaptures derived from *Nephrops* and demersal fish fisheries. However, there is a bias with the recaptures toward demersal trawl fisheries which contributed 73% of recaptures in the Irish Sea compared to 8% by *Nephrops* directed trawls, whilst landings in 2018 were comprised 65% by demersal fisheries and 25% by *Nephrops* directed trawl fisheries. Recaptures by recreational fishers in the Northern Irish Sea were limited, with a total of 10 recaptures made by recreational anglers, 8 of which were in ICES rectangle 33E4 and all but two above minimum landing size (7 were returned alive). Recreational fishing for cod tended to be shore based and mostly in the southern Irish Sea. Whilst the recreational catches are not considered within the annual assessment, the high return rate and shallow depth from which the cod are caught suggest the mortality rates from these catches are low.

Since 2003 landings in the Irish Sea stock assessment have been adjusted to exclude those taken from the southern rectangles (33-E2, 33-E3 and 33-E4), as they have been believed not to be part of this stock but rather of the stock in divisions 7e–k (western English Channel and Celtic Sea). Thus, the assessment and the advice exclude these southern rectangles for the present stock but include them in the assessment and advice for cod in ICES divisions 7e–k. No tagged Irish Sea cod or tagged Celtic Sea cod were re-captured in those rectangles.

Despite large reductions in whitefish trawling effort since the early 2000's, Irish Sea cod have shown only, recent, moderate indications of recovery – linked to rare strong recruit events in isolate years. The input into management advice from this project will be undertaken under the ICES framework of annual advice in line with the requirements of the CFP. The initial results of the project have been presented to the ICES Working Group for the Celtic Seas in May 2018 (ICES 2018) and in May 2019 (unpublished). It is through this communication and working directly with the ICES assessment groups that the conclusions from the study can be incorporated in the scientific assessment of the stock and placed in the context of current management and future management plans. The current study clearly indicates a greater mixing of the stocks than in previous observed. The implications of current management will be incorporated into the development of scenarios for both the 7a and 7b-k cod stocks.

From the late 1960s to early 2000s, the Irish Sea underwent an environmental regime shift, with accompanying changes in ecological processes and productivity (ICES 2015). From a physicochemical position this was exhibited as changes in average nutrient loadings and seasonal mean temperatures. These physical oceanographic changes were accompanied by an ecological shift, effecting primary and secondary production of phytoplankton and zooplankton, through the food chain to finfish, crustacean and gastropod shell fish communities. The effects of such a regime shift on the gadoid assemblage will have included reductions in spawning and recruitment, growth and size. These changes may be the reason why there have been shifts in the dominant species for fisheries in the Irish Sea during the 1970s and 1980s, cod and whiting, and into the later part of the century to the present *Nephrops* dominated system. Further, it may be postulated that the dramatic reductions seen in the herring, cod, whiting arose fundamentally not because of fishing pressure, but owing to the change to the physicochemical balance of the system.

This is not to down weight the significant effect of high fishing mortality on the stock. Under the stress of a changing ecosystem balance, high fishing pressure would have further accelerated stock declines. The causes of the regime shift may be aligned with land use patterns, increasing use of agricultural fertilizers, pesticides and herbicides, channelization of waterways and increases in urban run-off, and climate change. While such a regime shift is not necessarily directly taken into account in fisheries management, it is indirectly taken into consideration when making management decisions. Future management plans should be based on improved process understanding and be robust to the likely future regime scenarios. Policies which are not in line with the environmental limitations is unlikely to achieve their aims.

The series of WKIRISH ICES workshops are also engaged in investigating ecosystem based management, of which any Irish Sea cod focused management plan should be cognisant. These methods will explore the food web and fishery interactions to develop a more holistic approach to fishery management. To this end the recommendations of WKIRISH need to have bearing upon Irish Sea cod management.

The results from the current project, in conjunction with historic analysis of spatial distributions of Irish and Celtic Sea cod, provide details of widespread exchanges of cod across different management areas. Through population forecasts models it is possible to provide management option ranges under scenarios supported by the recapture data, exploring the sensitivity of catch management options, toward F_{MSY}, of migration and stock mixing scenarios for the Celtic Sea and Irish Sea stocks. Analysis of recapture records and biological data has provided new insights into the ecology of Irish Sea cod. Results show an area of stock mixing within cod of Celtic Sea and Irish Sea origin (Figure 33 & Figure 34). There is no evidence of long distance movements of cod tagged in the Celtic Sea moving north into Irish Sea. Scenario testing using population assessment models demonstrates that these migration patterns could have significant implication for the assessment of biomass of the Irish Sea cod stock and correct for the retrospective bias of SSB forecast as seen in the current ICES assessment (Figure 42).

The current study clearly indicates a greater mixing of the stocks than previously observed. It is possible that the migratory component of the population fluctuates over time and with longer term environmental conditions, and other factors such as strong recruitment enhancing density dependent migration. It is recommended that a method to monitor the contribution of the two spawning populations should be developed as used for management of herring in the North Sea and Western Baltic. Cod released in the Irish Sea and recaptured within the Irish Sea was 80.7%. Whilst cod released in the Irish Sea and recaptured in the Celtic Sea was 16.4%, only a single recapture of a cod released in the Celtic Sea was recaptured outside the Celtic Sea, in an inshore southern Area of the VIIa. Knowledge of such broad-scale movement is critical to fisheries management as unaccounted movements could expose parts of the stock to inappropriate management regimes in other regions but also fish that remain in reproductively isolated units (as observed in the Celtic Sea; Bendall *et al*., 2009; Neat *et al*., 2014) will be prone to localised depletion and are less likely to recover from high levels of historical exploitation (Neat *et al*., 2014). Movement beyond stock boundaries will expose individuals to unknown and often unconsidered sources of natural mortality (Cook *et al*., 2015; Alexander *et al*., 2015). Secondly, because current fisheries management considers the Irish Sea to be a discrete, self-contained unit, so movement beyond the spatial boundaries of ICES management Division 7a will result in individuals being open to exploitation as part of a separate fishery.

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4.1 Appendix 1.

Appendix 1. Overview of tagging events in both the initial and revised tagging phase. The number of fish tagged and below the minimum conservation reference size (MCRS) is given.

Date	Organisation	Phase	Trip	Type	Fish Tagged	Below MCRS	Days at sea	Hauls	Location	Capture method
24/03/2016	AFBI	1	Charter 1	Charter	475	0	4	13	W. Irish Sea and North Channel	Mid-water trawl
01/04/2016	AFBI	1	Charter 1	Charter	488	0	4	14	W. Irish Sea and North Channel	Mid-water trawl
03/05/2016	AFBI	1	NI-FSP	Scientific Survey	12	0	2	5	Mid Irish Sea haddock fishing grounds	Mid-water trawl
11/03/2017	AFBI	1	Charter 2	Charter	135	0	4	16	W. Irish Sea and North Channel	Mid-water trawl
14/03/2017	AFBI	1	*RV Corystes* Groundfish Survey	Scientific Survey	7	0	15	-	Various survey stations across the Irish Sea	'Rockhopper' otter trawl

Date	Organisation	Phase	Trip	Type	Fish Tagged	Below MCRS	Days at sea	Hauls	Location	Capture method
17/03/2017	AFBI	1	NI-FSP	Scientific Survey	11	0	3	4	W. Irish Sea and North Channel	Mid-water trawl
21/03/2017	AFBI	1	Charter 2	Charter	37	0	1	2	W. Irish Sea and North Channel	Mid-water trawl
28/03/2017	AFBI	1	NI-FSP	Scientific Survey	30	0	5	12	W. Irish Sea and North Channel	Mid-water trawl
29/03/2017	AFBI	1	Charter 2	Charter	368	0	7	18	W. Irish Sea and North Channel	Mid-water trawl
01/04/2017	AFBI	1	NI-FSP	Scientific Survey	3	0	2	2	W. Irish Sea and North Channel	Mid-water trawl
06/04/2017	AFBI	1	Charter 2	Charter	105	1	3	8	Western Irish Sea spawning grounds and North Channel	Mid-water trawl

Date	Organisation	Phase	Trip	Type	Fish Tagged	Below MCRS	Days at sea	Hauls	Location	Capture method
14/04/2017	MI	1	Charter 3	Charter	166	39	5	23	Southern Irish Sea/Celtic Sea	Mid-water seine net
17/04/2017	MI	1	Charter 4	Charter	25	1	2	10	Southern area of spawning grounds in Western Irish Sea	Mid-water seine net
06/06/2017	AFBI	1	Pot-fishing Observer	Commercial Observation	2	2	1	-	Down Coast	Pot bycatch
03/07/2017	MI	1	Charter 5	Charter	173	4	3	24	North/Mid Irish Sea	Mid-water seine net
05/07/2017	AFBI	1	*RV Corystes* Queen Scallop Survey	Scientific Survey	5	0	9	-	Various survey stations across the Irish Sea	Bottom trawl queen scallop net

Date	Organisation	Phase	Trip	Type	Fish Tagged	Below MCRS	Days at sea	Hauls	Location	Capture method
31/07/2017	AFBI	1	Charter 6	Charter	31	0	1	3	South-east of *Nephrops* grounds	Mid-water trawl
11/08/2017	AFBI	1	Charter 6	Charter	430	0	4	18	South-east of *Nephrops* grounds	Mid-water trawl
23/08/2017	MI	1	Pot-fishing Observer	Commercial Observation	1	0	1	-	Western Irish Sea	Pot bycatch
05/09/2017	AFBI	1	*RV Corystes* Groundfish Survey	Scientific Survey	2	0	8	-	Various survey stations across the Irish Sea	'Rockhopper' otter trawl
25/09/2017	MI	1	Angler - self tagging	Voluntary	2	1	1	-	Waterford	Rod and line
06/10/2017	MI	1	Angler - self tagging	Voluntary	3	2	1	-	Wexford	Rod and line

Date	Organisation	Phase	Trip	Type	Fish Tagged	Below MCRS	Days at sea	Hauls	Location	Capture method
08/10/2017	MI	1	Angling boat	Sea Angling	8	4	1	-	Waterford	Rod and line
13/10/2017	MI	1	Shore Competit ion	Shore Angling	37	34	0	-	Cheekpoint, Waterford	Rod and line
14/10/2017	MI	1	Shore Competit ion	Shore Angling	18	18	0	-	Passage East, Waterford	Rod and line
19/11/2017	MI	1	Shore Competit ion	Shore Angling	2	1	0	-	Youghal, Cork	Rod and line
30/11/2017	AFBI	1	Observer on TR1	Commerci al Observati on	3	0	0	5	Mid Irish Sea haddock fishing grounds	Mid-water trawl
03/12/2017	MI	2	Shore Competit ion	Shore Angling	12	12	0	-	Ballyhack, Wexford	Rod and line
16/12/2017	AFBI	2	Shore Competit ion	Shore Angling	6	6	0	-	Cushendun, Antrim	Rod and line

Date	Organisation	Phase	Trip	Type	Fish Tagged	Below MCRS	Days at sea	Hauls	Location	Capture method
17/12/2017	MI	2	Shore Fishing	Shore Angling	20	20	0	-	Arthurstown	Rod and line
05/01/2018	MI	2	Shore Fishing	Shore Angling	5	5	0	-	Arklow North	Rod and line
13/01/2018	AFBI	2	Shore Competition	Shore Angling	2	2	0	-	Cushendall, Antrim	Rod and line
21/01/2018	MI	2	Shore Competition	Shore Angling	2	2	0	-	Arklow South	Rod and line
27/01/2018	AFBI/MI	2	Shore Competition	Shore Angling	1	1	0	-	Kilmuckridge, Wexford	Rod and line
28/01/2018	AFBI/MI	2	Shore Competition	Shore Angling	1	1	0	-	Kilmuckridge, Wexford	Rod and line
29/01/2018	AFBI/MI	2	Shore Competition	Shore Angling	1	1	0	-	Kilmuckridge, Wexford	Rod and line

Date	Organisation	Phase	Trip	Type	Fish Tagged	Below MCRS	Days at sea	Hauls	Location	Capture method
10/02/2018	AFBI	2	Shore Competition	Shore Angling	9	9	0	-	Waterfoot, Antrim	Rod and line
17/02/2018	MI	2	Cod specific Shore Competition	Shore Angling	12	11	0	-	Cheekpoint, Waterford	Rod and line
18/02/2018	MI	2	Shore Competition	Shore Angling	16	16	0	-	Ballyhack, Wexford	Rod and line
24/02/2018	MI	2	Charter 7 (Trip 1)	Charter	41	0	3	13	Celtic Sea	Demersal trawl
25/02/2018	MI	2	Shore Competition	Shore Angling	6	6	0	0	Passage East, Waterford	Rod and line
25/02/2018	AFBI	2	Charter 8	Charter	143	0	3	12	Western Irish Sea spawning grounds	Mid-water trawl

Date	Organisation	Phase	Trip	Type	Fish Tagged	Below MCRS	Days at sea	Hauls	Location	Capture method
05/03/2018	AFBI	2	NI-FSP	Scientific Survey	113	0	0	21	Various survey stations across the Irish Sea	Mid-water trawl
13/03/2018	MI	2	Charter 7	Charter	225	1	4	28	Western Irish Sea spawning grounds	Demersal trawl
05/03/2018	AFBI	2	Charter 7(Trip 2)	Charter	608	0	5	22	North Channel	Mid-water trawl
12/03/2018	AFBI	2	Charter 7 (Trip 3)	Charter	156	0	3	13	W. Irish Sea and North Channel	Mid-water trawl
19/03/2018	AFBI	2	Charter 8	Charter	68	0	3	12	Western Irish Sea spawning grounds	Mid-water trawl
23/03/2018	AFBI	2	*RV Corystes* Groundfish Survey/ Cod Tagging	Scientific Survey	18	0	3	7	Western Irish Sea spawning grounds and North Channel	Mid-water trawl

Date	Organisation	Phase	Trip	Type	Fish Tagged	Below MCRS	Days at sea	Hauls	Location	Capture method
26/03/2018	MI	2	Charter 7	Charter	170	0	3	17	Western Irish Sea spawning grounds	Demersal trawl
07/04/2018	MI	2	Shore Competition	Shore Angling	7	4	0	-	Wexford	Rod and line
15/04/2018	MI	2	Shore competition	Shore Angling	9	8	0	-	Ballyhack, Wexford	Rod and line
22/04/2018	MI	2	Angling Boat Competition	Sea Angling	4	1	1	-	Kilmore Quay	Rod and line
24/04/2018	AFBI	2	Pot Fishing Trip	Commercial Observation	1	0	1	-	Down coast	Pot bycatch
28/04/2018	AFBI/MI	2	Cod specific Shore Competition	Shore Angling	3	3	0	-	East Antrim coast	Rod and line

Date	Organisation	Phase	Trip	Type	Fish Tagged	Below MCRS	Days at sea	Hauls	Location	Capture method
30/08/2018	MI	2	Charter 9	Charter	85		3	13	Western Irish Sea	Demersal trawl
30/08/2018	AFBI	2	Charter 10	Charter	203		5	16	Western Irish Sea	Mid-water trawl
29/04/2018	MI	2	Shore Angling	Shore Angling	1	1	0	-	Southern Irish Sea/Celtic Sea	Rod and line
06/05/2018	MI	2	Sea Angling	Sea Angling	32	19	1	-	Southern Irish Sea/Celtic Sea	Rod and line
08/05/2018	MI	2	Shore Angling	Shore Angling	2	2	0	-	Southern Irish Sea/Celtic Sea	Rod and line
08/05/2018	MI	2	Voluntary Tagger	Voluntary Tagger	4	4	0	-	Southern Irish Sea/Celtic Sea	Rod and line
02/06/2018	MI	2	Voluntary Tagger	Voluntary Tagger	2	2	0	-	Southern Irish Sea/Celtic Sea	Rod and line
04/06/2018	MI	2	Voluntary Tagger	Voluntary Tagger	4	4	0	-	Southern Irish Sea/Celtic Sea	Rod and line
11/06/2018	MI	2	Voluntary Tagger	Voluntary Tagger	2	2	0	-	Southern Irish Sea/Celtic Sea	Rod and line

Date	Organisation	Phase	Trip	Type	Fish Tagged	Below MCRS	Days at sea	Hauls	Location	Capture method
16/06/2018	MI	2	Sea Angling	Sea Angling	5	5	1	-	Southern Irish Sea/Celtic Sea	Rod and line
17/06/2018	MI/AFBI	2	Sea Angling	Sea Angling	25	22	1	-	Irish Sea/Southern Irish Sea	Rod and line
23/06/2018	MI	2	Voluntary Tagger	Voluntary Tagger	5	5	0	-	Southern Irish Sea/Celtic Sea	Rod and line
24/06/2018	MI	2	Voluntary Tagger	Voluntary Tagger	3	3	0	-	Southern Irish Sea/Celtic Sea	Rod and line
01/07/2018	MI	2	Sea Angling	Sea Angling	8	4	1	-	Southern Irish Sea/Celtic Sea	Rod and line
01/07/2018	MI	2	Voluntary Tagger	Voluntary Tagger	4	0	0	-	Southern Irish Sea/Celtic Sea	Rod and line
07/07/2018	MI	2	Voluntary Tagger	Voluntary Tagger	5	4	0	-	Southern Irish Sea/Celtic Sea	Rod and line
11/07/2018	MI	2	Sea Angling	Sea Angling	30	23	1	-	Southern Irish Sea/Celtic Sea	Rod and line
13/07/2018	AFBI	2	Sea Angling	Sea Angling	3	2	1	-	Southern Irish Sea/Celtic Sea	Rod and line

Date	Organisation	Phase	Trip	Type	Fish Tagged	Below MCRS	Days at sea	Hauls	Location	Capture method
13/07/2018	AFBI	2	Voluntary Tagger	Voluntary Tagger	1	0	0	-	North Coast Ireland	Rod and line
21/07/2018	MI	2	Voluntary Tagger	Voluntary Tagger	3	3	0	-	Southern Irish Sea/Celtic Sea	Rod and line
03/08/2018	MI	2	Sea Angling	Sea Angling	9	1	1	-	Southern Irish Sea/Celtic Sea	Rod and line
04/08/2018	MI	2	Sea Angling	Sea Angling	10	2	1	-	Southern Irish Sea/Celtic Sea	Rod and line
05/08/2018	AFBI	2	Sea Angling	Sea Angling	21	17	1	-	North Coast Ireland	Rod and line
12/08/2018	AFBI	2	Sea Angling	Sea Angling	5	1	1	-	North Coast Ireland	Rod and line
21/08/2018	MI	2	Voluntary Tagger	Voluntary Tagger	1	1	0	-	Southern Irish Sea/Celtic Sea	Rod and line
28/08/2018	MI	2	Voluntary Tagger	Voluntary Tagger	1	1	0	-	Southern Irish Sea/Celtic Sea	Rod and line
08/09/2018	AFBI	2	Voluntary Tagger	Voluntary Tagger	2	2	0	-	North Coast Ireland	Rod and line

Date	Organisation	Phase	Trip	Type	Fish Tagged	Below MCRS	Days at sea	Hauls	Location	Capture method
07/10/2018	AFBI	2	Voluntary Tagger	Voluntary Tagger	4	4	0	-	North Coast Ireland	Rod and line
16/10/2018	AFBI	2	Voluntary Tagger	Voluntary Tagger	1	1	0	-	North Coast Ireland	Rod and line
01/11/2018	AFBI	2	Voluntary Tagger	Voluntary Tagger	12	4	0	-	North Coast Ireland	Rod and line
23/11/2018	AFBI	2	Voluntary Tagger	Voluntary Tagger	1	1	0	-	North Coast Ireland	Rod and line
09/12/2018	AFBI	2	Voluntary Tagger	Voluntary Tagger	3	3	0	-	North Coast Ireland	Rod and line
17/12/2018	AFBI	2	Voluntary Tagger	Voluntary Tagger	1	1	0	-	North Coast Ireland	Rod and line
18/12/2018	AFBI	2	Voluntary Tagger	Voluntary Tagger	1	1	0	-	North Coast Ireland	Rod and line
24/12/2018	AFBI	2	Voluntary Tagger	Voluntary Tagger	6	6	0	-	North Coast Ireland	Rod and line

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