Fisheries ecology of the brown crab (*Cancer pagurus* L.) in the Isle of Man

A thesis presented to Bangor University for the Degree of Doctor in Philosophy

By

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ABSTRACT

The brown crab or European edible crab *Cancer pagurus* is one of the most economically important crab species in European waters with landings of 49 263 t in 2013. *C. pagurus* is also one of the most important commercial species in the United Kingdom with landings of 28 778 t in 2013 worth approximately £33.5M at first sale. The global capture production of brown crab has increased markedly during the last two decades. Despite this, the crab fishery is relatively data poor in terms of the ecology and catch characteristics of this species, particularly in the Irish Sea.

The aims of this study were to provide the information to fill science gaps needed to inform sustainable brown crab fisheries in the Isle of Man. This was done by studying the population structure, reproductive ecology and catch characteristics of the brown crab fishery, and by examining the impacts of scallop fisheries on brown crabs, as well as assessing the by-catch composition of the brown crab pot fishery.

A combination of sampling techniques was used to collect data which included: baited pots between Spring 2012 and Summer 2013, dredge, trawl and shore surveys. The catch per unit effort (CPUE) of crabs caught in traps was strongly influenced by environmental (i.e., temperature, season, area) and fishery specific factors (i.e., pot volume). This study compared fishery dependent data (FDD) and fishery independent data (FID) to assess the CPUE estimates. Both of these data sources gave similar results which indicated that fisher-based surveys provide good quality information for future monitoring of the population provided that environmental and gear effects are accounted for. This study also determined the total exploitation rate of brown crab using both commercial and recreational fisheries data. The latter contributed only a small percentage of total mortality which is largely due to strict controls on total recreational fishing effort.

Observations of the distribution of brown crabs around the Isle of Man indicated the presence of a reproductive migration. Ovigerous crabs were generally found in offshore areas. These egg carrying females varied in size from 134 to 215 mm CW and each individual carried an estimated 0.4-3.0 million eggs. However, examination of behavioural maturity indicated that the earliest presence of sperm plugs was at 110 mm CW while functional maturity was 134 mm CW. There appears to be a predictable trend across Europe in the minimum size of egg bearing which appears to be related to water temperature.

Based on quantitative data collected throughout the dredge surveys the potential impact of scallop dredging on the brown crab population was estimated in terms of by-catch, damage and mortality estimates. This study indicated that female crabs were particularly vulnerable to scallop dredging around the North-West coast of the island in November when fishing effort was highest in this area. Estimates of the potential mortality associated with scallop dredging led to a lower and higher estimate of a potential annual crab by-catch mortality of between 11 t and 17 t respectively (assuming 45% mortality of the crab by-catch), which represented 2.2 - 3.4% of the commercial landings of brown crab for the Isle of Man. Thus at present levels of fishing (up until 2014) this would seem to contribute a relatively small proportion of total mortality to the crab population. Nevertheless, an extension of the scallop dredging closed season until the end of November in the area of the Targets fishing ground might be a useful conservation measure if scallop dredging activity were to increase in the future.

By-catch in pot fisheries is poorly studied in general. A total of 43 by-catch species were found in crustacean pots lifted around the Isle of Man and the velvet swimming crab *Necora puber* was the most abundant by-catch species. This study identified significant spatial differences in the CPUE of by-catch species; the highest by-catch CPUE was recorded around the west coast of the Isle of Man. However, seasonal changes in by-catch were less important. There was a significant negative relationship between the two target species (brown crab and European common lobster). However, there was no significant relationship between by-catch composition and target species (a combination of crab and lobster) composition.

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CHAPTER 1 - GENERAL INTRODUCTION

Thesis introduction

The brown crab fishery in British waters was comprehensively reported by Edwards (1979) who suggested that many of the brown crab stocks were underexploited in the United Kingdom at that time. However, 30 years later Bannister (2009) reported that in England and Wales most of the brown crab stocks are subject to growth-overfishing while in Scotland most stocks are either fully exploited or tending towards growth overfishing. Increasing pressure on crab stocks in the UK is linked to the development of fishery technology (vessel design advances, pot design improvements), increased pot effort, an extension of crab fisheries from inshore to offshore grounds, and increasing market demand may threaten the brown crab stocks in the future. In this thesis, the fundamental characteristics related to the issues of the population ecology of the brown crab in the Isle of Man were examined and the catch characteristics were evaluated using the fishery dependent data, fishery independent data and local ecological knowledge to providing information necessary to inform sustainable fisheries management.

The global importance of the brown crab fisheries

Crustaceans are among the most highly valued of luxury foods and they are nutritionally valuable sources of protein and minerals (Wickins and Lee, 2002; Barrento et al., 2009). The capture production of crustacean species accounted for 7.2% (5 750 655 tonnes) of global fisheries landings in 2012 (FAO, 2015). One of the most important crab species targeted in European waters is *Cancer pagurus*, commonly known as the European edible crab or brown crab, which accounted for 0.8% (49 263 t) of total marine crustacean landings in 2013 (FAO, 2015). The global capture production of brown crab has increased markedly during the last two decades (FAO, 2015) (Figure 1.1a). The countries with the largest catches were UK (28 778 t) (58%) and Ireland (6 378 t) (13%) in 2013 (FAO, 2015) (Figure 1.1b). Figure 1.1b also shows that landings of the brown crab in the Isle of Man accounting for 0.9% of the total global production.

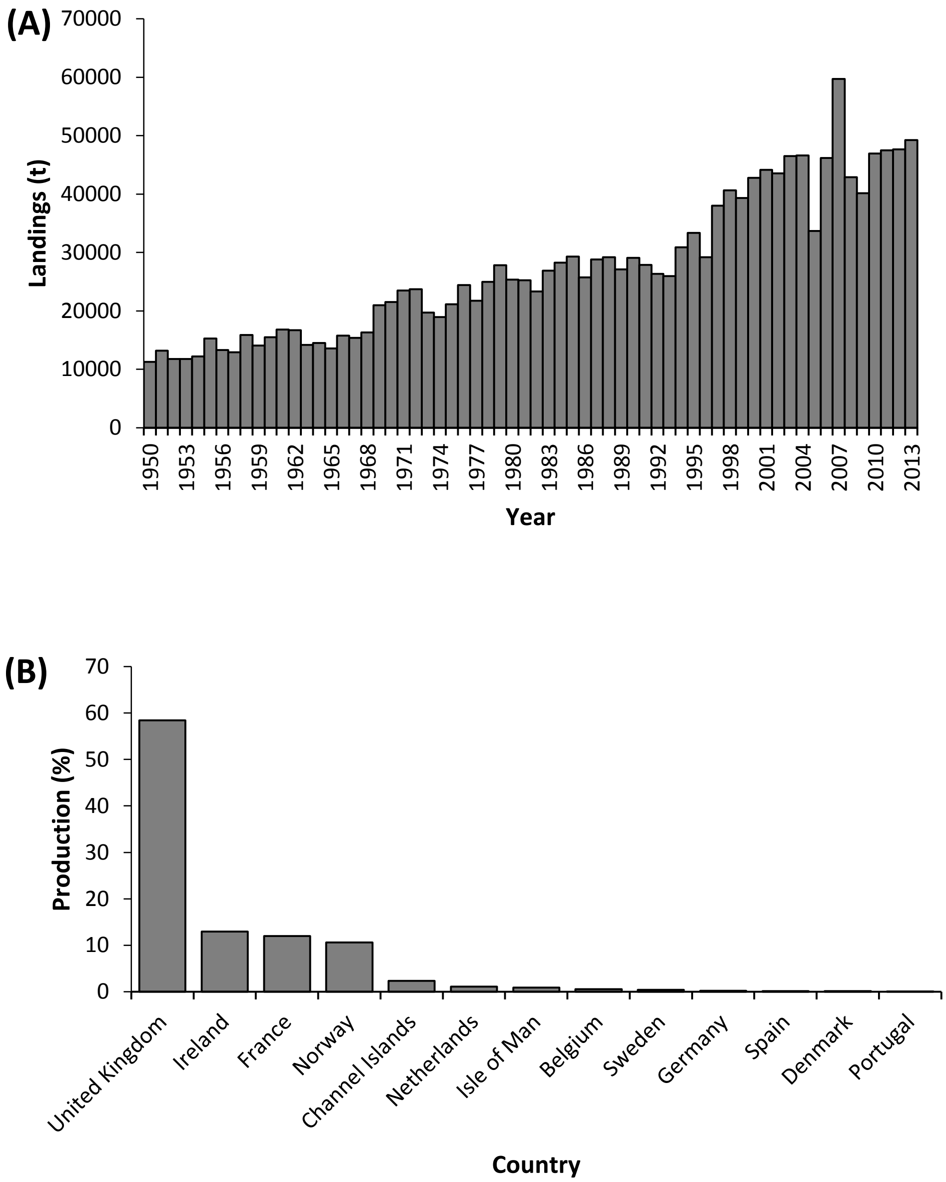

Figure1.1. A, Global capture production for the brown crab *Cancer pagurus* (for the period between 1950 and 2013); B, Capture production (%) of the brown crab *Cancer pagurus* in thirteen countries in 2013 (Modified from FAO, 2015).

In the United Kingdom**,** most of the catch of the brown crabs is sold to processing factories, generally sited at ports (Edwards, 1979). These factories cook the crabs and extract the meat for pastes and other canned products or dress the crab for wholesale. In addition, some crabs are sometimes sold live to markets and wholesalers (Parker, 2009). In some European countries (Scotland, England, Ireland and Wales), de-clawing is permitted and these are sold as a separate product (Patterson et al., 2007). Brown crabs are also used as a bait (particularly soft and thin shelled crab) to catch whelks in some regions of the United Kingdom (Bannister, 2009) and in the Isle of Man (personal observations).

Biology and life history of the brown crab Cancer pagurus

Taxonomically the brown crab belongs to the class Malacostraca, the Order: Decopoda, Infraorder: Brachyura, Family: Cancridae, and Genus: Cancer. *Cancer fimbriatus* Olivi, 1792 and *Cancer luederwaldti* Rathbun, 1930 were also reported as synonyms (WoRMS, 2012).

Cancer pagurus lives in both inshore and offshore waters to depths of 100 m or more (Keltz and Bailey, 2010). They are found in a variety of different habitat types, from rocky bottoms to sand, gravel, pebbles, crevices, muddy substrata and seaweed (Edwards, 1979; Woll and Alesund, 2006; Parker, 2009; NMFCA, 2011; SIFCA, 2011). In particular, male crabs are generally found on rocky bottoms, whereas female crabs tend to inhabit sandy bottoms and sheltered areas (Pawson, 1995; Woll and Alesund, 2006; NMFCA, 2011). In addition, juveniles seem to prefer shallow water (Woll and Alesund, 2006). *C. pagurus* is distributed in the NE Atlantic, and occurs from Norway to the North Coast of Africa (Parker, 2009), the Mediterranean, the Black Sea (Anosov, 2000) and the Sea of Marmara (Balkis, 2003).

C. pagurus is a nocturnal species (Skajaa et al., 1998) and is both predator and scavenger (Woll and Alesund, 2006). It feeds on both sessile and mobile species (Beaver, 1991). Its main prey are bivalves, gastropods, barnacles, decapods, echinoderms, worms and fish species (Lawton, 1983; Woll and Alesund, 2006). Throughout moulting and mating, adult crabs reduce their normal foraging area from 1000 m^2 to almost nothing since activity is much reduced. In spite of the fact that male crabs forage all year round except when protecting a female, ovigerous female crabs do not feed (or have limited feeding activity) (Howard, 1982; Aston, 1996).

In *C. pagurus* limb-loss has been shown to affect growth by decreasing the increment at ecdysis (Bennett, 1973, 1995; Tallack, 2002). Crabs also may lose their appendages because of stress conditions (e.g. sudden temperature changes) (Woll and Alesund, 2006). Tallack (2002) investigated physical injury, limb loss and disease in *C. pagurus*, and found that crab carapaces were sometimes cracked due to physical contact with fish boxes as a result of rough handling and "thumbing" injuries as the crabs are removed from pots. Soft crabs may be particularly vulnerable to mortality associated with these fishing related activities (Tallack, 2002).

Numerous studies have studied the movement and migration of *C. pagurus* (Williamson, 1900; Meek, 1913; Gundersen, 1977, 1979; Camus, 1982; Bennett and Brown, 1983; Latrouite and Le Foll, 1989; Ungfors, 2008). Tagged crabs exhibited local and long-distance migrations (Bannister, 2009). For crabs the distance of dispersal is affected by the biology of the species and regional oceanographic conditions (Ungfors, 2008). Tagging studies have identified that crabs may travel from a few kms per day to over 100 kms over periods of one to two years) (Williamson, 1900; Meek, 1913; Jones et al., 2010). Adult females appear to migrate over longer distances than males and immature females (Bennett and Brown, 1983; Latrouite and Le Foll, 1989; Edwards, 1979; Pawson, 1995; Skajaa et al., 1998; Ungfors, 2008; Bannister, 2009). Although Nichols et al (1982) reported that ovigerous females tend to move to deeper and calmer water to incubate their eggs, according to Woll (2003) not all ovigerous females migrate to deeper water to incubate their eggs. Generally, the recapture of ovigerous females happened within 1-2 years of release (Bennett and Brown, 1983; Ungfors, 2008).

C. pagurus has a long lifespan, typically living for 15 years and reaching a maximum size of 267 mm carapace width (CW) in males and 242 mm in females (Brown and Bennett, 1980; Beaver, 1991; Aston, 1996; Tully et al., 2006; Mill et al. 2009). The lifecycle consists of a short pelagic stage and a long benthic stage (Cobb et al., 1997; Woll and Alesund, 2006).

As in all decapods, growth occurs as a result of the moulting or ecdysis process (Edwards, 1979; Ungfors, 2008; Parker, 2009). Growth data is an important aspect of stock assessment and sustainable fisheries management (Tallack, 2002). Growth rate is dependent upon many factors such as geographical location, sex, damage level, and other unidentified environmental factors (Bennett, 1973).

In addition, brown crab reaches the minimum landing size (about 130-140mm CW) at around 4 to 7 years of age (Tully et al., 2006; Keltz and Bailey, 2010; IMR, 2011). Two types of criteria are used for the purpose of establishing size at maturity for *C. pagurus*: ‘‘Reproductive’’ characteristics of maturity, which relate to internal gonad staging, and externally displayed reproductive condition, and ‘‘Allometric’’ characters of maturity, which supply information in relation to changes in growth of body parts in particular chelipeds and abdomen (Edwards, 1979; Brown and Bennett, 1980; Tallack, 2002; Tallack, 2007b; Ungfors, 2008). Numerous studies have indicated that reproductive indicators determined size at maturity (Edwards, 1979; Brown and Bennett, 1980; Wilhelm, 1995; Tallack, 2002; 2007b; Ungfors, 2008). Edwards (1979) investigated ripeness of the *vasa deferentia* for *C. pagurus* around the Yorkshire and southwest coast of Ireland. According to Edwards' studies most crabs whose carapace width is over 110 mm are sexually mature. Furthermore, Edwards (1979) found that male crabs were mature throughout all seasons of the year, whereas the main period of moulting and copulation were encountered during the summer months. ''Behavioural maturity'' and ''functional maturity'' were explained by some scientists; behavioural maturity can be inferred from the presence of sperm plugs and direct observations of mating behaviour (Tallack, 2007b; Ungfors, 2008, Pardo et al., 2009). The presence of eggs externally is evidence of functional maturity in females, however the determination of functional maturity in males is more difficult (McQuaid et al., 2006; Claverie and Smith, 2009).

It is generally accepted that berried crabs avoid entering traps due to timidity (vulnerability to attack while carrying eggs) or the inability to climb through the entrance of the trap (Edwards, 1979; Bennett, 1995). According to Bennett (1995) the smallest berried crabs reported by some researchers; range from 115mm CW (Pearson, 1908, northern North Sea), 129mm CW (Edwards, 1979, central North Sea), 133mm CW (Brown and Bennett, 1980, English Channel) to 152mm CW (Pearson, 1908, Irish Sea). Mating occurs when females have recently moulted and are still soft-bodied (Edwards 1979; Beaver, 1991; Bennett, 1995). Spawning takes place in the late autumn and winter (Bennett, 1995). The primary hatching period was also noted as May to July (Bennett, 1995; Parker, 2009). However, these periods can shows differences depending on the sampling areas. For example, Tallack (2002) found berried females from February to October and the highest berried crab number was recorded in April around Shetland Islands. Similarly, Tallack (2002) also reported the hatching season as between April to September around Shetland Islands.

Gove (1981) defined fecundity as the potential reproductive capacity, measured in individual mature egg or sperm production. Cobb et al (1997) reported that *Cancer* crabs generally produce only one clutch per year. Edwards (1979) reported the number of eggs carried as between ~0.82 and ~2.6 million which has been confirmed in a number of studies. For example, the significant positive size-fecundity relationship in *C. pagurus* was reported by Tallack (2007a); in females of 129 mm carapace width (CW) and 212 mm CW carried ~0.78 and ~2.4 million eggs respectively. Similarly, Ungfors (2008) determined positive relationship between CW and fecundity, and eggs number was noted between 0.5 and 2.5 million.

Study area and the Isle of Man brown crab fisheries

The Isle of Man is a self-governing crown dependency of the UK, is situated in the northern Irish Sea, NE Atlantic (Figures 2.1, 4.1, 5.1, 6.1 and 7.1). The waters within the Isle of Man's 12 mile territorial limits are shallow, in particular to the east of the island, where they are mostly less than 30 m deep (Craven et al., 2012). Nearshore sediments are predominantly fine sand, whilst offshore sediments mainly categorised in four classes; coarse sands and gravel, fine sand, muddy sand and mud (Barne et al., 1996; Craven et al., 2012).

In the Isle of Man, six marine species constitute the main productions of seafood, which are: great scallop *Pecten maximus*, queen scallop *Aequipecten opercularis*, brown crab *Cancer pagurus*, European lobster *Homarus gammarus*, common whelk *Buccinum undatum* and Norway lobster *Nephrops norvegicus* (Murray et al., 2008). In the Isle of Man, the same pots are used to catch both brown crab (*Cancer pagurus*) and European lobster (*Homarus gammarus*). Additionally, other species of commercial crabs are caught by these pots, such as velvet crab (*Necora puber*), spider crab (*Maja squinado*) and green crab (*Carcinus maenas*), however they are not regularly landed by fishermen due to the small catches of these species.

The capture production of the brown crab peaked in 2011 and it was the third most important commercial fishery species in terms of landing weight (554t) and 4th by value economic value (£443,293) in the Isle of Man in 2011 (ICES, 2012). In 2013, the landing weight of this species was determined as 453t. The production of brown crab in the Isle of Man shows a marked increase from 1983 to 2013, although there were decreases during this period (Figure 1.2).

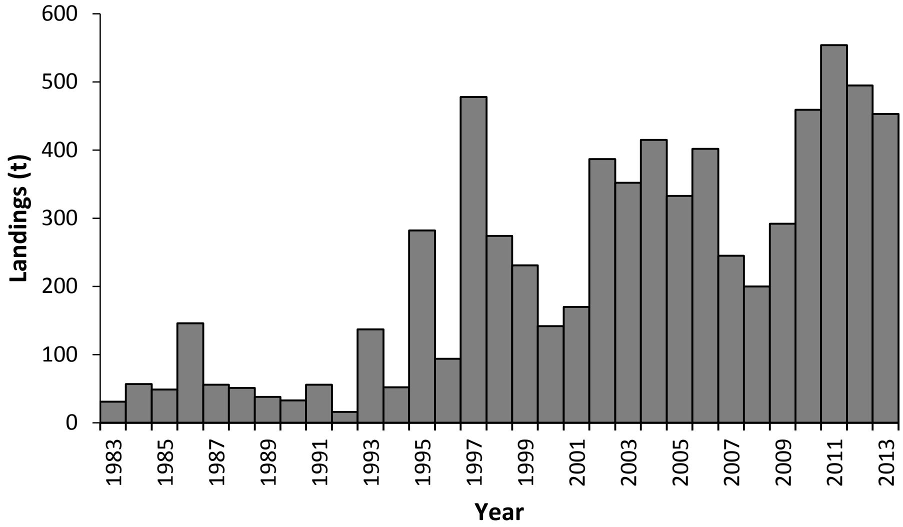

Figure 1.2. Capture production for the brown crab *Cancer pagurus* in the Isle of Man for the period between 1983 and 2013 (FAO, 2015).

In recent years the allocated licences (which covers both crab and lobster fishing sectors) and allocated pot numbers in the Isle of Man have increased significantly after a relatively long period of stability (ICES, 2012) (Figure 1.3). The total boat number used for crab fishing sector varied between 15 and 27 boat in the Isle of Man for the period between 2007 and 2012. The average vessel size of the fleet is 7.6 m (DEFA, 2013) and small vessels are commonly used for this sector with a smaller proportion of larger vessels (> 10 m) also present in the Isle of Man (Figure 1.4).

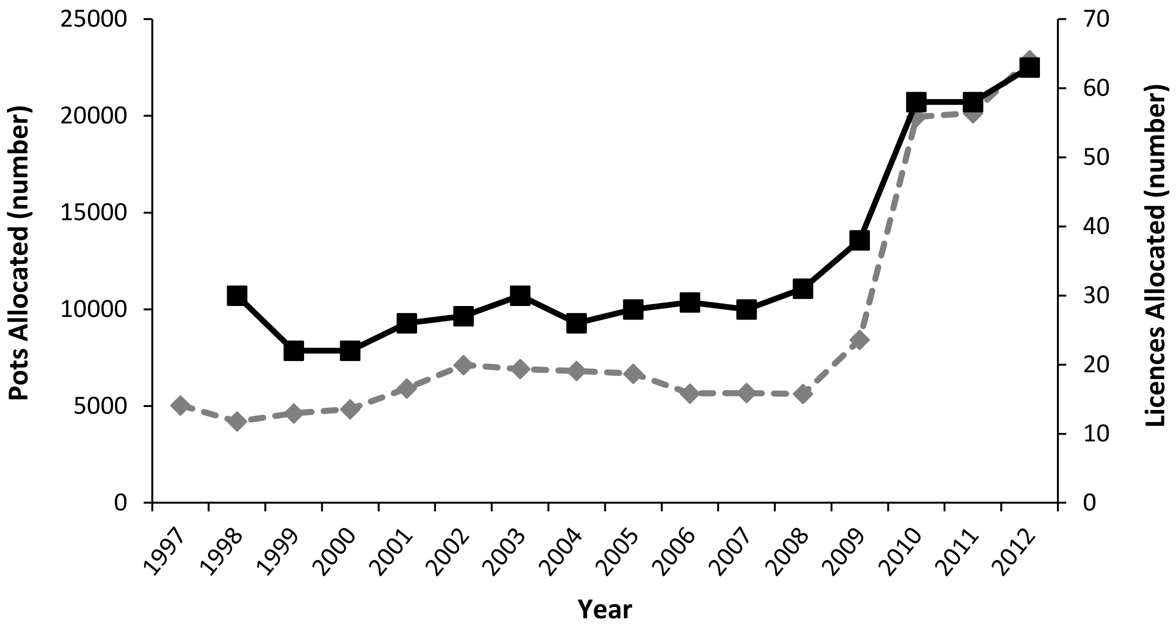

Figure 1.3. Effort in the Isle of Man pot fishery; data indicates the number of licences issued (solid line) and number of pots allocated (dashed line) for the brown crab and European lobster between 1997 and 2012 (modified from ICES, 2012; DEFA, 2013).

Figure 1.4. Two different sized fishing boats used to catch the brown crab in the Isle of Man (Photo by Fikret Ondes).

There is no standardization of pot type in the Isle of Man crab fishery, but fishermen generally use traditional creels (Figure 1.5b), fitted predominantly with “soft eyes”, though hard eye top mounted entrances are in use (Hanley et al., 2013) (Figure 1.5). Similarly, pot volume is not standardized in Manx waters and varies from 0.11 m^3 to 0.20 m^3 (0.11 m^3 and 0.14 m^3 are the most common sizes used, Chapter 2). All pots have escape panels (80 mm wide×45 mm high) to minimize discards and by-catch and have pot tags for the purposes of enforcement.

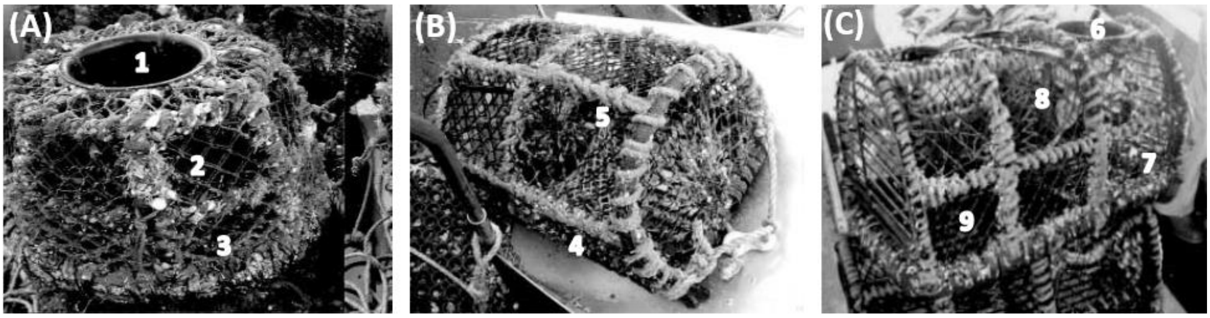

Figure 1.5. Different pot types used in the United Kingdom and the Isle of Man. (a) Inkwell (diameter 65 cm). (b) Soft-eyed creel (length 90 cm). (c) Parlour (length 105 cm). 1 _ rigid plastic top entrance, 2 _ location of rubber skirt used to slow escape of captured animals, 3 _ heavily weighted base, 4 _ side entrance, 5 _ soft mesh non-return valve, 6 _ rigid plastic top entrance, 7 _ baited chamber, 8 _ soft mesh non-return valve exit to parlour, 9 _ parlour chamber (Modified from Blyth et al., 2002).

Pots are mainly baited with herring, mackerel, small spotted catshark, and gurnard. Most bait is sourced from the mainland, but fishermen use some by-catch species, such as small spotted catshark *Scyliorhinus canicula*, ballan wrasse *Labrus bergylta* and European conger *Conger conger* to catch brown crab and lobster. Soak time, the length of time the pot is in the water, ranges between 1 and 12 days, depending on fishermen’s practices and weather conditions, although the most common soak time is 2 days.

Current management measures

The crab fishery in the Isle of Man is regulated by the Department of Environment, Food and Agriculture (DEFA). The current minimum landing size (MLS) for brown crab is 130 mm shell width in the Isle of Man. Landing of ovigerous, or berried, crab is forbidden and a person must not land detached claws. There are no seasonal or spatial closures in the Isle of Man crab fisheries. More information about the fisheries regulations are discussed in Chapter 2. In addition, recreational (hobby) crustacean fisheries are monitored in the Isle of Man. Hobby fishers' licence conditions restrict individuals to five pots per person with a bag limit of five brown crabs and two lobsters per day, and they use a crab and lobster catch return form (Kaiser et al., 2008).

Interactions with other fisheries

Mobile fishing gears such as dredges and trawls are potential threats to brown crab stocks because *C. pagurus* is caught as by-catch in these fishing gears (Howard, 1982; Hill et al. 1996; Kaiser et al., 1996; Jenkins et al. 2001; Veale et al. 2001; Beukers-Stewart et al., 2001; Cooper, 2005; Bannister, 2006; Tully et al., 2006; ICES, 2007; Montgomery, 2008; Beukers-Steward and Steward, 2009; Duncan, 2009). In particular, ovigerous (berried) crabs are vulnerable to dredging operations (Howard, 1982). In the Isle of Man, Duncan (2009) noted by-catch species in queen scallop trawls. Nevertheless, the potential by-catch from these fisheries is not well understood in the context of commercial landings.

In addition, although static fishing gear is considered to be ‘‘environmentally friendly’’ because it is highly selective for target species (Jennings and Kaiser, 1998; Pawson, 2003), *C. pagurus* was reported as a non-target species in gillnets (Tallack, 2002; ICES, 2003; Bannister, 2006; ICES, 2007; Ungfors, 2008). This fish gear caused high levels of ovigerous female crab mortality and Swedish brown crab stock was threatened from by-catches of berried females in (Ungfors, 2008). However, gill and tangle nets are not typically used in the Isle of Man, hence mobile fishing gears are the gear type with the greatest potential to have an effect on brown crab populations (Hill et al., 1996).

By-catch in crab pots

Crab pots have a comparatively small effect on the benthic marine environment in comparison with towed bottom gears, such as beam trawls and scallop dredges (Eleftheriou and Robertson, 1992; Witbaard and Klein, 1994; Hill et al., 1996; Murray et al., 2009). However, non-target species are captured by crab pots (Brown, 1982; Shanks et al., 1997; Tallack, 2002; Henderson and Leslie, 2006). Around Northern European, little is known about the pot by-catch species and there is no comprehensive study which is related to the quantitative information in the literature. In addition to pots that are actively fishing, lost gear (ghost-fishing gear) can continue to fish for many months or years and will catch not only crustaceans but also fish, some of which may be commercially important (Bullimore et al., 2001).

Objectives of the thesis and outline of the chapters

The aim of the study was to evaluate ecological characteristics (population structure, migration patterns, reproductive ecology) and catch characteristics of the brown crab (*Cancer pagurus*) in the Isle of Man and the interactions between crab fisheries and scallop fisheries sectors to inform sustainable fisheries management.

Chapter 2 describes the basic issues of the population structure (e.g. sex distribution, size distribution and migration patterns) of the brown crab in the Isle of Man. This chapter also determines the catch per unit effort (CPUE) of the brown crab in the Isle of Man using fishery dependent data and fishery independent data. Therefore, this chapter compares the scientific and commercial CPUE values. Moreover, the effects of various environmental and fishery-specific factors on the CPUE of the brown crabs are analysed.

Chapter 3 deals with the issue of relative growth and size at maturity of the brown crab in the Isle of Man. This chapter provides an opportunity to test the relevance of the current minimum landing size (MLS) using the observed size at maturity from observations in the present study. The relationships between the carapace width-body weight for males and females were examined to ascertain morphometric indicators of maturity that might act as proxies for more time-consuming indices of maturity.

Chapter 4 reports the fecundity of the brown crab in Manx waters. Chapter 4 also deals with the issue of explaining which factors influence the fecundity, egg size and egg quality (elemental composition) of this species. Furthermore, the results compared the relationship between the minimum size at which females are first observed to carry eggs and the minimum bottom seawater temperature of different sampling areas in a wider European context.

Chapter 5 describes the impacts of scallop dredging on the brown crab fishery. The spatial and seasonal patterns in crab catches in scallop dredges were examined. This chapter provides an estimation of the distribution of crabs and berried females around the inshore and offshore areas in the Isle of Man. In this chapter vessel monitoring system (VMS) information is used together with the spatial and temporal observations of the crab by-catch. Damage caused by the scallop dredges was also studied. Estimations of the total tonnage of brown crabs killed as by-catch in the scallop dredge fishery are estimated using best-case and worst-case scenarios and compared to the annual reported landings of crab in the Isle of Man fishery.

In Chapter 6, observations are presented of the non-target fish and invertebrate species composition in the Isle of Man pot fishery sector. The spatial and temporal catch of these non-target species are examined. In Europe, there is now a move to ban discards of target species and as such it will be necessary for all fisheries to quantify and report their by-catches. Thus, the chapter aims to highlight catches of species of conservation importance or those that might be relevant to the EU landings obligation. The chapter also focuses on the comparison of the CPUE values of crab, lobster (target species) and by-catch species.

In Chapter 7, in addition to commercial crab fisheries, recreational fisheries were evaluated using government return forms (2007-2012) to ensure a full understanding of the total exploitation rate of brown crab *Cancer pagurus* in the Isle of Man.

Finally a general discussion and implications for the crab fishery are presented in Chapter 8.

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CHAPTER 2 - THE CATCH CHARACTERISTICS AND POPULATION STRUCTURE OF THE BROWN CRAB (*CANCER PAGURUS*) FISHERY IN THE ISLE OF MAN

2.1 Abstract

Brown crab contributes to small-scale fisheries in the Isle of Man and landings (495t) were worth in excess of £0.5 million in 2012 (DEFA, 2013). The present study sought to fill evidence gaps needed to improve the scientific understanding of this fishery. Fishery independent data (FID) were collected to examine the spatial and temporal variations in the size distribution and sex ratio of crabs around the Isle of Man. This study also aimed to evaluate the catch characteristics of brown crab using the fishery dependent data (FDD) (2007-2012), the FID (2012-2013) and local ecological knowledge (LEK). The sex ratio is highly variable in different areas across seasons and was perhaps indicative of migration patterns in relation to mating. This change was most notable with a strong increase in the proportion of females to the south and west of the Isle of Man in the autumn months. The water temperature, depth, and pot volume were all important factors that influenced the catch per unit effort (CPUE). A strong correlation was found between the scientific CPUE and commercial CPUE which indicated that industry catches would provide reliable and representative data for assessment of populations status.

Future survey designs would need to ensure adequate spatial coverage of the east and west coast of the Isle of Man together with a seasonal sampling regime that captures the spatial change in the distribution and abundance of male and female crabs.

Keywords: *Cancer pagurus*, CPUE, fishery dependent data, fishery in-dependent data, commercial fisheries, population structure, fisheries management, Isle of Man

2.2 Introduction

Assessment of the catch characteristics and population patterns of target species can be undertaken using a number of different approaches. These approaches include the use of scientific observations, fishermen's logbooks (Hilborn and Walters, 1992; Woll et al., 2006; King, 2007), and local ecological knowledge (LEK) (Berkes et al., 2000; Bergmann et al., 2004; McLeod and Leslie, 2009) all of which can provide information to underpin the sustainable use of stocks and conservation of their habitats. Despite the variety of data gathering techniques that can be deployed they are rarely evaluated together, e.g. geo-referenced catch and effort data from commercial logbooks and the effort data from experimental fishery surveys (Vigneaux et al., 1998; Jennings et al., 1999; Petitgas et al., 2003). In the present study, a range of different approaches are implemented to provide a full understanding of catch per unit effort (CPUE), population structure, sex ratio and size distribution of economically important brown crab fishery.

Brown crab, *Cancer pagurus* Linnaeus, 1758, is distributed in the NE Atlantic, and occurs from Norway to the North Coast of Africa (Parker, 2009), the Mediterranean Sea, the Black Sea (Anosov, 2000) and the Sea of Marmara (Balkis, 2003). *C. pagurus* can live for up to 15 years and reach a maximum size of 267 mm carapace width (CW) in males and 242 mm CW in females (Brown and Bennett, 1980; Beaver, 1991; Aston, 1996; Mill et al. 2009). The lifecycle consists of a short pelagic stage and a long benthic stage (Cobb et al., 1997; Woll and Alesund, 2006). Male and female crabs appear to undertake migrations that are linked to mating and the development and release of larvae by female crabs (Bennett and Brown, 1983; Hunter et al., 2013). Brown crab is commercially fished in thirteen countries with total landings of 47,640 tonnes in 2012 (FAO, 2014), with the largest catches from the UK (27,273 t), Ireland (6,269 t) and France (6,141 t) (FAO, 2014). The landings of brown crab have increased markedly in the UK during the last 40 years. Despite the recent increases in fishing intensity and efficiency, the quantification of potting effort and stock assessment of brown crab have been poorly documented to date (ICES, 2005; Bannister, 2009, 2011).

As for many rural areas in the UK, brown crab is an important contributor to the Isle of Man fishing economy with landings in 2012 of around 495t worth in excess of £0.5 million (DEFA, 2013). The commercial potting vessels range from 4 to 12 m in length and are registered with a UK potting license. The pot fishing occurs all around the island within 3 nm of the coast (with the possible exception of the NE coast), and out to the territorial sea boundary (12 nm) off the central-west and southwest coasts. Fishers use traditional inkwell pots as well as more modern steel framed parlour pots of a variety of different sizes. Several fish species (mainly herring, mackerel, spotted catshark, and gurnard) are used as bait in pots. Soak time, the length of time the pot is in the water, ranges between 1 and 12 days, depending on fishermen's practices and weather conditions, although 1-2 days is most typical. There are a number of regulations that promote conservation of brown crab populations in the Isle of Man. Fisheries legislation requires escape gaps (80 mm wide×45 mm high) to be fitted to allow undersized crabs and lobsters to escape. The minimum landing size (MLS) for brown crab is 130 mm carapace width and the landing of berried crab and landing of claws (i.e. de-clawing) is prohibited. Commercial fishermen record their catches in logbooks.

Catch per unit effort (CPUE) is generally used as an index of relative abundance in fisheries stock assessment (Bell et al., 2001; Maunder and Langley, 2004; Su et al., 2008). However, catchability of crustaceans can vary with environmental and fishery-specific factors such as water temperature and wind stress (Drinkwater et al., 2006), habitat structure (Addison and Lovewell, 1991; Tremblay and Smith, 2001), location of fishing areas (Woll et al., 2006), season (Brown and Bennett, 1980; Hart, 1998; Trisak et al., 2009), depth (Linnane et al., 2013), gear type (Thomas, 1959; Lovewell et al., 1988; Addison and Lovewell, 1991), position of trap in the string (Bell et al., 2001), escape gaps (Brown, 1982), bait (Chapman and Smith, 1979), and soak time (Bennett, 1974; Fogarty and Addison, 1997). Hence, in order to remove the effects of these factors, CPUE data is commonly standardised using various methods such as generalized linear models (GLMs), generalized additive models (GAMs) and generalized linear mixed models (GLMMs) (McDonald et al., 2001; Maunder and Langley, 2004; Maunder and Punt, 2004; Maunder et al., 2006; Ye and Dennis, 2009; Murray et al., 2013). Nevertheless, despite the standardisation of catch and effort data, there is still no guarantee that the resultant index of abundance is linearly proportional to abundance (Maunder and Punt, 2004; Branch et al., 2006). Information on catch and effort can be collected either from fishermen's logbooks or catch returns (fishery dependent data – FDD) or from direct scientific observations (fishery independent data – FID). FDD is relatively inexpensive to collect and provides more comprehensive information in terms of space and time coverage than FID observations (Ye and Dennis, 2009). In contrast, FID provides more reliable estimates of CPUE that are precisely geo-referenced and can provide useful information on additional bio-ecological (e.g. distribution and abundance of young individuals) and economic characteristics (Verdoit et al., 2003; Lordan et al., 2011). The use of fishers' knowledge also can contribute to a better understanding of spatio-temporal trends in the abundance of the target species and historical patterns in ecosystem parameters that may influence the target species (Whiteley, 2009; Macdonald et al., 2014). The comparison of FDD, FID and fisher's knowledge is rare (Fox and Starr, 1996; Potier et al., 1997; Petitgas et al., 2003).

The first aim of this study was to determine the population structure of brown crab in the waters surrounding the Isle of Man (Irish Sea) using FID that related to the spatial and temporal variations in the size distributions and sex ratio of brown crab. The FID (2012-2013) was related to FDD for the period 2007-2012 to examine the spatial and temporal variations in CPUE. In addition, estimates of CPUE from commercial and scientific pot deployments were compared in 2012. The effects of environmental and fishery specific factors (e.g. water temperature, location of fishing areas, season, depth, bait and soak time) on CPUE were also examined.

2.3 Materials and methods

Study area and fishery- independent data (FID)

The Isle of Man is situated in the northern Irish Sea, NE Atlantic (Figure 2.1a). The waters within the Isle of Man's 12 mile territorial limits are shallow, in particular to the east of the island, where they are mostly less than 30 m deep (Craven et al., 2012). Nearshore sediments are predominantly fine sand, whilst offshore sediments mainly categorised in four classes; coarse sands and gravel, fine sand, muddy sand and mud (Barne et al., 1996; Craven et al., 2012).

Data collection of the crab population was undertaken around the Isle of Man during 6 seasonal experimental pot surveys from spring 2012 to summer 2013. Sampling was undertaken from eight commercial fishing boats that operated in different locations spaced out around the Isle of Man. In some seasons the sampling area was reduced because of limited fishing activity and the restrictions imposed by weather conditions. Fishermen do not fish in the north of the Isle of Man, hence no sampling was undertaken in these areas. To provide spatial and temporal comparisons of catch ratio, data were standardised to reporting areas of c. 75 km^2, which subdivide the 37E5 (ICES) rectangle (Figure 2.1b). A day's fishing on a crab boat generally started at approximately c. 7.00 am and finished at c. 4 pm. Commercial fishing pots fitted with escape gaps were fished at depths ranging between 2 m and 65 m. The location of each haul was recorded using a GPS system. Environmental factors such as depth as well as fishery-specific factors included the number of pots fished, the number of fleets of pots hauled and soak time were recorded. Soak time varied from 24 to 288 hours. Pot volume was variable among fishers (0.11, 0.12, 0.14, 0.17, and 0.20 m^3) hence the effect of this on CPUE was examined. Similarly, the effect of bait types (spotted catshark, cod, gurnard, haddock, herring, mackerel and pollack) on CPUE was compared. Information related to crab catch composition (sex, carapace width, body weight, moult stage, and egg bearing) was recorded at sea.

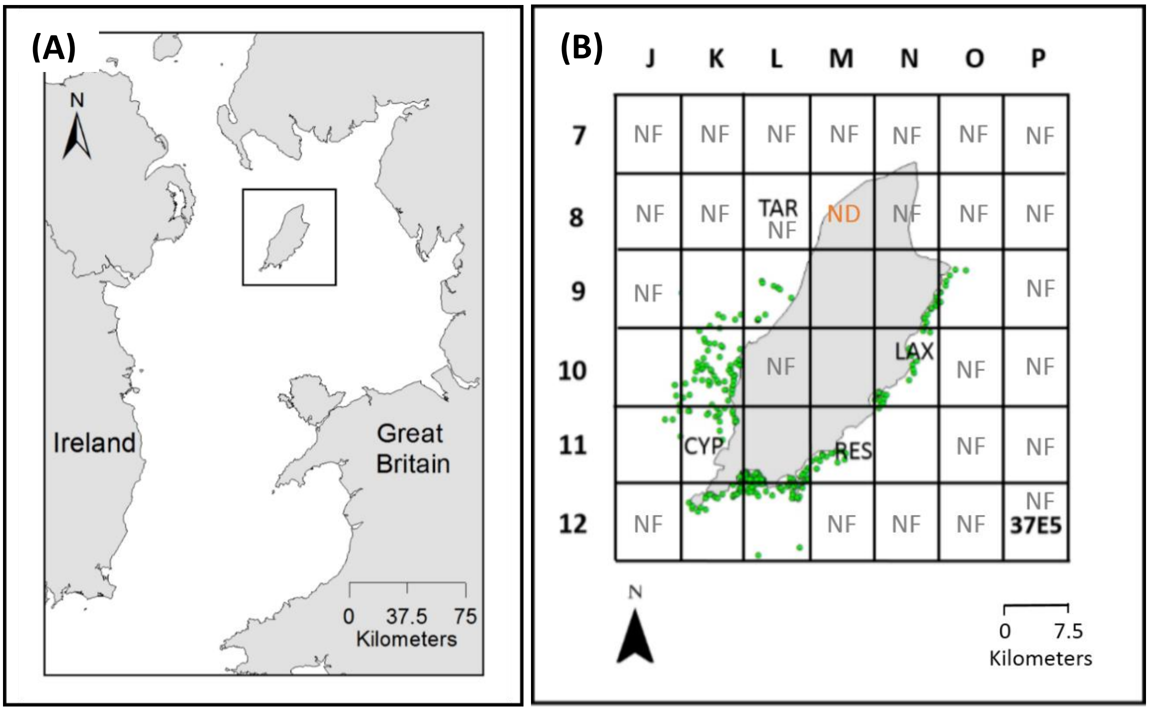

Figure 2.1. A, location of the Isle of Man in Northern Irish Sea (ICES subdivision VII A). B, study area subdivided into 42 areas of approximately 75 km². The grid shows the alpha-numeric coordinates for ICES statistical rectangle 37E5. The green data points show the sample locations for the period between spring 2012 and summer 2013. The environmental data stations (Targets (Tar), Cypris (Cyp), Resa (Res), and Laxey (Lax)) are also shown. The abbreviations are: No fishing (NF), crab fishing occurs there but no data (ND).

Fishery- dependent data (FDD)

Logbooks are completed by licensed fishers during each day of fishing activity. Fishermen are required to report the fishing dates, fishing ports, number of hauled pots and the total live weight of crabs landed. In contrast to fishery-independent surveys, logbook data does not include the information about the proportion of the catch under the MLS. Landings returns were used to calculate CPUE of brown crab in the period 2007-2012. A spatial analysis of this data was only possible for 2007 when the industry used the grid square reporting scheme (Figure 2.1b), thereafter, landings were reported in relation to the vessel's home port only. The catching capacity of vessels in the Isle of Man was determined from the relationship between boat size and the number of hauled pots.

Local ecological knowledge (LEK)

Local ecological knowledge was collected using face to face interviews based on a semi-structured questionnaire in July 2013 (Appendix 2.1). Interviewees were owners of fishing vessels that actively fish for brown crab. A total of 10 interviews were conducted (represents 40% of total fishermen population). The questionnaire study aimed to access general information about the spatial and temporal variations in crab catch and migration patterns that occur in the waters of the Isle of Man. The questions were designed to capture information about the ecology of the brown crab (e.g. patterns in moulting, and discards) and basic information of the fishery-specific factors (soak time, pot volume, and bait type) which were considered relevant in consideration of factors that influence CPUE.

Environmental data

In addition to the crab fisheries survey data, monthly time series of marine quality data for the period 2007-2013 at 4 sites (Targets, Cypris, Resa, and Laxey) around the Isle of Man (Figure 2.1b) obtained from the Isle of Man Government Laboratory. The data included bottom water temperature and dissolved oxygen values of these aforementioned stations (DEFA, 2014).

Data analyses and CPUE modelling

Statistical analyses were performed with the SPSS software (Version 20). Spatial data was evaluated using ArcGIS (Version 10.1). To test the CPUE data for normality and homogeneity of variance, a Kolmogorov-Smirnov K-S test and Levene's test were used respectively (Field, 2005). Data were ln transformed when appropriate. Linear regression was used to test the relationship between carapace width (CW) and depth to understand whether depth was related to the size of crabs caught. Spatial (statistical square) and temporal variations (monthly or seasonal) in CW with sex as a covariate were examined using general linear model (GLM). For the fishery independent data, the general linear model (GLM) was used to test the relationship between ln - catch per unit effort (lnCPUE) and (1) sampling season; (2) sampling area; and (3) interaction between season and area. For the aforementioned model, season and area were fixed factors, whereas soak time and depth were chosen as covariates. In order to estimate more reliable lnCPUE, if there is only one soak time value in the fishing area, this observation has been deleted. In addition, the relationship between CPUE and depth is quadratic (Figure 2.7c). Thus, depth was modified for the general linear model. Linear regression were used in order to test the relationship between ln - catch per unit effort (lnCPUE) and pot volume.

Concerning fishery dependent data (2007-2012), ANOVA was used to test the relationship between catch per unit effort (CPUE) and sampling season. For the logbook data (2007), the relationship between CPUE and sampling area was tested using ANOVA. The sampling area was pooled because fishermen recorded several areas at the same day on their logbooks. Linear regression were used in order to test the relationship between catch per unit effort (CPUE) and monthly mean bottom water temperature.

During the field study, crabs' weight were recorded using the balance at the boat. Thus, total crab weight a day was calculated. However, during some trips fishermen captured a high number of crabs thus in order to estimate crab weight a day, the average crab weight value in 2012 (669 gr) was used. Then, scientific weight data and fishermen's logbook data were compared. Spearman's rank correlation was used to test the relationship between scientific CPUE (FID) and commercial CPUE (FDD).

Scientific CPUE (Fishery independent data)

*Where *all C* (all catch included undersized, soft and berried crabs) is the crab catch in number per string, *thp* the total hauled pot per string.

$$\text{Scientific CPUE} = \frac{all\ C\ (number)}{thp}$$

*Scientific CPUE was also calculated based on legal catch (legal sized hard crabs). Where *LC* (legal catch) is the crab catch in terms of weight (kg); *thp* the total hauled pot per string.

$$\text{Scientific CPUE} = \frac{LC\ (kg)}{thp}$$

Commercial CPUE (fishery dependent data)

*Where *LC* (legal catch) is the crab catch kg; *thp* the total hauled pot per trip.

$$\text{Commercial CPUE} = \frac{LC\ (kg)}{thp}$$

To understand the relationship between catching capacity and vessel size the relationship between mean number of pots hauled per trip of boats and deck area (length X breadth) was examined using a linear regression.

2.4 Results

Environmental data

During 2007-2013 (pooled data), September was the warmest month (T_{mean} = 14.70°C) in terms of bottom seawater temperature, and March the coldest (T_{mean} = 7.43°C). The monthly water (bottom) temperature values showed similar trends at all the stations (Figure 2.2a). The highest value of mean dissolved oxygen was determined in April in Laxey (9.82 mg/l), whereas the lowest value found in October in Resa (7.83 mg/l) (Figure 2.2b). The bottom temperature and dissolved oxygen strongly correlated in the each data stations: Targets (Spearman's rank correlation, $r = -0.90$, $P < 0.001$); Cypris (Spearman's rank correlation, $r = -0.87$, $P < 0.001$); Resa (Spearman's rank correlation, $r = -0.79$, $P = 0.002$); Laxey (Spearman's rank correlation, $r = -0.81$, $P = 0.001$).

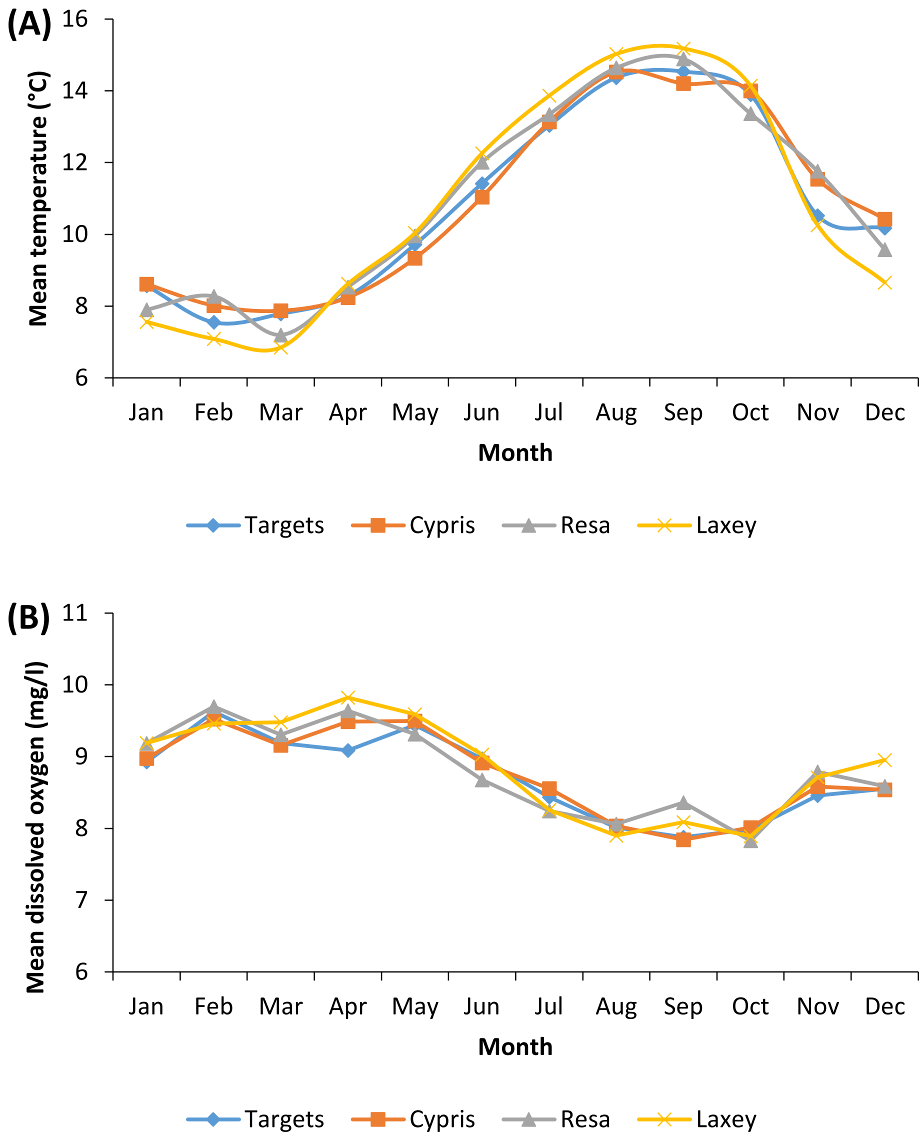

Figure 2.2. Temporal variations of mean seawater (bottom) temperature (°C) (A), mean dissolved oxygen (mg/l) (B) at four sampling stations (Resa, Laxey, Targets and Cypris) for the period between 2007 and 2013 (modified from the Isle of Man Government Data – DEFA, 2014).

Catch composition, size and sex distribution

Throughout the experimental surveys, a total of 5,795 commercial pots were hauled and only 16 ovigerous females were found in the pots. Despite the use of escape gaps the traps still retained, 13 % of females, 20 % of males that were under the MLS (130 mm). The highest percentage of undersized (sub-legal) crabs in catches was 27 % in spring 2012, whilst the lowest percentage was 6 % in autumn 2012 (Figure 2.3a). The highest catches of soft and pale shelled crabs were most prevalent in catches in autumn 2012 (8%) and were least common in spring

2012 (3%) (Figure 2.3a). The highest landings of soft crabs exhibited seasonal differences depending on sex and perhaps suggested that males to moult earlier than females (Figure 2.3 b, c).

Based on the fishery independent surveys, the mean carapace width of sampled crabs was 151 ± 25 mm (n = 3680). Mean female CW was significantly higher than that for males (Females 155 ± 24 mm (n = 2228), males 145 ± 25 mm (n = 1452) (t =11.80, P < 0.001) (Figure 2.4 a, b, c). CW of females, males and combined crabs significantly increased with depth (Linear regression, females: r= 0.26, P < 0.001, males: r = 0.13, P < 0.001). During the sampling period, male and female crabs from the west coast were larger than those from the fished areas of the east coast of the island (Appendix 2.2). During the 6 seasonal experimental pot surveys, the highest mean CW of females was found in autumn 2012 (167 ± 19 mm) and CW varied significantly by the sampling seasons (Table 2.1). The highest mean CW of males was recorded in winter 2012 (151 ± 30 mm) and there was a significant difference in sampling seasons (Table 2.1).

The sex ratio observed in the different areas appears to follow a pattern, with male crabs more prevalent that female crabs in both the spring of 2012 and 2013 (Figure 2.5). In the summer female crabs become more prevalent. The high proportion of female crabs to the west of the Isle of Man appears to be stable through the autumn and winter, however the data are limited in these seasons (Figure 2.5).

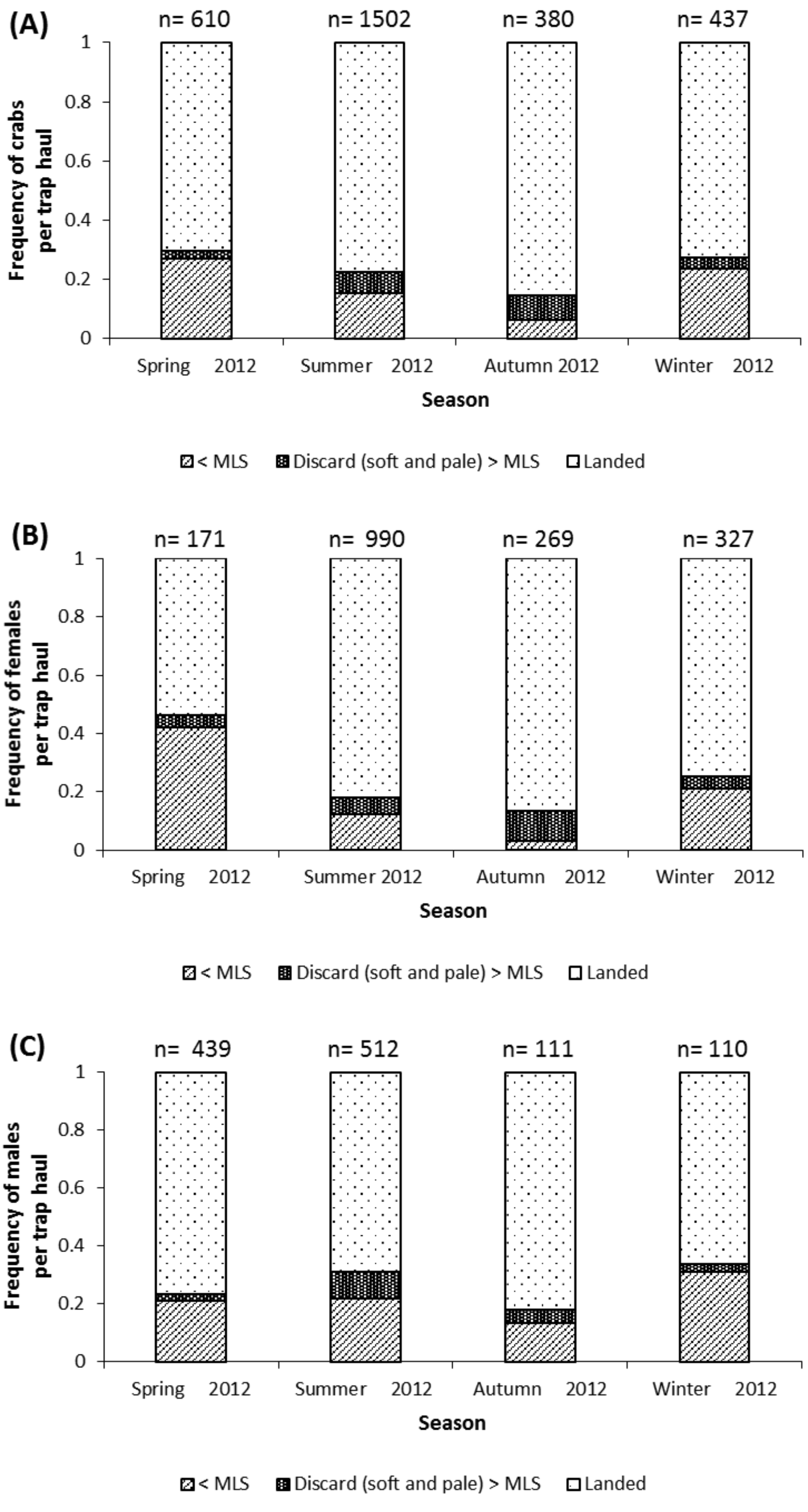

Figure 2.3. Proportional catch composition of A) combined sexes, B) females, and C) males in different seasons. The average number of crabs per trap haul is indicated above each histogram. The minimum landing size is 130 mm. Categories: undersized crabs (< MLS), discard (soft and pale crabs) ≥ MLS and landed crabs (≥ MLS). During the study only 16 ovigerous crabs were found, thus these egg-bearing crabs were not added the stacked columns.

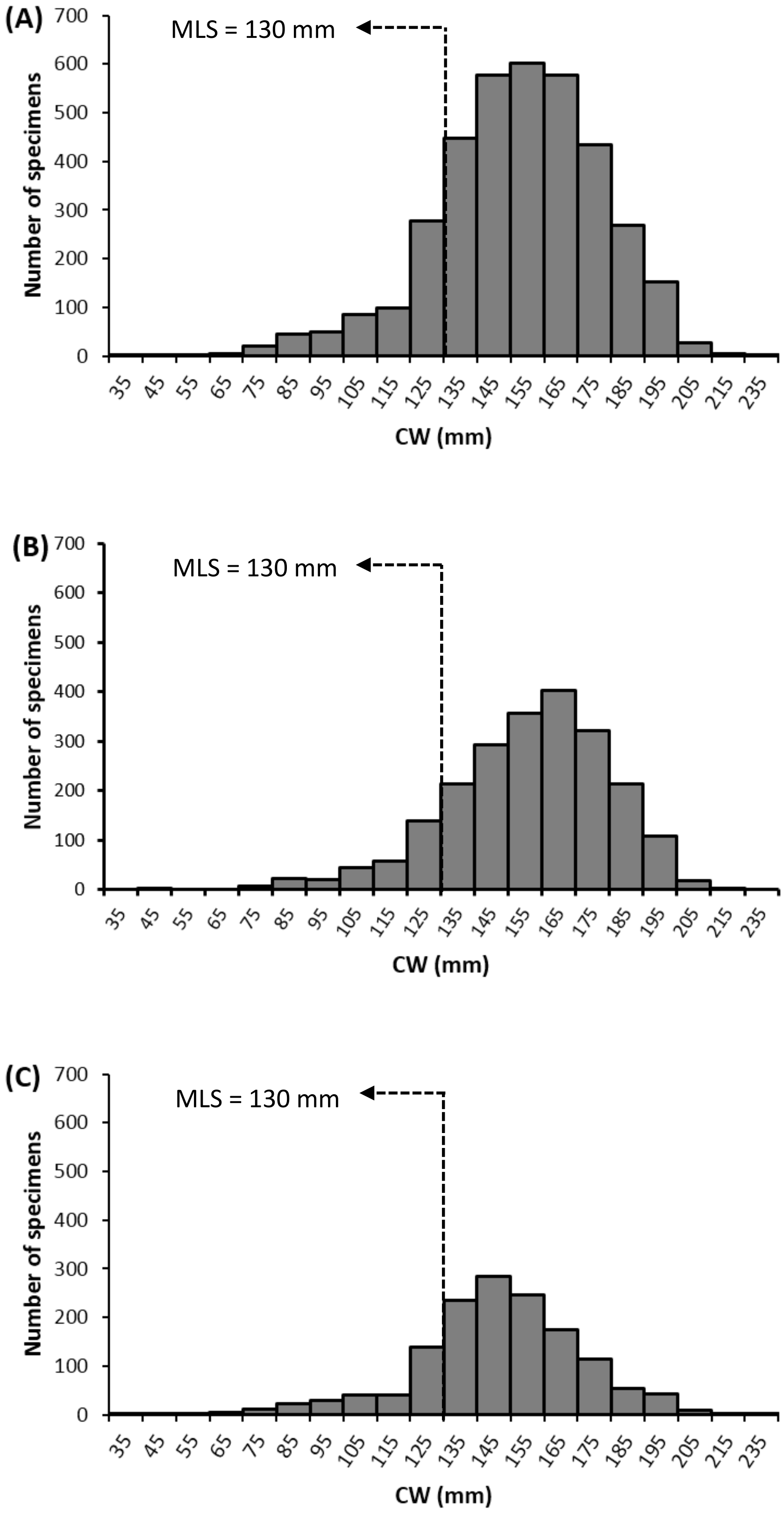

Figure 2.4. Size (CW) distribution of A) combined sexes, B) female, C) male taken in commercial catches during 2012 and 2013 (n = 3680, 2228 and 1452 respectively). The MLS of 130 mm is indicated with the broken line. Data came from 8 fishing boats.

Table 2.1. Summary of fitting a General linear model (GLM) using FID for the period between spring 2012 and summer 2013. Dependent variable: Carapace width (CW), fixed factors: season and area, covariate: sex (male and female).

Source	**Type III Sum of Squares**	**Mean Square**	**F-ratio**	***P*-value**
Corrected Model	495527	12705.833	26.927	< 0.001
Intercept	4278576	4278576.138	9067.397	< 0.001
Season	14429	2885.848	6.116	< 0.001
Area	48450	3726.974	7.898	< 0.001
Sex	4898	4898.630	10.381	0.001
Season * Area	62984	3149.212	6.674	< 0.001
Error	1717584	471.864		
Total	86193891			
Corrected Total	2213111			

R Squared = 0.22

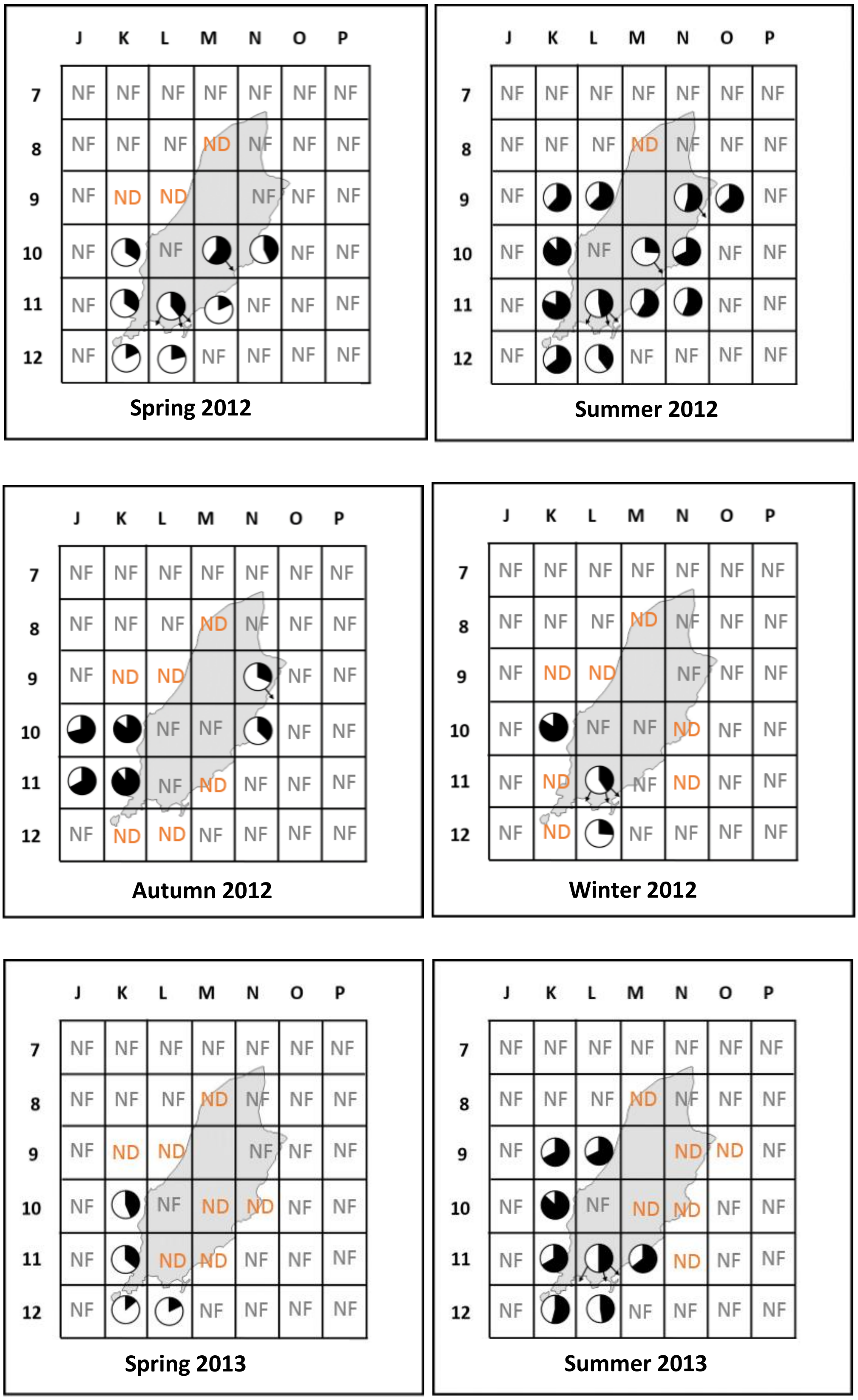

Figure 2.5. Seasonal sex ratios of *C. pagurus* for different statistical areas around the Isle of Man (for the period between spring 2012 and summer 2013). Black = females, white = males. The abbreviations are: No fishing (NF), crab fishing occurs there but no data (ND).

The relationships among CPUE and environmental and fishery-specific factors

Scientific CPUE

During the period of the experimental surveys (spring 2012-summer 2013), there were significant seasonal differences in the ln - catch per unit effort (lnCPUE) of brown crabs (included both sub-legal and legal sized crabs) (Table 2.2). The highest mean CPUE value of crabs was recorded in autumn 2012, which coincides with the warmest bottom temperatures (Figure 2.2. and Figure 2.6a). CPUE of brown crab exhibited the highest values around the west coasts (Figure 2.6b) and fishing area significantly affected the lnCPUE (Table 2.2). lnCPUE of brown crab significantly increased with increasing depth until about 30m (Table 2.2 and Figure 2.6c). The soak time did not significantly affected the lnCPUE (Table 2.2 and Figure 2.6d).

Table 2.2. Summary of fitting a General linear model (GLM) using FID for the period between spring 2012 and summer 2013. Dependent variable: LnCPUE, fixed factors: season and area, covariates: soak time, and depth.

Source	Type III Sum of Squares	Mean Square	F-ratio	*P*-value
Corrected Model	208	5.632	8.035	< 0.001
Intercept	21	21.454	30.610	< 0.001
Season	26	5.227	7.458	< 0.001
Area	64	5.869	8.374	< 0.001
Soak time	1	1.852	2.643	0.106
Depth	17	17.225	24.576	< 0.001
Season * Area	23	1.212	1.729	0.036
Error	114	0.701		
Total	326			
Corrected Total	323			

R Squared = 0.64

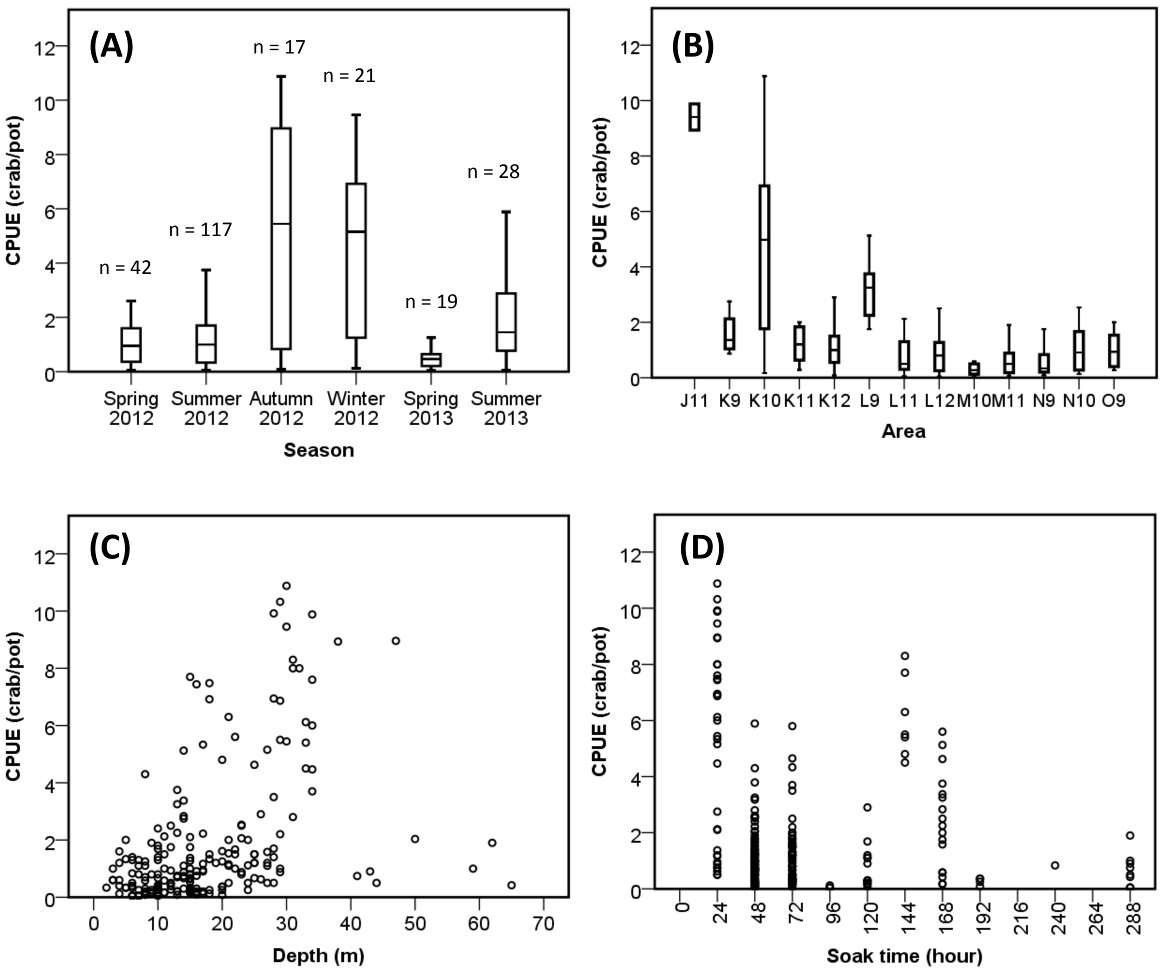

Figure 2.6. Scientific CPUE of brown crab depends on (A) season (from spring 2012-summer 2013) (B) fishing area; (C) depth (m) range from 2-65m; (D); soak time range from 24-288 hour.

The lnCPUE of brown crab significantly increased with increasing pot volume (Linear regression: r = 66.58, $P < 0.001$) (Figure 2.7a). The mean CPUE of crabs, in the pots that were baited with gurnard, was the highest with 3.72 ± 3.63 crab/pot, then the pots were baited with herring and cat shark had a lower mean CPUE with 3.67 ± 2.82 and 2.78 ± 0.57 crab/pot respectively (Figure 2.7b). The mean CPUE varied depending on boats (Figure 2.7c). In addition, Table 2.3 shows that the sex ratio is other factor which influences the CPUE significantly.

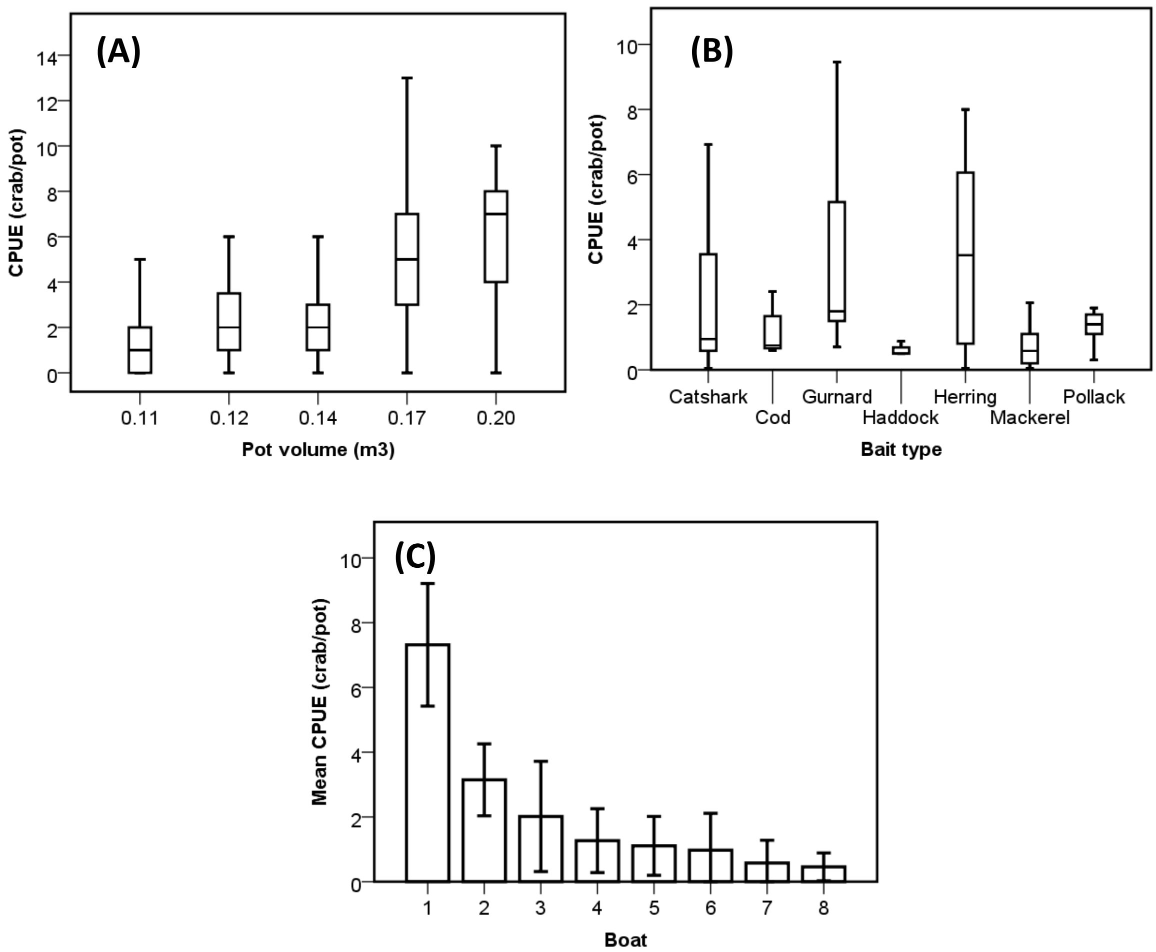

Figure 2.7. Scientific CPUE of brown crab depends on (A) pot volume range from 0.11-0.20 m^3; (B) bait type; (C) boat.

Table 2.3. Summary of fitting a General linear model (GLM) using FID for the period between spring 2012 and summer 2013. Dependent variable: LnCPUE, fixed factors: season and area, covariates: soak time, depth and sex ratio (f/m).

Source	Type III Sum of Squares	Mean Square	F-ratio	*P*-value
Corrected Model	137.252[a]	3.710	5.372	< 0.001
Intercept	12.814	12.814	18.555	< 0.001
Season	17.410	3.482	5.042	< 0.001
Area	51.711	4.309	6.240	< 0.001
Soak time	0.005	0.005	0.008	0.931
Depth	12.705	12.705	18.398	< 0.001
Sex ratio	7.180	7.180	10.398	0.002
Season * Area	9.575	0.563	0.816	0.673
Error	92.535	0.691		

Total	241.326
Corrected Total	229.786

R Squared = 0.60

Commercial CPUE

The commercial CPUE significantly changed during the seasons for the period 2007-2012 (ANOVA: $F_{3,\ 2755} = 184.19$, $P < 0.001$; Figure 2.8a). Similarly, the commercial CPUE changed depending on fishing areas in 2007 (ANOVA: $F_{2,\ 1403} = 102.74$, $P < 0.001$; Figure. 2.8b). Based on the logbook data, the monthly mean CPUE increased with increasing monthly mean bottom water temperature (Linear regression: r = 0.198, P = 0.002; Figure 2.9). Based on fishery dependent data, annual CPUE (kg/pot/trip) for the period of 2007-2012 is presented in Figure 2.10. The CPUE of brown crab showed the smallest value with 0.92 ±1.12 kg/pot/trip in 2008 and peaked at a record of 2.03 ±1.76 kg/pot/trip in 2011. Furthermore, six years average CPUE value was determined as 1.22±0.48 kg/pot/trip.

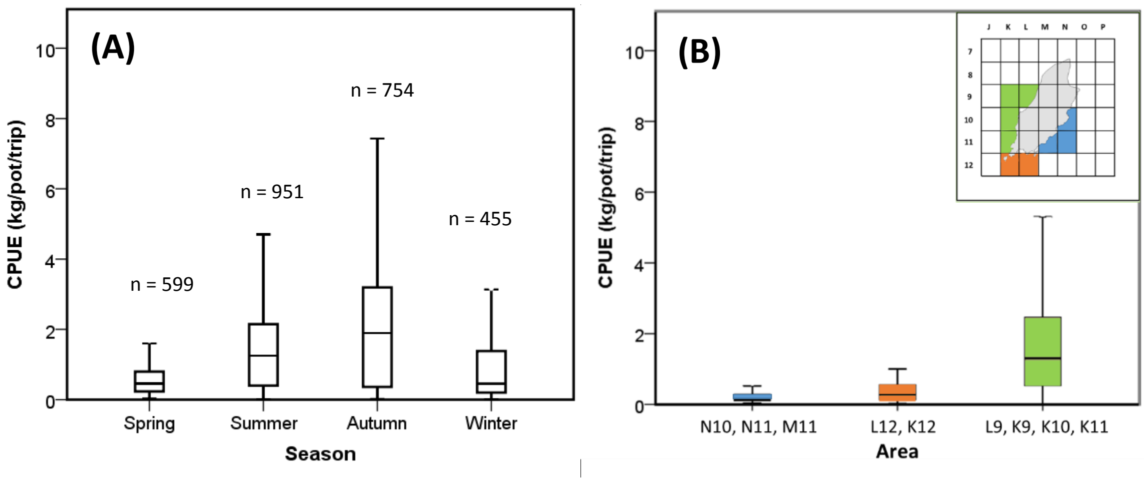

Figure 2.8. CPUE of brown crab depends on (A) season from the pooled 6 years (2007-2012) fishery dependent (logbook) data; (B) fishing area (from the year 2007 fishery dependent (logbook) data.

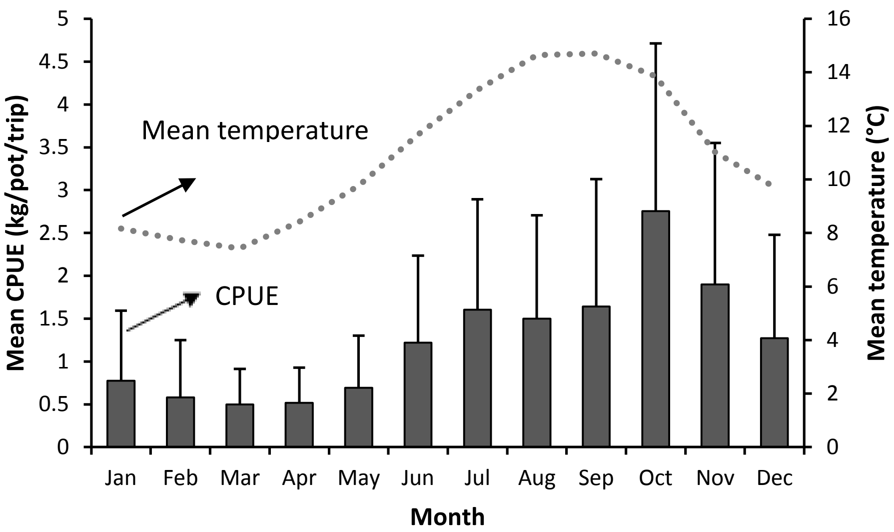

Figure 2.9. Monthly variations in mean CPUE (kg/pot/trip) (±SD) of brown crab (FDD) for the period 2007-2012 (column chart) and mean bottom water temperature (°C) for the period 2007-2013 (dashed line chart) pooled across all environmental data stations. The correlation between these two variables was significant (Spearman's rank correlation, r = 0.81, $P = 0.001$).

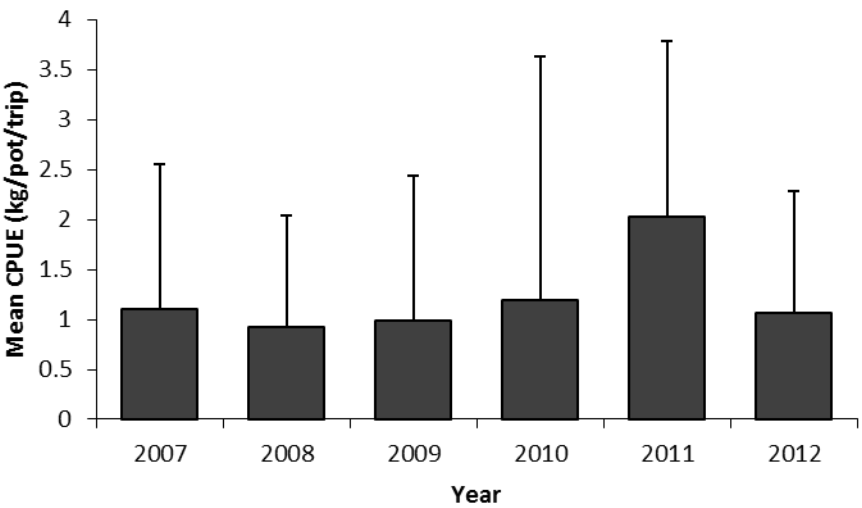

Figure 2.10. Mean CPUE (kg/pot/trip) (±SD) of brown crab in the Isle of Man. The active commercial boat numbers were counted as 17, 15, 18, 23, 25 and 27 respectively for the period 2007-2012 (source: Isle of Man Government fishermen logbooks).

Comparison of scientific and commercial CPUE

There was a positive correlation between the commercial CPUE (logbook records) and scientific CPUE (legal sized hard crabs from fishery independent surveys) (Spearman's rank correlation: r = 0.90, $P < 0.001$; Figure 2.11).

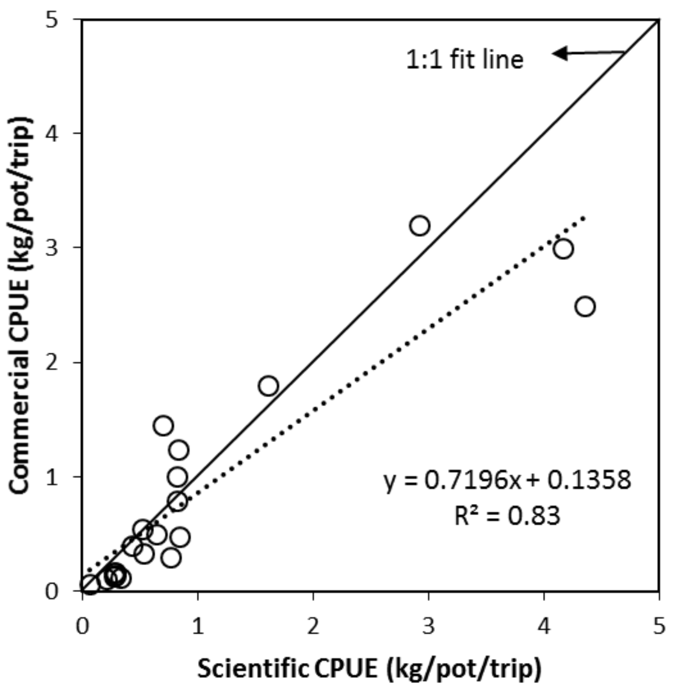

Figure 2.11. Comparison of CPUE (crab/pot) from commercial fisheries logbooks (FDD) and scientific surveys (FID) for the year 2012 (n = 21 points which came from 8 fishing boats).

Local ecological knowledge (LEK)

Results of questionnaire study showed that the highest numbers of soft crabs were caught in traps in the summer and autumn. Fishermen reported that the highest number of undersized crabs were caught in pots in spring. These patterns could not be differentiated between males and females. According to questionnaire study, soak time varied between 24 and 120 hours. The most common mean soak time is 48 hours. Six out of 10 fishermen reported that they use 3 different sizes of pots of which 0.11 and 0.14 m^3 pots were the most common. The most commonly used baits are dogfish (catshark) and herring. These responses agree closely with the patterns seen in the scientific pot surveys (Figure 2.7).

Fishing effort

According to fishermen's logbook data, the 6 year averaged hauled pot number peaked in summer months, whilst the numbers were considerably lower in winter and early spring (for the period between 2007 and 2012) (Figure 2.12). According to fishery independent surveys, spatial variations of mean hauled pot number was highest further offshore and lowest inshore (Figure 2.13). The mean hauled pot per trip increased with increasing boat space (length x breadth) (m^2) (Spearman rank correlation; r = 0.76, P < 0.001; Figure 2.14) which indicated that larger vessels fish with a greater number of pots in deeper water further offshore.

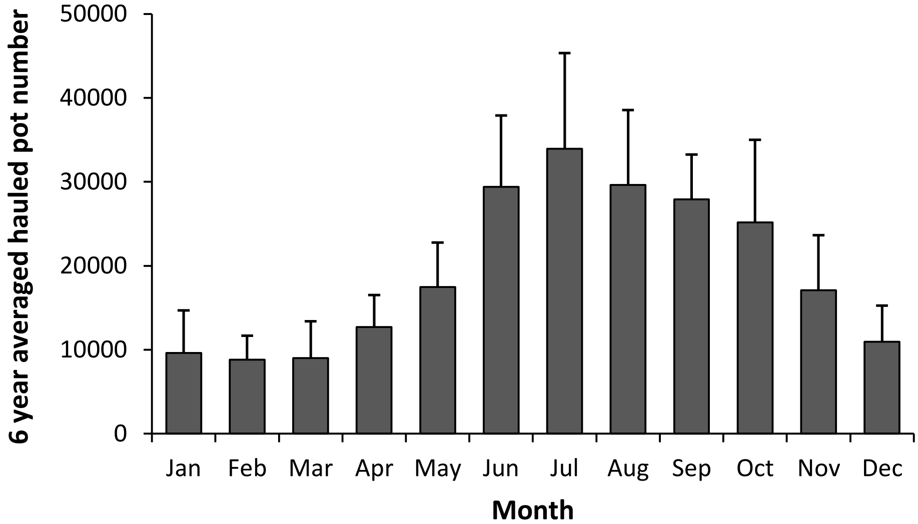

Figure 2.12. Mean (±SD) monthly variations of 6 years averaged hauled pot (fishing effort) in the Isle of Man for the period 2007- 2012 (n varied between 15 and 27 fishing boat) (fishery dependent data).

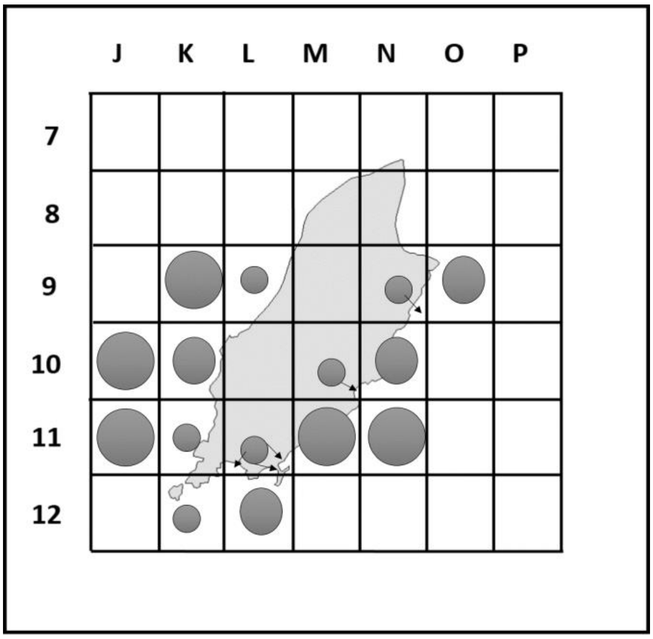

Figure 2.13. Spatial variations of mean hauled pot per string in the Isle of Man in 2012 and 2013 (n = 8 fishing boat) (fishery in-dependent data). ; 20 or over 20 pots, ;15-20 pots, ; less than 15 pots.

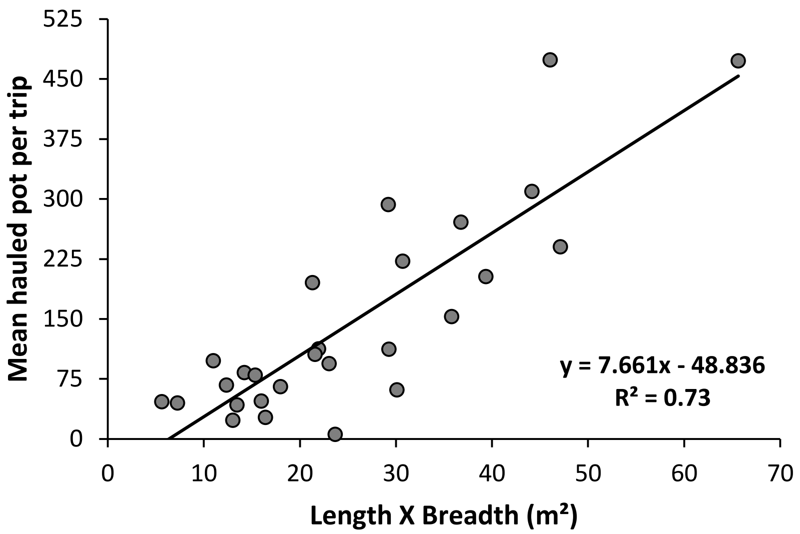

Figure 2.14. The relationship between mean hauled pot per trip of boats and length X breadth (m^2) (n = 27 fishing boat) (Fishers logbooks, 2012).

2.5. Discussion

Catch composition, CW distribution and sex ratio

The present study provides important information about the seasonal and spatial patterns in catch composition in the waters around the Isle of Man. In general, the present study shows that the proportion of female and male crabs discarded in this fishery is relatively low and that this varies seasonally, with most discards occurring in spring and the fewest discards occurring in autumn. This may be related to on onshore migration by larger individuals in summer/ autumn or could reflect the moult increment that occurs over the spring/summer season. The moulting frequency of *C. pagurus* is highly variable in the Northern Europe (Table 2.4, Edwards, 1979; Bennett, 1974; Mill et al., 2009). The present study showed that the proportion of soft-shelled crabs in the catches was highest in summer and autumn for males and females respectively. The moulting period of crabs in the Isle of Man would appear to be similar to the moulting periods of crabs in Scotland, the east coast of England, Norway and Sweden (Table 2.4) which indicates that the temporal differences in moulting may be due to environmental factors (Bennett, 1979; Cosgrove, 1998).

Table 2.4. The main moulting periods of brown crab populations in Northern Europe.

Location	Main moulting period	Study
Scotland	July to September	Williamson, 1904
East coast of England	July to October	Edwards, 1979
English Channel	Spring and Summer	Brown and Bennett,1980
Norway	August to October and December	Karlsson and Christiansen, 1996
Sweden	July to October	Ungfors, 2008
Isle of Man	June to October	This study

The mean size of male and female crabs differed around the Isle of Man such that larger individuals were more prevalent on the West coast where water is much deeper on average compared to the east coast of the island. Similarly, Brown and Bennett (1980) reported that larger crabs were found in deeper water at the western end of the English Channel.

The sex ratio of crabs entering pots differs both spatially and seasonally (Brown and Bennett, 1980; Bennett, 1995). For example, Brown and Bennett (1980) noted that the sex ratio was about 1:1 in the first six months of the year, and then female crabs started to become dominant in the Western Channel. However, they also reported that male crabs were always dominant in the Eastern Channel throughout the year. The sex ratio of brown crab populations may vary among fishing grounds depending on, sampling season, habitat structure, mating behaviour, food and competition for space between sexes (Brown and Bennett, 1980; Bennett, 1995; Mill et al., 2009). In particular, mature female crabs tend to live in muddy and sandy habitats (Howards, 1982; Woll, 2003) and berried females half-bury in soft sediment to avoid strong currents (Hall, 1993), whilst male crabs prefer to live in rocky habitats (Woll, 2003). Additionally, reproductive migration is an important factor which affects the sex ratio of crab landings; in particular female crabs generally migrate from inshore to offshore (Brown and Bennett, 1980; Ungfors, 2008). Hunter et al. (2013) investigated the migration and incubation cycle of mature female *C. pagurus* individuals using an electronic tags. They reported the Westward migration related to their reproductive behaviours during the autumn. Together, these studies suggest directional migration of female brown crab from inshore to offshore and from east to west in the English Channel presumably for the purpose of reproduction or to incubate and release larvae. In the present study, catches of female crabs in the southern and southwestern waters off the Isle of Man occurred mainly in the summer and autumn (Figure 2. 5) and were considered to relate to migratory behaviour. Presumably, following mating in summer, females migrated to the west and south towards sandy substrata where they prepare to extrude their eggs and bury themselves in the sediment to incubate them. A further line of evidence to support this observation is from the seasonal patterns in bycatch of berried females in scallop dredges which were most commonly caught to the south and west of the Isle of Man in autumn. While female crabs were dominant in catches of the pot fishery in the autumn, by the end of winter and early spring male crabs were dominant in many fishing grounds around the Isle of Man.

CPUE

Catchability of crustaceans in trap gear is not well understood (Green et al., 2014) due to a variety of environmental and biological factors that affect catch rate (e.g. current flow, water temperature) and do not provide direct estimates of abundance. Estimates of actual abundance necessitate the use of mark-recaptures techniques. For example, Bell et al. (2003) and Ungfors (2008) used a mark-recapture experiment and estimated a density of 0.0021 crab m^{-2} and 0.0038 crab m^{-2} for edible crab on the east coast of UK and the west coast of Sweden respectively. Nevertheless, even this technique assumes that all animals in the population are likely to be active and attracted to bait which may be a flawed assumption.

Despite these issues, catches in traps do provide a means of establishing a relative index of abundance. For this reason, it is important to understand seasonal patterns in CPUE and whether this differs among areas and among male and female crabs. In the UK, the main period for the brown crab fishery is between April and November, with the highest catches recorded in October and November (Edwards, 1979; Hart, 1998; Mill et al., 2009). Similarly, seasonal gaps in crab landings were observed in Norway (Woll et al., 2006), Ireland (Fahy et al. 2002; Tully et al., 2006), and France (ICES, 2007). The present study shows that the highest catch of brown crab was in autumn in the Isle of Man (Figures 2.6a, 2.8a). In addition, fishery independent data were limited in winter because of bad weather which also affects commercial landings at this time of year. Increases in water temperature generally result in an increased catchability of crustaceans because of the increase in metabolic demand (and hence hunger) and the increased rate of diffusion of bait molecules with temperature (Green et al., 2014). For instance, cold weather has negatively affected the brown crab catches in Norway (Woll et al., 2006). In the present study the CPUE of brown crab increased with increasing mean bottom temperature values.

Brown crabs live in both inshore and offshore waters to depths of 100 meters or more (Keltz and Bailey, 2010). Furthermore, Whiteley (2009) reported the change in crab abundance over time in the Isle of Man using a questionnaire study. Fishermen who have fished for long years in the Isle of Man informed that there was a decline in the crab abundance over the last 30-40 years around inshore areas. Thus, fishing grounds tend to change with distance offshore. Similar situation was reported for the brown crab around Western Channel, Yorkshire and East Anglia (Bannister, 2009). The present study reports CPUE of brown crab increases with depth in the Isle of Man.

Despite a wide range of soak times (24-288 h) encompassed in the present study, there was no discernible effect of soak time on CPUE. Similarly, previous studies have suggested that pot catch does not increase linearly with the soak time (Caddy, 1979; Robertson, 1989; ICES, 2005; Woll et al., 2006), yet increases towards an asymptote (Bennett and Brown, 1979; Briand et al., 2001; Bell et al., 2003). Interestingly, Cosgrove (1998) and Ungfors (2008) found a positive correlation between soak time and landed brown crab number. Bennett (1974) pointed out that the impact of soak time on CPUE of male and female brown crabs were different in different sampling seasons. When male crabs were most abundant, in particular during January to May and November and December, the CPUE of males increased with soak time. However, for female crabs the CPUE generally decreased with an increase in soak time. Another important issue is trap saturation (Beverton and Holt, 1957; Miller, 1978). Caddy (1979), Miller (1979). Robertson (1989) reported that trap saturation relates to reduced entry of crabs into a trap and/or escapement from the trap. Moreover, crabs are commonly known as nocturnal animals, which mainly feed at night (Karlsson and Christiansen, 1996; Skajaa et al., 1998). Thus, catch rates can be higher at night than during the day (Brown, 1982). In conclusion, the effects of localised and seasonal differences in crab abundance around the Isle of Man may have masked any potential effect of soak time in the current dataset.

In brown crab fisheries, pot type and size are not standardised as part of fisheries legislation. For this reason there is considerable freedom for fishermen to utilise a range of different pot designs. Shelton and Hall (1981) compared the efficiency of the Scottish creel and inkwell pot in the capture of brown crab. They could not find any significant difference between the numbers caught by these two fishing gears. According to Lovewell et al. (1988), double-chambered parlour pots caught more crabs than single-chambered Yorkshire creels. To date, the effect of trap size on brown crab catches has not been evaluated clearly in the literature. In the current study, a statistically significant correlation was found between the pot volume and amount of catch per pot such that larger pots catch more crabs than small pots. Fisheries management should account for both pot number and pot size or pot volume when considering effort controls.

Bait type may affect catches of some crustacean species which have well-developed chemoreceptory senses (Krouse, 1989; Montgomery, 2005). It is clear that from the results of present study that bait type affected the catch rates of brown crab; the mean CPUE of crabs in pots baited with gurnard was the highest, followed by herring and catshark. According to local ecological knowledge, the baits commonly used in the Isle of Man are catshark and herring.

There has been some interest in the idea of marketing as bait the bycatch that must be retained and landed under the forthcoming EU Landings Obligation (Boyle and Thompson, 2012). Both gurnards and small-spotted catsharks occur as bycatch in the Isle of Man queen scallop net fishery and thus may provide a ready supply of bait in the future.

Fishing effort

The comparison of commercial and scientific data to estimate CPUE is rare in the literature (Fox and Starr, 1996; Potier et al., 1997; Starr and Vignaux, 1997; Petitgas et al., 2003). In the present study, a strong correlation was found between the scientific CPUE and commercial CPUE. This indicated that fishermen logbooks can be considered as a reliable source to estimate CPUE. Nevertheless, the aforementioned comparison includes 8 fishing boats. The total boat number varied between 15 and 27 fishing boat for the period between 2007 and 2012. Therefore, this relationship may change depending on boat number.

Although a major problem in shellfish science is lack of the effort data, it is assumed that potting effort has increased in many fisheries due to the modernisation of inshore fleet and extension of the fisheries to offshore grounds (Bannister, 2009). The present study reports the seasonal variations in hauled pot number in the Isle of Man. The 6 years-averaged hauled pot number peaked in summer months, whilst the numbers were considerably lower in winter and early spring (for the period between 2007 and 2012). Similarly, there were considerable spatial variations in the mean hauled pot number. The mean hauled pot number highest in some areas off the west coast (K9, J 10 and J11) and, south-east coast (M11 and N11). Additionally, Whiteley (2009) reported (Calf of Man: K12) that fishing effort is fairly high in the summer in comparison with the winter around the Southern tip of the Isle of Man.

Fisheries management

The current regulations in the Isle of Man achieve a number of conservation objectives in relation to crab fisheries. In particular, regulations ban the retention of berried crabs and prevent deliberate de-clawing (Table 2.5).

Table 2.5. Management measures and current regulations that relate to edible crab fisheries in the Isle of Man.

Management tool	Current situation
Minimum landing size	Yes, 130 mm
Maximum landing size	No
Ban on landing of berried animals	Yes
Ban on claw and crab part landing	Yes
Ban on landing of soft animals	No, but fishermen don't fish them due to low meat quality.
Ban on landing for bait	No, some fishermen use crabs as a bait for whelk fisheries
Licenced pots	Yes
Escape gap in pots	Yes
Pot limit	No (except exclusion zone (Bay Ny Carrickey))
Quota	No
Temporary closure	No
Regional closure	No

Marine reserve	No
Vessel size restrictions	No

One feature of the Manx fleet that became apparent during the study was the relationship between catch capacity and vessel size. The commercial potting vessels varied from 4 to 12 m in length with most vessels <10 m. More importantly, the present study points out that the mean hauled pot per trip increased with increasing boat deck space (length x breadth). The introduction of a greater number of large vessels into the Isle of Man fishery would indicate increasing fishing capacity and may act as a warning of increasing fishing effort. This also indicates that fishing effort could be controlled through the use of measures that limit vessel size.

According to LEK, fishermen believed that the MLS, pot number limits and enforcement of MLS are the most effective regulatory tools for the conservation of the crab population (Whiteley, 2009). Whiteley (2009) reported that there appears to have been a change in crab abundance over time in the Isle of Man based on a questionnaire study. Fishermen who had fished for more than 10 years in the Isle of Man, reported a decline in crab perceived abundance over the last 30-40 years around inshore areas. Thus, fishing grounds tend to change to further offshore. However, more recent entrants into the fishery did not perceive this effect. According to Whiteley (2009), 40% of Manx pot fishermen believed that individual pot numbers should be decreased, and 15% of fishermen suggested that total number of pots fished in the Isle of Man should be decreased. However, limiting pot numbers has both advantages and disadvantages. For example, the pressure on the grounds can be reduced by reducing the numbers of pots but limitations of individual pot allocation would mean a greater number of vessels possible leading to greater conflict over access to ground (Whiteley, 2009). The present study also showed that CPUE was significantly increased with increasing pot volume and as such a maximum size restriction on pots should perhaps be considered.

2.6 Conclusions

The integration of fishery dependent data, fishery independent data and LEK together provides useful insights into stock abundance and hence the sustainable management of marine resources (Campbell, 2004; Lordan et al., 2011). In summary, the results presented in this study suggest that scientific potting yields comparable data to commercial CPUE which can be predicted adequately from scientific catches for the purpose of using a catch index. However, the study also demonstrates the seasonal and spatial complexity in catch which indicates that sampling regimes should account for this variability, particularly if migratory patterns in male and female crabs are to be taken into account. The use of a 'sentinel' commercial fleet with automated monitoring (e.g. through the use of on-board cameras) could achieve this objective (Hold et al., 2015). Although the crab population size-structure is skewed well to the right of the MLS result presented in Chapters 3 and 4 demonstrate that no crabs under 134 mm CW were found to be carrying eggs. Thus it may be the case that the current MLS does not adequately protect female crabs such that they are able to breed at least once.

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CHAPTER 3 - RELATIVE GROWTH AND SIZE AT ONSET OF SEXUAL MATURITY OF THE BROWN CRAB, *CANCER PAGURUS* LINNAEUS, 1758, IN THE ISLE OF MAN

3.1 Abstract

In this study, the relative growth, size-weight relationships and size at onset of maturity (SOM) of the brown crab *Cancer pagurus* were investigated in the Isle of Man. For the analyses of relative growth and SOM, the samples were collected between autumn 2012 and spring 2013 using several methods: pot surveys, dredge and trawl surveys, market surveys and shore surveys. Results showed that allometric growth occurred in the cheliped of male and in the abdomen of female. Three different measures of maturity were examined. With respect to the behavioural maturity, the smallest female crab found with sperm plug measured 110 mm CW, whereas in terms of functional maturity the smallest ovigerous female had a CW of 134mm. The latter was based on a relatively small sample size (n=108). Based on direct observations of gonad maturity, fifty percent of females were mature at 108 mm CW, whereas 50% of males were mature at 89 mm CW. These SOM measurements of female and male *C. pagurus* based on gonad development is smaller than the current minimum landing size (130 mm), and therefore this suggests that the current MLS is an adequate management measure.

Keywords: *Cancer pagurus*, relative growth, size-weight relationships, size at maturity, minimum landing size, Isle of Man.

3.2 Introduction

Crustacean growth is discontinuous and different body parts of males and females often exhibit different growth rates. This phenomenon is commonly known as “relative growth” or “allometric growth” (Hartnoll, 1978; Frigotto et al., 2013). In particular, the changes in size of secondary sexual characters (e.g. abdomen, chelipeds) with growth have been used to estimate the size at maturity of aquatic animals (Hartnoll, 1974; Farias et al., 2014; Williner et al., 2014).These changes in growth rate of secondary sexual characteristics often occur after what is termed the ‘puberty’ moult.

Age and size at the onset of sexual maturity are commonly used by fisheries managers as biological proxies to establish the appropriate minimum landing size of exploited marine species. For the Crustacea, body size is generally used to access maturity data because the determination of age is expensive and time consuming and not particularly accurate (Sheehy and Prior, 2008; Murray et al., 2009). Consistent and accurate estimates of size at the onset of maturity (SOM) are needed to determine the appropriate minimum landing size (MLS) to avoid growth-overfishing and recruitment-overfishing (Ungfors, 2007; Pardo et al., 2009). However, some authors have reported that SOM of decapod crustaceans vary both spatially and temporally, depending upon environmental factors (water temperature, depth, habitat) and population density (Tuck et al., 2000; Landers et al., 2001; Lizarraga-Cobedo et al., 2003; Melville-Smith and de Lestang, 2006; Zheng, 2008). Thus for widely distributed species it is important to have regional measures of SOM that reflect the responses of the animals to local environmental conditions.

For crustacean fisheries, the carapace width (or length) at which 50% of the sampled animals are mature is often reported as size at maturity (CW_{50}). In order to determine the SOM in decapod crustaceans, four types of criteria can be applied (Waddy and Aiken, 2005; Pardo et al., 2009): (1) physiological sexual maturity; (2) behavioural sexual maturity; (3) morphometrical sexual maturity and (4) functional sexual maturity. Physiological maturity is generally difficult to determine as it is estimated based on microscopic investigation of the gonads or histological observations of ovaries, testes and the *vas deferens* (Claverie and Smith, 2009 and Pardo et al., 2009). Behavioural maturity can be inferred from the presence of sperm plugs and direct observations of mating behaviour (Tallack, 2007; Ungfors, 2007, Pardo et al., 2009). Morphometric maturity in many decapod species is indicated by positive allometry in characteristics such as chelal length, height and/or width for males and in abdomen width for females (Hartnoll, 1974; Zheng, 2008). These defined positive allometries in relative growth indicate the passage from the juvenile stage to adulthood and prepares the males for intrasexual competition for mates and carrying eggs in females (Hartnoll, 1974; Claverie and Smith, 2009). However, morphometric maturity does not always indicate functional maturity (Oh and Hartnoll, 1999; Marochi et al., 2013). The presence of eggs externally is evidence of functional maturity in females, however the determination of functional maturity in males is more difficult (McQuaid et al., 2006; Claverie and Smith, 2009) and has not been sufficiently or accurately identified to date for many species.

Cancer pagurus Linnaeus 1758, is commonly known as the brown crab or European edible crab, and is found along the NE Atlantic Coast from Norway to the North Coast of Africa (Parker, 2009), Mediterranean, Black Sea (Anosov, 2000) and Sea of Marmara (Balkis, 2003). The brown crab is one of the most important commercial fishery species in terms of economic value (nearly £ 31 m in 2011) in the United Kingdom (MMO, 2014). The MLS used in brown crab fisheries varies considerably across northern Europe, ranging from 110mm to 160mm carapace width (CW) (ICES, 2014). Around the Irish Sea, the minimum landing size (MLS) of both female and male crabs varies between 130mm and 140mm CW depending on local management regimes (ICES, 2014). The present study focused on the Isle of Man (Irish Sea) brown crab fishery which is primarily a small-scale fishery worth approximately £0.5M per annum and supports between 20 – 30 fishers. At present the MLS for brown crab is 130 mm CW, but there has been little research to understand whether this is the appropriate size at which to set this limit. The current MLS was identified by reference to other *C. pagurus* populations in the United Kingdom.

The first objective of the present study was to estimate the SOM of female and male *C. pagurus* in the Isle of Man by determining sexual dimorphism from allometric relationships and then using morphometric and reproductive characteristics as indicators to identify when crabs begin to become sexually mature. The second objective was to determine the timing of mating and spawning periods to understand better the biology of brown crab in the Isle of Man fishery. Understanding these relationships would help managers understand whether the current MLS is appropriate and to understand in which periods of the year the brown crab population is most vulnerable to potential negative interactions with other fisheries (e.g. the scallop dredge fishery).

3.3 Materials and methods

Data collection

To determine the relative growth and size at maturity of brown crabs, male and female specimens were collected from commercial baited pots in the Isle of Man from autumn 2012 to spring 2013. Crabs under and over the MLS were collected. Pots tend to under sample small body-sized animals due to the use of escape gaps in the Isle of Man fishery. In order to supplement the sample of immature specimens more were collected during shore surveys between autumn 2012 and spring 2013. In addition, ovigerous females rarely enter baited pots because these crabs fast or have reduced feeding activity during this egg-carrying period and the large egg mass on the abdomen also restricts their movement (Bennett and Brown, 1983). Therefore, in order to gather trap independent data, crabs were also collected from the otter trawl surveys conducted in autumn 2012 and scallop dredge surveys conducted between November 2012 and May 2013. Subsamples of the catch were brought to the laboratory for further analysis.

Size – wet weight relationships

To determine the relationship between the carapace width (CW) and body wet weight of female and male crabs, the data were collected during pot surveys on the boat.

Laboratory procedures

Morphometric measurements

Changes in body morphometry have been shown previously to indicate the onset of maturity in decapod crustaceans (Hartnoll, 1974; Farias et al., 2014; Williner et al., 2014), for this reason, cheliped propodus length and abdomen width were measured because these are strong indicators of the presence of allometric growth. In addition, the relationship between carapace width and carapace length was determined because this relationship provides an information on allometry. Measurements of the following body parts were recorded using vernier calipers (to the nearest 0.1 mm): carapace width (CW); carapace length (CL); right cheliped propodus length (RChL); and abdomen width (AW) (Figure 3.1). When the right cheliped missing, the left one was measured as brown crabs are not heterochelous (Tallack, 2007; Ungfors, 2008).

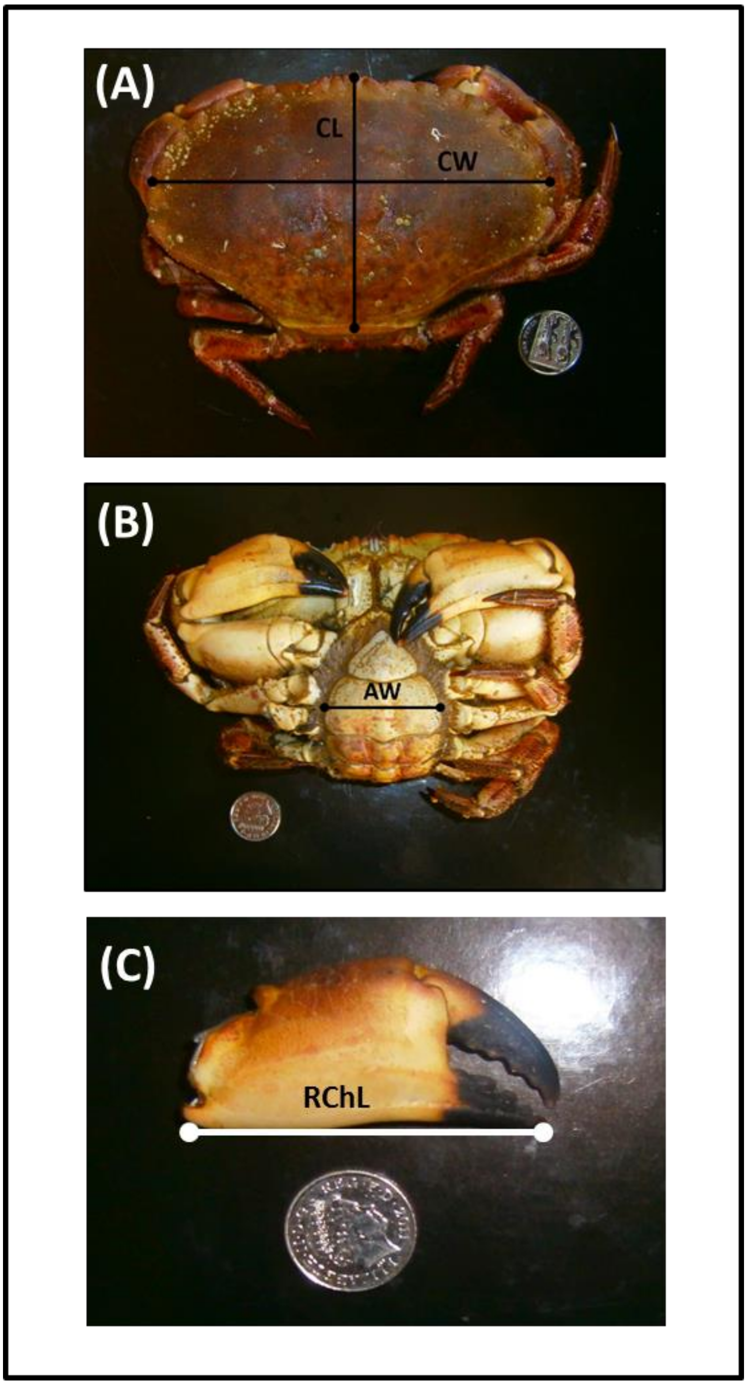

Figure 3.1. Morphometric measurements of A) Carapace width (CW), carapace length (CL); B) abdomen width (AW); C) chela length (ChL). The diameter of ten pence is 24.5 mm. Photos by Fikret Ondes.

Size at onset of maturity

In order to understand better the timing of mating and spawning seasons, the presence of sperm plugs were noted (Figure 3.2) and extrusion of eggs in the samples collected throughout the year (Tallack, 2007). Based on microscopic observations of dissected crabs, the ovarian and testes development stages were classified into 5 and 3 classes respectively (Table 3.1).

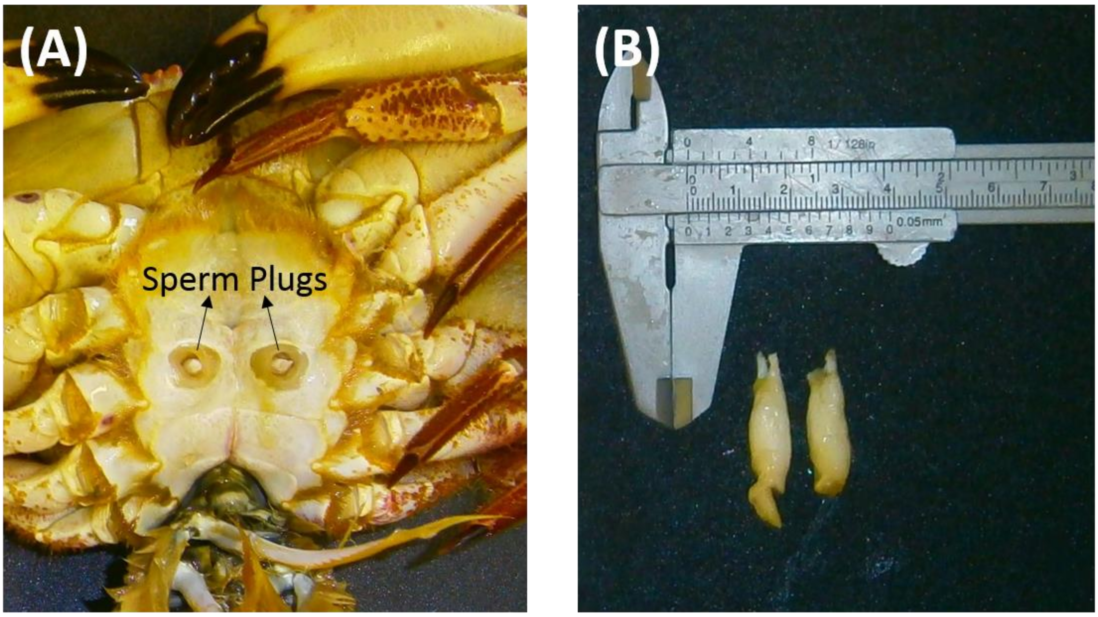

Figure 3.2. a) The position of the sperm plugs in a female *Cancer pagurus*, b) the sperm plugs removed from the body. Photos by Fikret Ondes.

Table 3.1. Female (1-5) and male (1-3) visually determined gonad development stages for *Cancer pagurus* modified from the literature (Edwards, 1979; Ungfors, 2008; Wójcik and Normant, 2014).

Female	1	2	3	4	5
Description	**Immature**	**Undeveloped**	**Developing**	**Mature**	**Resting / Recovery**
Stage	No egg cells present	Pre-vitellogenesis	Early secondary vitellogenesis	Late secondary vitellogenesis	Post reproductive
Visual	Thin translucent gonad. White and pale	Lobes present, greyish pink	Slight Pink appearance, covering <50% of cavity	Orange, red obvious ovaries. Covers >50% of cavity	Whitish ovary with loose appearance. Easily separable eggs, in pleopodal setae of abdomen
Male	1	2	3		
Description	**Immature**	**Developing**	**Mature**		
Stage	Spermatids	Spermatozoa	Spermatophore		
Visual	Testes small and transparent or undetectable	Testes obvious and white	Testes and *vas deferens* swollen and white		

Data analysis

The relationships between CW versus CL, CW versus AW and CW versus ChL were compared and the allometric growth defined by the equation $Y = aX^b$. CW was used as predictor variable and other body measurements were selected as the dependent variables (Hartnoll, 1978; 1982; Baeza et al., 2012). The allometric growth constant or relative growth rate is given by the constant b. The data were log-transformed to give the formula:

$\log y = \log a + b \cdot \log x$ (Hartnoll, 1982).

If b > 1, then positive allometry exists, with the variable growing faster than a standard measure of body size (in this case carapace width). If b < 1 then there is a negative allometry, and when b = 1 this indicates isometry (Hartnoll, 1982).

The standard power function $W = a \cdot L^b$ was used in order to determine carapace width (CW) weight relationships for female and male crabs. Where W is total body wet weight (g); L is carapace width (CW) (mm); the a (intercept) and b (slope) are constants (Ricker, 1975). The ANCOVA was used to compare size-weight relationships of female and male crabs.

In order to calculate the expected size at maturity values of the crabs, the maturity stage data was converted to binary data (immature = 0, mature = 1). Stage 1 was considered immature, whilst all other stages were considered mature. To determine the size at maturity size of the population (CW_{50}), the the logistic equation was used (Perera-García et al., 2011):

$$M = 1/(1 + e^{(S1-S2*CW)})$$

Where M is the accumulated relative frequency of mature individuals, and S1 and S2 are the constants. The SPSS (version 22) was used for statistical analyses and the software of Sigmaplot (version 12.3) was used to draw sigmoid graphs related to the size at maturity.

3.4 Results

Relative growth and size at onset of sexual maturity

The CL - CW relationship revealed that negative allometric growth occurred for both males and females (Table 3.2; Figure 3.3a). There was a significant relationship between chela length and

CW in both sexes (Table 3.2). Males exhibited stronger allometry with respect to the growth pattern of chela in comparison with females (Table 3.2). Male chelipeds size began to increment more rapidly after a carapace width of 107 mm was achieved (Figure 3.3b). Female abdomen width became significantly larger at a carapace width of 155 mm (Figure 3.3c).

Female crabs observed with sperm plugs; ranged in size from 110 to 200 mm CW. Sperm plugs were found in the autumn (September, October, and November). Based on these observations, the main mating season was estimated to be the autumn. The observed ovigerous females varied in size from 134 to 215 mm CW. Based on dredge surveys ovigerous crabs were found from November to June, and were found in autumn and late winter-early spring in pot surveys (see Chapter 4 and 5). However, the peak occurrence of egg bearing females occurred in November in dredge surveys (Chapter 5).

Table 3.2. The summary of the log-transformed regression analyses of the relationships between morphometric parameters (carapace length (CL), right cheliped propodus length (RChL) and abdomen width (AW)) and carapace width (CW) in *Cancer pagurus* using the equation for allometry.

Variable	Sex	Equation $\log y = \log a + b \cdot \log x$	R^2	*P*-value	Allometry
CL	Female	logCL = -0.163 + 0.977 logCW	0.99	< 0.001	- ve
	Male	logCL = -0.065 + 0.927 logCW	0.99	< 0.001	- ve
RChL	Female	logRChL = -0.410 + 1.023 logCW	0.95	< 0.001	+ ve
	Male	logRChL = -0.841 + 1.279 logCW	0.99	< 0.001	+ ve
AW	Female	logAW = -1.712 + 1.531 logCW	0.97	< 0.001	+ ve

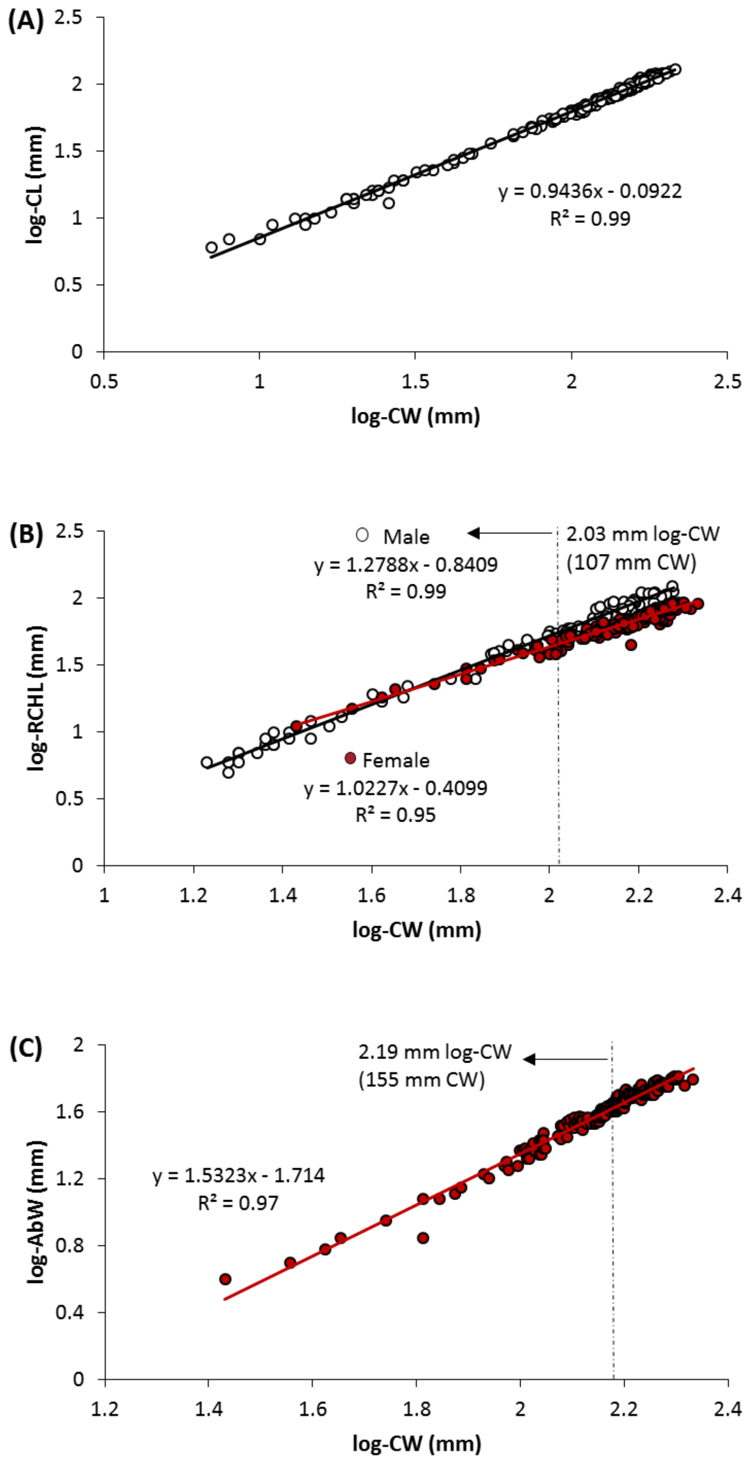

Figure 3.3. A) Morphometric relationship between the carapace width (log-CW) and carapace length (log-CL); B) sexual dimorphsim for females and males in the relationship between right cheliped length (log-RCHL) and carapace width (log-CW); C) morphometric relationship between the carapace width (log-CW) and abdomen width (log-AbW) of female specimens of *Cancer pagurus*. The dash dots show inflection points (the values of inflection points based on non-transformed data were showed in the parenthesis).

Based on direct observations of gonad development, the CW_{50} of females was estimated as 108 mm CW, while CW_{50} was determined as 89 mm CW for males (Figure 3.4).

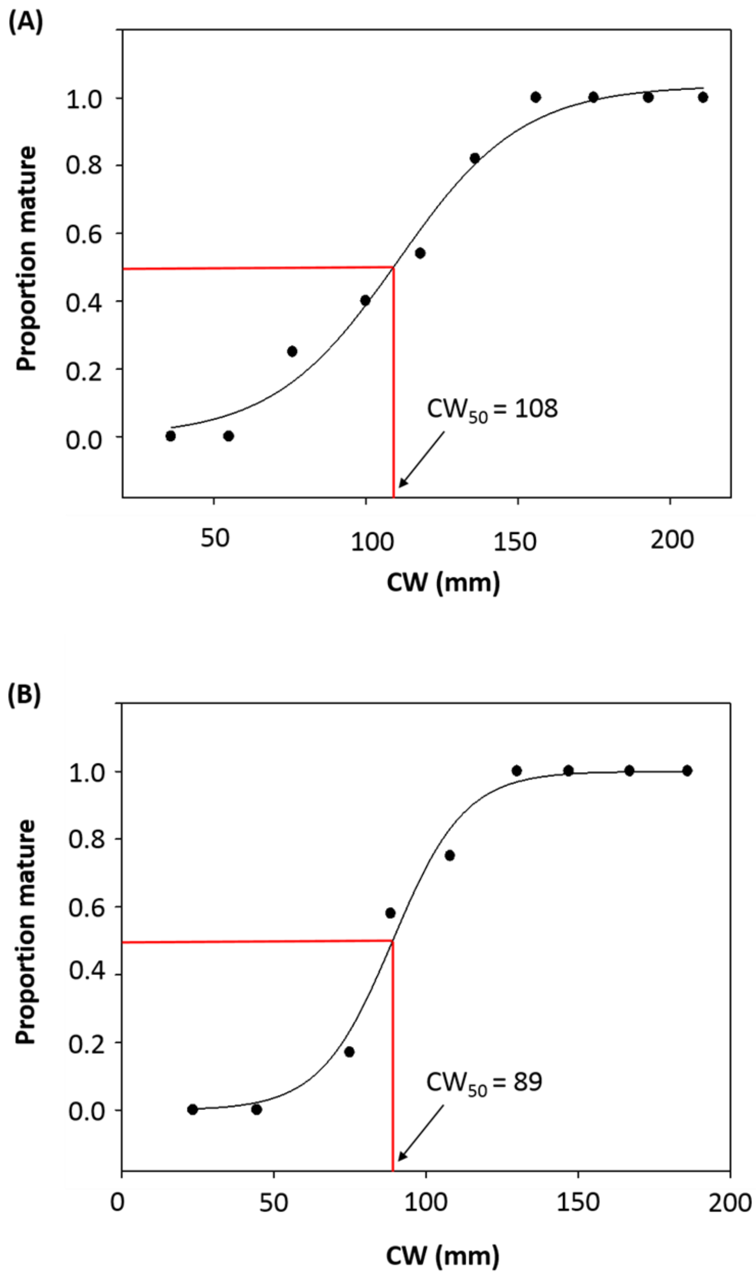

Figure 3.4. A) Predicted size at maturity based on ovary development in female *Cancer pagurus* (n = 215); B) Predicted size at maturity based on testes development in male *Cancer pagurus* (n = 82).

Size - wet weight relationships

The CW-weight relationship for the overall population (both females and males) was: W = $0.0002CW^{2.933}$, R^2 = 0.83. Figure 3.5 shows the equations of CW-weight relationship for females and males *C. pagurus*; males were significantly heavier in comparison to females of the same size and/or weight (ANCOVA, $F_{44, 2067}$ = 2.03, $P < 0.001$).

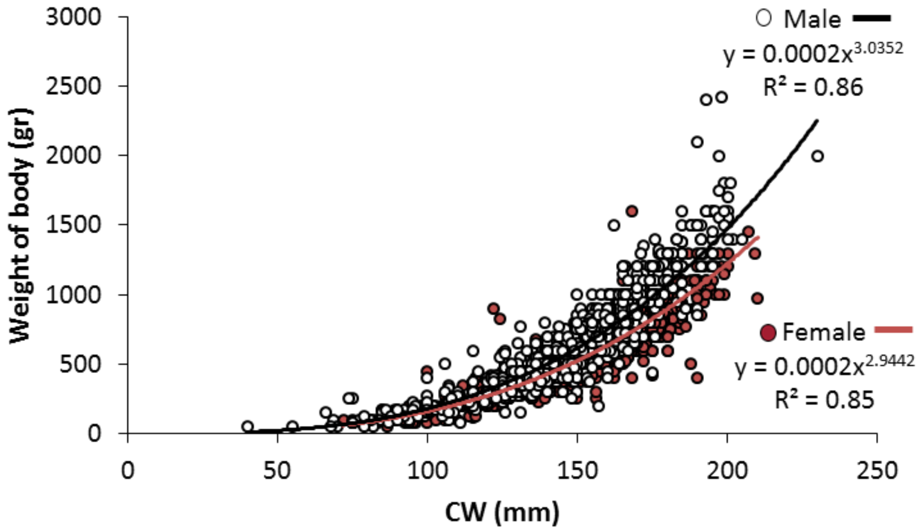

Figure 3.5. The relationship between carapace width (CW) and body wet weight of female (n = 1091) and male (n = 1090) specimens of *Cancer pagurus*.

3.5 Discussion

Numerous studies have indicated that discontinuities in the relative growth rate of crustacean body parts can be used to determine the morphological size of maturity, in particular the chelipeds in males and the abdomen width in females (Hartnoll, 1974, 1982; Claverie and Smith, 2009). In the present study, positive allometry in cheliped length was found in males and females, however this allometry is stronger in males than females. Hartnoll (1974, 1982) suggested that an increase in cheliped length of male specimens of crustaceans occurs after puberty. In the present study, females exhibited positive allometry in abdomen width. Similar findings were recorded for the female *C. pagurus* in Scotland (Tallack, 2007) and Sweden (Ungfors, 2008). Sexual dimorphism in chelipeds in males can be related to the feeding, mate-guarding and fighting (Hartnoll, 1969; Lizarraga-Cubedo et al., 2003), while in females wider abdomens can accomodate larger clutch size (Baeza et al., 2012).

Depending on the technique used, the estimate of SOM was found to be extremely variable. In the present study, with respect to behavioural sexual maturity, the smallest female crab found with sperm plugs was 110 mm CW. In contrast, when the morphometric sexual maturity method was used, the estimated SOM was 155 mm and 107 mm CW for females and males respectively. However, in terms of functional maturity, the smallest ovigerous female crab was 134 mm CW (although it should be noted that this is based on a limited range of observations that are area, season or gear specific (Chapter 4)). Based on gonad maturity, fifty percent of females were mature at 108 mm CW, whereas 50% of males were mature at 89 mm CW. The latter figures seem to be reasonably consistent across the U.K. (Haig et al. unpublished data) which may indicate that this is the most reliable method.

Geographic variation in SOM has been recorded for many crustacean species (Lizarraga-Cubedo et al., 2003). Similarly, the current study evaluated published observations of the SOM of *C. pagurus* from different regions based on behavioural, functional and morphometric criteria (Table 3.3). Across six different studies, based on gonad development, CW_{50} varied between 108 and 139 mm in females, whilst this character varied between and 89 and 105 mm in males (Figure 3.6). Population density, the availability of mates and environmental factors may account for the observed differences in values of crustaceans in different regions (Landers et al., 2001; Lizarraga-Cubedo et al., 2003). In particular, water temperature may influence the size at maturity such that maturity occurs at a larger size in warmer waters (see Chapter 4) (Ungfors, 2008). For example, Le Foll (1984) reported that based on gonad development the CW_{50} of female *C. pagurus* is 110mm CW around Bay of Biscay. Earlier maturation results in shorter generation times and higher survival to maturity due to less time spent in the juvenile stage (McQuaid et al., 2006).

There was a significant difference between the CW_{50} of female and male crabs according to pooled data (results of this study and literature) (Figure 3.6). The sexes generally exhibit different growth rates after the puberty moult as females divert more energy to reproduction than males (Hartnoll, 1982, 1985; Abello et al., 1990).

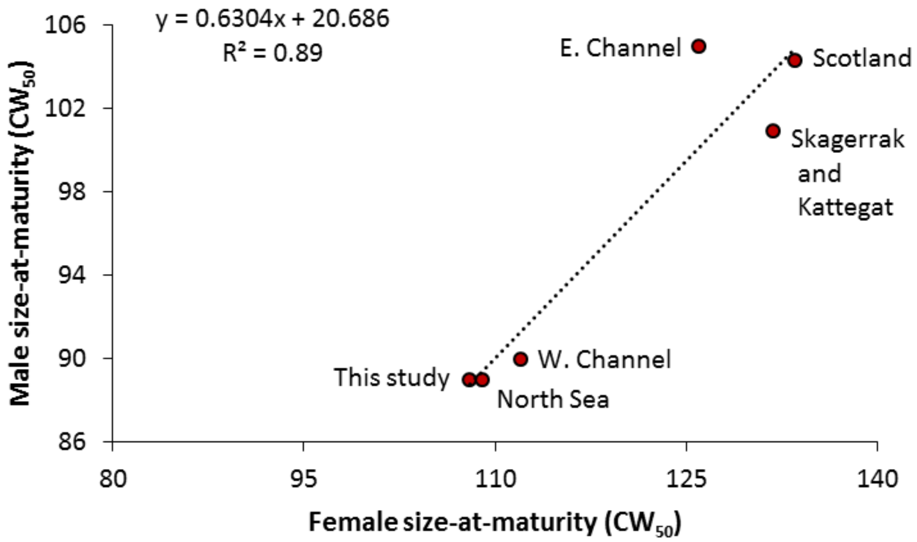

Figure 3.6. Male versus female size at maturity, estimated from gonad development and size at 50% maturity for *Cancer pagurus* in different studies. References of studies across Europe: Scotland (Tallack, 2007), Skagerrak and Kattegat (Ungfors, 2008), Eastern Channel, Western Channel, North Sea (Smith et al., 2007 (Cefas, Lawler, 2006; unpubl)) and the Isle of Man (Current study).

Table 3.3. Size at maturity of *Cancer pagurus* in the published literature and current study. Table shows the methods used, sex (females in bold), location and year of study. CW mature is when the smallest mature individual is reported in the range of sampled crabs (and no CW50 was reported).

Maturity	CW_{50} (mm)	CW mature (mm)	Method	Country	Year	n	Sex	Reference
Behavioural	106.6		Sperm in spermathaeca	Sweden	2002	399	F	(Ungfors, 2008)
Behavioural	118.5		Sperm plug present	Sweden	2002	399	F	(Ungfors, 2008)
Behavioural	116		Sperm plug present	England			F	(Edwards, 1979)
Behavioural		105-211	Sperm plug present	England			F	(Brown and Bennett, 1980)
Behavioural	122.9		Sperm plug present	Scotland	1999-2001	812	F	(Tallack, 2007b)
Behavioural		**110-200**	**Sperm plug present**	**Isle of Man**	**2012-2013**	**215**	**F**	**This study**
Physiological	127-139		Gonad development	SW Ireland			F	(Edwards, 1979)
Physiological	110		Gonad development	Bay of Biscay			F	(Le Foll, 1984)
Physiological	126		Gonad development	Eastern Channel			F	*(Cefas, Lawler, 2006; unpubl.)
Physiological	112		Gonad development	Western Channel			F	*Cefas, Lawler, 2006; unpubl.)
Physiological	109		Gonad development	North Sea			F	*Cefas, Lawler, 2006; unpubl.)
Physiological	131.8		Gonad development	Sweden	2002	399	F	(Ungfors, 2008)
Physiological	133.5		Gonad development	Scotland	1999-2001	114	F	(Tallack, 2002)

Table 3.3 continue. Size at maturity of *Cancer pagurus* in the published literature and current study. Table shows the methods used, sex (females in bold), location and year of study. CW mature is when the smallest mature individual is reported in the range of sampled crabs (and no CW50 was reported).

Maturity	CW_{50} (mm)	CW mature (mm)	Method	Country	Year	n	Sex	Reference
Physiological	120		Gonad development	Ireland	1998		F	(Tully et al., 2006)
Physiological	**108**		**Gonad development**	**Isle of Man**	**2012-2013**	**215**	**F**	**This study**
Physiological	105		Gonad development	Eastern Channel			M	*Cefas, Lawler, 2006; unpubl.)
Physiological	90		Gonad development	Western Channel			M	*Cefas, Lawler, 2006; unpubl.)
Physiological	89		Gonad development	North Sea			M	*Cefas, Lawler, 2006; unpubl.)
Physiological	100.9		Gonad development	Sweden	2002	271	M	(Ungfors, 2008)
Physiological		>110	Gonad development	England	1961-1966		M	(Edwards, 1979)
Physiological	104.3		Gonad development	Scotland	1999-2001	73	M	(Tallack, 2007)
Physiological	**89**		**Gonad development**	**Isle of Man**	**2012-2013**	**82**	**M**	**This study**
Functional		111	Ovigerous	France			F	(Le Foll, 1984)
Functional		122-159	Ovigerous	Norway			F	(Woll, 2003)
Functional		115	Ovigerous	England			F	(Pearson, 1908)
Functional		133-205	Ovigerous	England	1968-1972	35	F	(Brown and Bennett, 1980)
Functional		140-184	Ovigerous	Scotland	1985		F	(Hines, 1991)
Functional		118	Ovigerous	Scotland	1999-2001	1396	F	(Tallack, 2007)
Functional		127-216	Ovigerous	England	1961-1966		F	(Edwards, 1979)
Functional	143.7	100	Ovigerous	Scotland	1999-2001	1025	F	(Tallack, 2007)
Functional		**134-215**	**Ovigerous**	**Isle of Man**	**2012-2013**	**108**	**F**	**This study**
Morphometric	103.7		Abdomen	Sweden	2002	399	F	(Ungfors, 2008)

Table 3.3 continue. Size at maturity of *Cancer pagurus* in the published literature and current study. Table shows the methods used, sex (females in bold), location and year of study. CW mature is when the smallest mature individual is reported in the range of sampled crabs (and no CW50 was reported). *This unpublished data (Cefas, Lawler, 2006; unpubl.) were obtained from Smith et al., 2007.

Maturity	CW_{50} (mm)	CW mature (mm)	Method	Country	Year	n	Sex	Reference
Morphometric	**155**		**Abdomen**	**Isle of Man**	**2012-2013**	**222**	**F**	**This study**
Morphometric	115.9		Abdomen	Scotland	1999-2001	412	F	(Tallack, 2007)
Morphometric		110	Chelae	England	1961-1966		M	(Edwards, 1979)
Morphometric	101.6-109.5		Chelae	Scotland	1999-2001	402	M	(Tallack, 2007)
Morphometric	**107**		**Chelae length**	**Isle of Man**	**2012-2013**	**87**	**M**	**This study**
Morphometric	147.3		Pleopod	Scotland	1999-2001	131	F	(Tallack, 2007)
Morphometric	119.5		Chelae width	Sweden	2002	271	M	(Ungfors, 2008)
Morphometric	122.3		Chelae height	Sweden	2002	271	M	(Ungfors, 2008)
Morphometric	122.5		Chelae depth	Sweden	2002	271	M	(Ungfors, 2008)

Table 3.4. Minimum landing size (MLS) of *Cancer pagurus* in different fishing regions (Source: ICES, 2014). CRH: Crab hens (females and small males), CRC: cocks (large males).

Area	Irish Sea	Central North Sea	Southern North Sea	Eastern Channel	Western Channel	Celtic Sea
Management measure	UK	UK	UK	UK	UK	UK
Minimum Landing Size (MLS)	Various/ regional 130mm – 140mm(CRH) 130-140mm (CRC)	130mm CW (140mm north of 56N)	115 and 130mm CW	130mm in Southern Bight and 140mm CW	Various/ regional 140mm - 150mm(CRH) 140-160mm (CRC)	Various/ regional 130mm - 150mm(CRH) 130-160mm (CRC)

Table 3.4 continue. Minimum landing size (MLS) of *Cancer pagurus* in different fishing regions (Source: ICES, 2014). CRH: Crab hens (females and small males), CRC: cocks (large males).

Area	Norway	Scotland	Eastern Channel	Western Channel	Celtic Sea	Bay of Biscay
Management measure		UK	FR	FR	FR	
Minimum Landing Size (MLS)	110mm Swedish border-59 30 N, 130 mm northwards	130mm CW (140mm north of 56N)	140mm CW	140mm CW	140mm CW	130mm South of 48°

Tallack (2007) suggested that more conservative MLS should been estimated based on not only behavioural maturity but also functional maturity; hence, immature individuals will be protected until they reach the size at which they can contribute to the reproductive capacity of the stock. Minimum landing size (MLS) of *Cancer pagurus* varied from 110 mm to 160 mm carapace width (CW) in different fishing areas (Table3.4; ICES, 2014).

3.6 Conclusion

The results from the present study shows that both female and male *C. pagurus* specimens are maturing at a smaller size than the current minimum landing size (130 mm) in the Isle of Man, therefore crabs reproduce at least once prior to capture. Though the current minimum landing size (130 mm CW) of brown crab is available in the Isle of Man according to results of this study, the Data Collection Framework (DCF) (European Commission) suggests that SOM data should be collected at least every three years to determine temporal variations.

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CHAPTER 4 - REPRODUCTIVE ECOLOGY, FECUNDITY AND ELEMENTAL COMPOSITION OF EGGS IN BROWN CRAB, *CANCER PAGURUS* LINNAEUS, 1758, IN THE ISLE OF MAN

This chapter has been submitted as a scientific paper to the Journal of Crustacean Biology and is currently in review:

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4.1 Abstract

The brown crab (*Cancer pagurus*) is an important fishery resource in northern Europe. Understanding factors that affect fecundity in this species is complicated by the fact that ovigerous females enter traps infrequently. The present study aimed to understand factors that affect brown crab fecundity and egg quality for crabs sampled from the waters around the Isle of Man. The size-fecundity relationship for the Isle of Man matched closely with those published for other geographical areas where a fishery exists for this species. Ovigerous crabs varied in size from 134 to 215 mm carapace width and each individual carried an estimated 0.4-3.0 million eggs. Fecundity was not affected by factors such as sampling season, location, loss of chelae or black shell disease. Egg volume was independent of the number of eggs per batch or female body size. However, egg volume was reduced significantly in crabs that had lost chelae. Egg dry weight, C and N composition did not vary with body size or any other explanatory factors such as chelal loss or the occurrence of black shell disease. While the importance of the effect of claw loss on egg volume remains unclear, it may be an important consideration in fisheries in which the landing of claws is permitted.

Keywords: *Cancer pagurus*, reproductive ecology, fecundity, chela loss, egg size, elemental composition, sustainable fisheries

4.2 Introduction

Sustainable fisheries management requires a full understanding of life history traits and environmental factors that influence reproduction, growth and mortality of exploited species (Jennings et al., 2001; Ficker et al., 2014). Well managed stocks are characterised by sufficient reproductive adults and egg production to maintain an adequate level recruitment (Carter et al., 2014). Understanding reproductive patterns, the size at maturity, the behaviour of ovigerous females, fecundity and egg/larval quality all contribute to estimates of the turnover capacity of natural populations. Such information informs management recommendations and the use of appropriate technical measures (e.g. minimum landing size) for exploited species (Pinheiro et al., 2003; Mente, 2008).

Fecundity commonly refers to the number of eggs produced by a female in a single egg batch (Bourdon, 1962; Sastry, 1983; Pinheiro and Terceiro, 2000; Pinheiro et al., 2003). Fecundity data should consist of three main parts: the unit counted (e.g. oocytes, eggs, embryos, larvae); the individual in which the unit is counted (e.g. batch of eggs, female, colony); and the timescale (e.g. spawning event, breeding season, year, and lifetime) (Ramirez-Llodra, 2002). In the case of crabs, many studies indicate that their fecundity is affected by environmental factors: temperature, photoperiod and food availability (Hines, 1988; Pinheiro et al., 2003; Verisimo et al., 2011), geographic area (Brante et al., 2004), season (Bas et al., 2007), chemicals (pollutants) and biological agents (bacteria, fungi) (Shields, 1991), and biology of the species: body size (Hines, 1991; Shields, 1991), body weight (Haddon, 1994), female age (Przemysław and Marcello, 2013), moulting stage (Somerton and Meyers, 1983), injury or damage, limb loss (Gardner, 1997) and subsequent brood production (Verisimo et al., 2011).

In addition to the influence of environmental factors, some studies show that the reproductive patterns in oogenesis, embryogenesis, egg and larval quality may be affected by factors such as female nutritional condition (Palacios et al., 1998, 1999; Wehrtmann and Kattner, 1998), temperature (Paschke, 1998; Gimenez and Anger, 2001; Thatje et al., 2004; Fischer et al., 2009; Weiss et al., 2009) and salinity (Gimenez and Anger, 2001; Torres et al., 2002). Moreover, some diseases in decapod crustaceans cause egg mortality and mortality of animals (Shields, 2012) and limb loss negatively affects the reproduction, foraging efficiency and growth of crustaceans (Juanes and Smith, 1995; Mariappan et al., 2000; Patterson et al., 2009). Blackspot disease is a bacterial infection that causes black lesions on the exoskeleton (Ayres and Edwards, 1982). Exoskeleton lesions have been reported from many decapod crustaceans for three decades

(Roald et al., 1981; Joseph and Ravichandran, 2012; King et al., 2014). However, the potential impacts of the blackspot disease and limb loss on reproductive system and development of animals have not been investigated sufficiently yet. In crabs, the newly laid eggs contain all the energy necessary for embryonic development (Gimenez and Anger, 2001). The quality of eggs (indicated by carbon and nitrogen content and/or egg size) is important as larval survival and growth are affected by the amount of energy reserves that remain after hatching (Gimenez and Anger, 2001; Churchill, 2003; Ouellet and Plante, 2004; Urzua et al., 2012). Thus, it is important to understand whether there are spatial or temporal factors that might affect egg quality when attempting to estimate fecundity in the context of an exploited population.

The brown crab, *C. pagurus*, is one of the most important commercial species in terms of first-sale economic value (nearly £ 31 M in 2011) in the United Kingdom (MMO, 2014). The fishery is prosecuted by mainly small-scale inshore fleets and larger-scale offshore vivier vessels. The present study focused on the brown crab fishery in the Isle of Man where the management measures include a current minimum landing size of 130mm carapace width (CW) and where the fishing of ovigerous crab is banned in order to protect egg production and to avoid overfishing. In addition, the landing of crab claws is prohibited which has stopped the practice of 'de-clawing' by fishers that land their catches in the Isle of Man (Kaiser et al., 2008).

Studying ovigerous brown crabs is complicated by sampling limitations that occur as a result of their behaviour. In the autumn/early winter ovigerous (berried) female *C. pagurus* migrate to deeper water where they remain hidden and half buried in the sand, gravel or silt to incubate their eggs for periods to time up to 9 months in duration (Nichols et al., 1982; Naylor et al., 1999; Woll, 2003). During this egg-carrying period, ovigerous females either do not feed or they exhibit limited feeding activity and the large egg mass on the abdomen restricts their movement ability (Bennett and Brown, 1983). As a consequence, these less active female crabs rarely enter baited traps (Edwards, 1979; Brown and Bennett, 1980; Howard, 1982; Bennett and Brown, 1983; Bennett, 1995; Karlsson and Christiansen, 1996; Hunter et al., 2013). Traditional studies of brown crabs have relied mainly on trap based surveys. For this reason, little is known about the distribution and abundance of ovigerous females and the factors that affect their fecundity (Howard, 1982; Addison and Bennett, 1992). In addition, there are few insights into how the elemental composition (and hence egg quality) of *C.pagurus* eggs may be influenced by environmental factors (but see Torres et al., 2002; Weiss et al., 2009).

The present study examined the fecundity of *C. pagurus* in the northern Irish Sea in the territorial sea of the Isle of Man. In addition the study investigated whether egg size was affected by maternal factors (crab body size, limb loss, occurrence of blackspot disease, etc.). Lastly, the possible effects of chela loss and occurrence of black spot disease on egg quality (dry weight, carbon and nitrogen content) was examined.

4.3 Materials and methods

Collection of crabs

A total of 5795 pots were hauled during fishery independent surveys in the Isle of Man (Figure 4.1) from spring 2012 to summer 2013, however only 16 ovigerous crabs were captured during this period. Additional samples of female ovigerous crabs were obtained from autumn 2012 until the early spring 2013 during scallop dredge fishery surveys and from commercial scallop fishing boats (Figure 4.1). The survey design was inevitably constrained by the need to work with existing commercial fishing activity which was confined to specific areas. Although the samples size was relatively low (n=78) it was greater than that reported for other studies (Williamson, 1900; Edwards, 1967; Cosgrove, 1998; Tallack, 2002; Ungfors, 2007). Ovigerous crabs were placed in plastic bags separately in order to avoid the loss of eggs and appendages. These crabs were held on ice in insulated boxes at sea and returned to the laboratory for further analysis.

Environmental data

A time-series of seawater temperature data is maintained at three different sites around the Isle of Man territorial area (Resa, Targets, Cypris) (Figure 4.1). Monthly observations for the period between autumn 2012 and summer 2013 were extracted for bottom temperature (DEFA, 2010; Shephard et al., 2010). The annual average water temperature values were 10.9 ± 2.8℃ in Targets, 11.1 ± 2.7℃ in Cypris, and 11.3 ± 2.9℃ in Resa. To place the current study in a wider European context, the minimum, maximum and average bottom water temperature values were calculated for the period between 1965 and end of 2013 obtained from the ICES data portal and compared to the mean value for the Isle of Man (Figure 4.5). Water depth across the areas sampled varied between 3 and 100 m which reflected the distribution of the main commercial fishing activity in the Isle of Man.

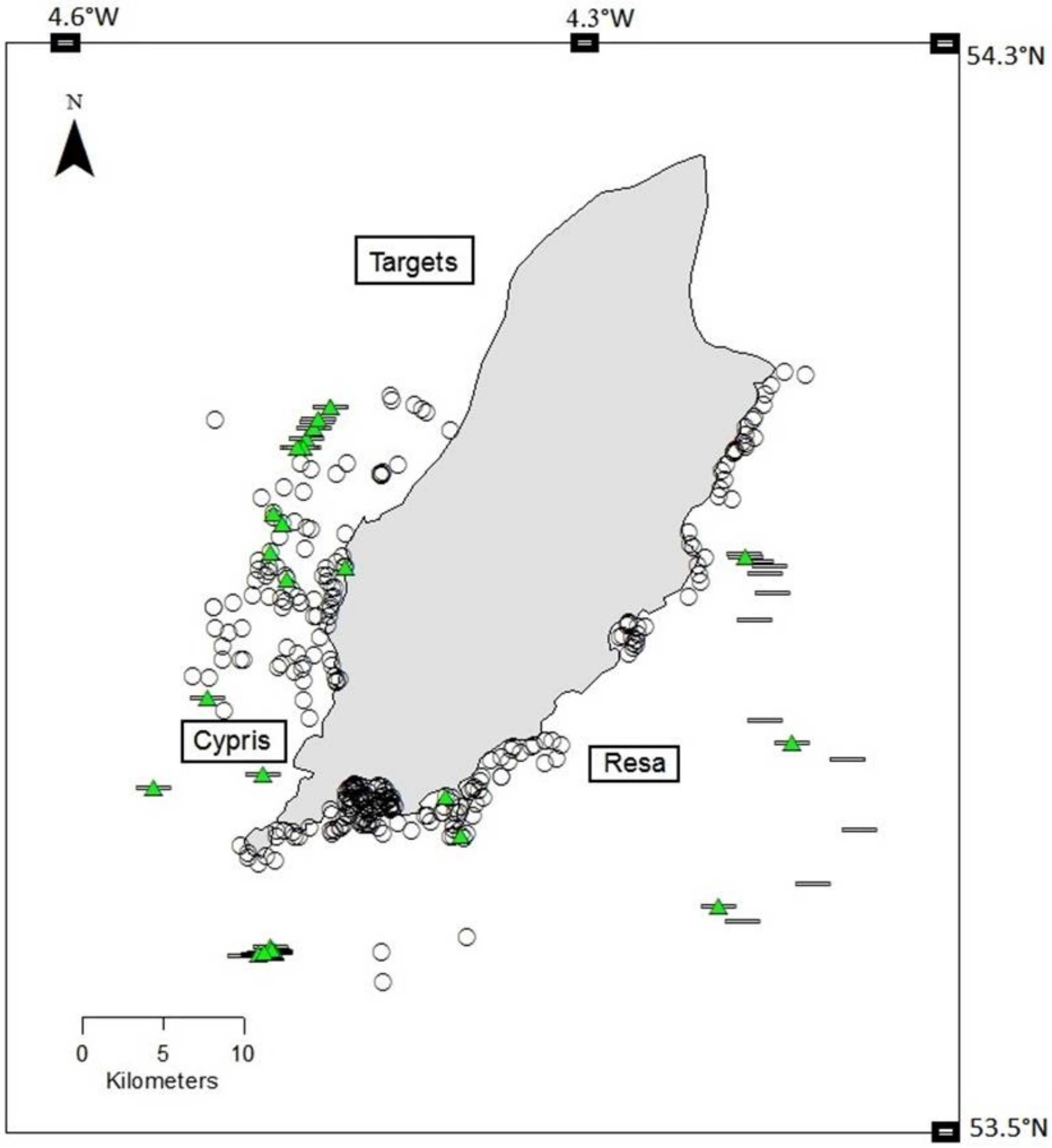

Figure 4.1. Location of the sites sampled. Open circles show the location of pot surveys, open lines show the location of scallop dredge surveys. The filled triangles show those scallop dredge tows or hauled pots which yielded ovigerous female brown crab (*C. pagurus*). The location of the environmental data stations are shown (Targets, Cypris, and Resa).

Morphological characteristics

In the laboratory, for each crab morphometric measurements were taken to determine which of these gave the most reliable estimate of fecundity, these were; carapace width (CW), carapace length (CL), 5^{th} abdominal somite width (S5W), 5^{th} abdominal somite length (S5L), 6^{th} abdominal somite width (S6W), and 6^{th} abdominal somite length (S6L) (all measured to the nearest mm) (Figure 4.2). Based on Ungfors (2007), moult stage was classified into 4 classes: (1) early post moult (soft carapace); (2) late post moult (recently moulted, colouration still bright and no epifaunal growth); (3) intermoult (fully hardened carapace with some fouling organisms); (4) late intermoult (evidenced from shell necrosis and the presence of many fouling organisms).

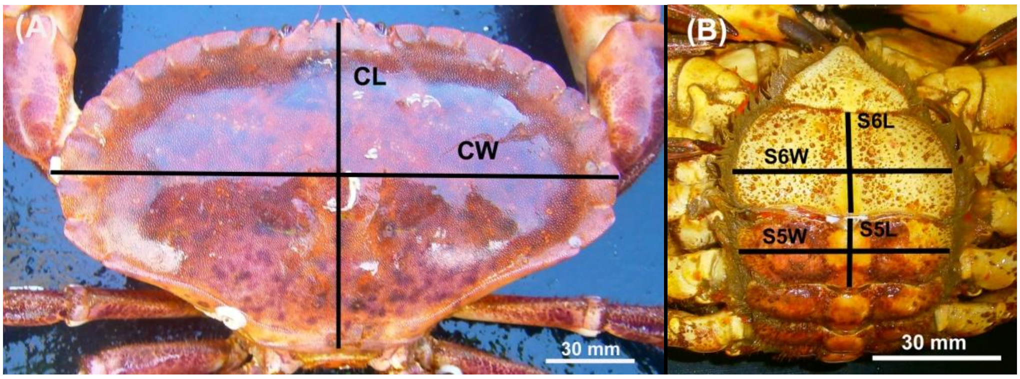

Figure 4.2. A, Morphometric measurements of carapace width (CW), carapace length (CL); B, 5th abdominal somite width (S5W), 5th abdominal somite length (S5L), 6th abdominal somite width (S6W), and 6th abdominal somite length (S6L) in *C. pagurus*.

Fecundity

Fecundity was estimated using the methods in Tallack (2002 and 2007). The wet weight of each egg mass was determined for each female. In order to avoid egg loss, the egg mass was carefully removed by cutting the pleopods from the abdominal flap. Eggs were removed from the pleopods. A total egg mass weight (TEW) was determined by weighing the entire egg mass to the nearest 0.001g using an analytical balance. Three similar sized separate subsamples of eggs were taken randomly from each brood, weighed to the nearest 0.001g and the eggs counted under a stereo microscope. The weight of each individual egg was determined by dividing the mass of the subsample of eggs by the number of eggs in that subsample. The individual egg weights from the three sub-samples (W1, W2, and W3) were then averaged to provide a mean individual egg weight (EW). The total number of eggs per brood (T_{eggs}) was calculated from equation;

Equation: $T_{eggs} = TEW/EW$

Egg diameter and development stages of eggs

Ten eggs per brood were removed to measure their size and biomass. Egg volume was determined by measuring the mean egg diameter (measured to the nearest µm) from two measurements (length: D_1 and width: D_2) made with a stereo microscope (Kyowa, model SZM) equipped with a calibrated eye-piece micrometer. Diameter was then converted to a radius and this value was used to calculate the volume of each egg assuming it was spherical. Development stage was determined by removing the egg mass from the pleopods. Forty eggs from each brood were chosen at random and were investigated under a dissecting microscope to estimate their development stage based on Fischer (2009) (Table 4.1).

Table 4.1. The morphological description of embryonic development stages of *Cancer* spp. (Fischer, 2009).

Egg stage	Description (After Baeza and Fernandez, 2002)
I. Blastula	— no yolk used; 1 to 2 days after oviposition
II. Gastrula	— 25% of the yolk used, still no eyes visible
III. Eye-placode	— eyes are visible as kidney-shaped small dark spots, but still no chromatophores present and no heartbeat
IV. Pre-hatching	— all yolk utilized, eyes completely round, chromatophores well developed, heart beats vigorously and embryo moves inside the egg; 1 to 2 days before larvae hatching.

Elemental composition of eggs

The elemental composition of the eggs of a smaller number of crabs (n=54) was determined to understand if the quality of the eggs varied in relation to loss of appendages or black spot disease. In order to determine the dry weight (DW) and elemental composition (carbon (C), and nitrogen (N) content) of the eggs within a single brood the procedure outlined in Gimenez and Anger (2001) was followed. For each brood, three replicate samples of 40 eggs were removed and rinsed for a few seconds in distilled water, then dried on filter paper, and subsequently transferred to tin cartridges. Samples were dried for 48 h in a vacuum drier (Edwards Super - modulyo 12k), weighed on a microbalance (Mettler Toledo, precision: 1µg), and analysed in a CHNS-O Analyser (Flash EA 1112).

Factors that might affect fecundity or egg quality

Crabs that have lost appendages or that are infected with black spot disease may have incurred energetic costs that had a negative impact on fecundity. For this reason the following parameters were recorded; leg loss, chelal loss, the severity of blackspot disease. When recording leg and chelal loss, only those crabs that had older wounds with evidence of melanisation at the site of injury were considered. This was to avoid mis-reporting of instantaneous limb loss that occurred at the time of sampling. The severity of blackspot disease was classified on a scale from 0 to 4: (0) no discolouration present; (1) one to five distinct spot, generally only on chelipeds; (2) the spot number varied between 6 and 10; (3) many distinct spots (more than 11), usually covering surfaces of chelipeds, abdomen and carapace; (4) much discolouration; much of the surface of cheliped, abdomen or carapace are affected, and solid black patches can be seen.

Statistical analysis

For the morphometric relationships a linear regression (ln-transformed data) was used to determine: the relationship between fecundity and 1) various external morphometric parameters; 2) CW of *C. pagurus* in this and other published studies. The data were tested for normality and homogeneity of variance using a Kolmogorov-Smirnov K-S test and Levene's test respectively (Field, 2005; Becerra-Jurado et al., 2014).

As the fecundity of crabs can vary seasonally (Samuel and Soundarapandian, 2009), and there are distinctly different oceanographic regimes around the Isle of Man (stratified [west coast] versus mixed water masses), a General Linear Modelling approach was used to examine variation in fecundity with season (autumn vs winter-spring) and location (east and south vs west). The waters to the west of the Isle of Man are strongly stratified in the summer and autumn, which leads to strong differences in patterns of production (Dickey-Collas et al., 1996; Lambert, 2011). Given the constraint of relatively low numbers of animals it was necessary to group crabs into broad categories to examine the seasonal and spatial differences in fecundity. The following covariates were included in the model; carapace width which is a proxy for crab size, egg volume which may affect estimates of fecundity that are based on the weight of the egg mass, leg and chelal loss which may incur energy costs that affect fecundity, blackspot disease which may impair crab condition and moult stage. The effects of egg development stage was checked using a GLM procedure with carapace width as a covariate. When significant effects were revealed these were examined using univariate analysis if appropriate.

There was a smaller sample size for the analysis of elemental composition. Again, a GLM approach was adopted in which the effects of chelal loss and black spot disease were the main factors and egg development stage (stage 1 or 2), egg volume, and crab size (CW) were included as covariates in the analysis.

4.4 Results

Fecundity

The seventy-eight ovigerous females used for the counts of egg number varied in size from 134 to 215 mm carapace width, and they carried an estimated 0.4 – 3.0 million eggs each. The mean fecundity of the crabs in this study was estimated as $1.5 \times 10^6 \pm 0.6 \times 10^6$ eggs per ovigerous female. Statistically significant positive linear relationships were found between all of the morphometric measurements and the ln-fecundity (Table 4.2, Figure 4.3). A general linear model demonstrated that carapace width was a strong predictor of fecundity (Table 4.3). Eggs were either in development stage 1 or 2, but there was no effect of egg development stage on the estimate of fecundity for the 54 crabs for which this was ascertained (GLM, $F_{1,52}$= 0.18, P=0.68).

Fecundity did not vary between crabs sampled in the autumn vs winter-spring and there was no effect on fecundity of the area from which the crabs were sampled. Similarly there was no effect of black spot disease, limb or chelal loss on egg volume (Table 4.3).

Table 4.2. Linear regression of morphometric measurements (ln-carapace length, ln-5th abdominal somite width and length, ln-6th abdominal somite width and length) and the ln-fecundity of brown crabs sampled from waters around the Isle of Man.

Linear regression descriptors								
Measurement	Intercept	Slope	R^2	SE	Lower 95%	Upper 95%	r	*P*
Ln CL	-2.430	3.603	0.71	0.26	3.08	4.13	0.85	< 0.001
Ln S5W	4.173	2.588	0.72	0.19	2.22	2.96	0.85	< 0.001
Ln S5L	7.109	2.645	0.63	0.23	2.18	3.11	0.80	< 0.001
Ln S6W	4.576	2.481	0.68	0.20	2.09	2.87	0.82	< 0.001
Ln S6L	5.834	2.534	0.61	0.23	2.08	2.99	0.78	< 0.001

Table 4.3. The general linear model (GLM) of possible explanatory variables for variation in fecundity (Factors: area, season and area*season, Covariates: carapace width (CW), chela loss, other pereipod loss, blackspot disease, moult stage) and egg volume (Factors: blackspot disease and chela loss, Covariates: carapace width (CW) and fecundity).

Source	Fecundity			Egg Volume		
Factors	df	F	*P*	df	F	*P*
Season	1	1.54	0.219			
Area	1	0.50	0.481			
Season*Area	1	2.12	0.150			
Blackspot disease				4	0.12	0.975

Chela loss				1	7.14	0.009
Covariates						
Ln Carapace width (Ln CW)	1	161.26	0.000	1	0.48	0.490
Egg volume	1	0.12	0.734			
Chela loss	1	0.51	0.478			
Other pereipod loss	1	1.69	0.198			
Blackspot disease	1	1.30	0.258			
Moult Stage	1	0.16	0.686			
Fecundity				1	0.01	0.973

Note: The interaction between blackspot disease and chela loss (blackspot disease*chela loss) did not show a significant effect on egg volume. Thus, aforementioned interaction was removed from the model.

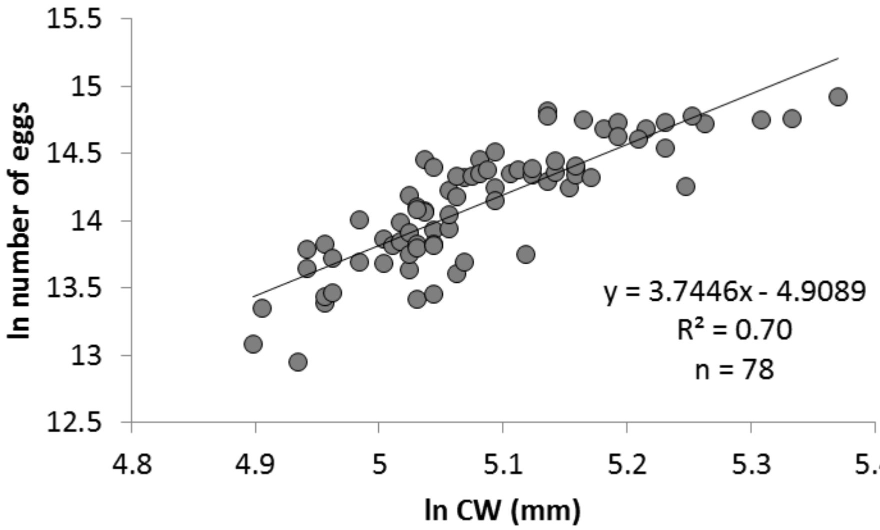

Figure 4.3. The relationship between ln number of eggs and ln carapace width (ln CW) for brown crab (*C. pagurus*) sampled from the waters around the Isle of Man. Linear regression, r = 0.83, df = 77, $P < 0.001$.

Egg volume ranged from 15.8 x 10^6 to 41.2 x 10^6 µm^3 in volume**.** Egg diameter or volume was independent of fecundity or female CW (Table 4.3, Figure 4.4a) and it was clear that there was considerable individual variation in egg size for a given size of individual crab. The GLM demonstrated that egg size declined when crabs had lost their chelae (note loss of one or two chelae was not differentiated due to the low number of crabs that had lost two chelae) (Table 4.3, Figure 4.4b). None of the other environmental factors or covariables had an effect on egg volume (Table 4.3).

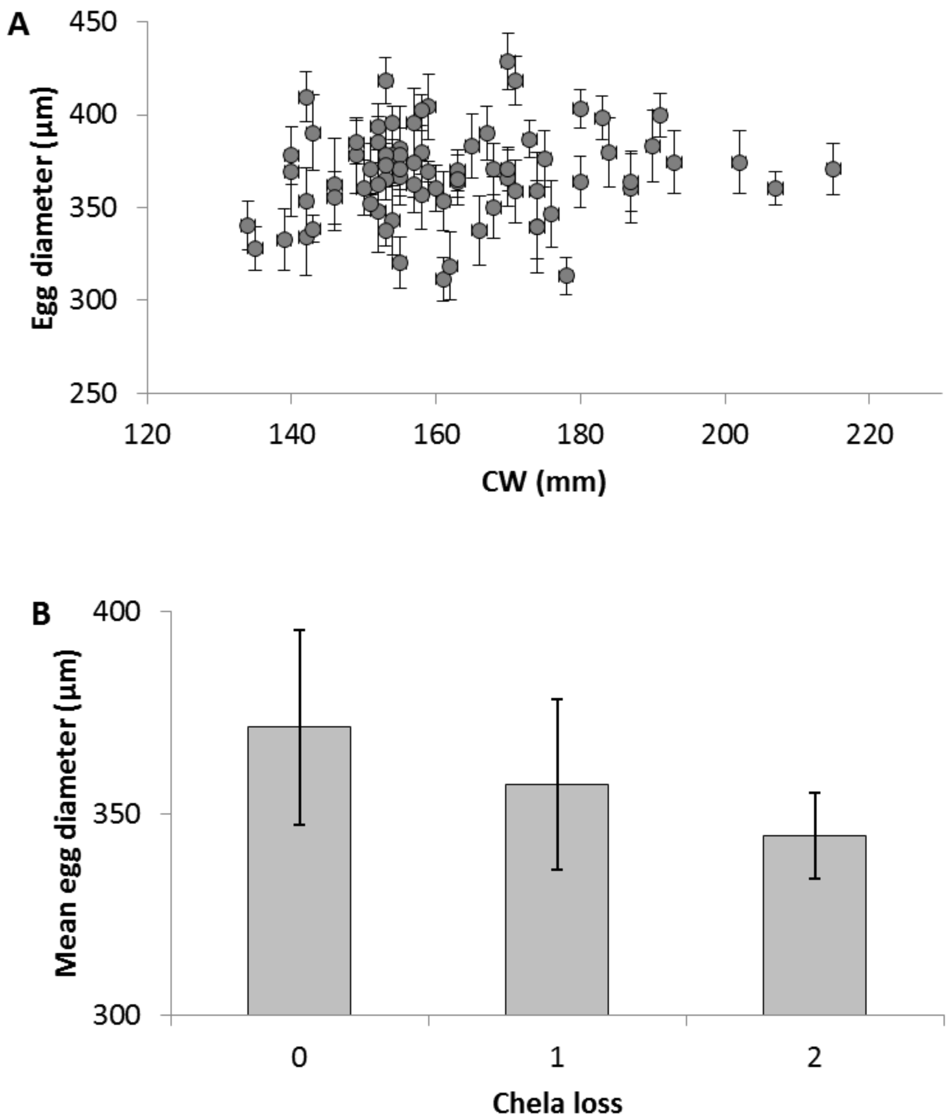

Figure 4.4. A, The relationship between egg diameter (µm) and CW (mm) (±SD); B, The relationship between mean (±SD) egg diameter (µm) and chela loss (n = 78) for brown crabs (*C.pagurus*). Only those individuals that showed evidence of melanisation at the point of chelal loss were recorded.

Elemental composition of eggs

Whole egg biomass ranged between 13.47 and 19.95 µg DW, 6.96 and 10.03 µg C, 1.26 and 2.90 µg N. The C/N ratio ranged between 3.32 and 6.10. Table 4.4 shows the mean, minimum and maximum values (per individuals ± SD) of DW, C and N in first two egg development stages. There was no effect of chelal loss or the severity of black spot disease on the elemental composition of the eggs. There was also no effect of any of the covariates (development stage, egg volume or CW) on the elemental composition of the eggs (Table 4.5).

Table 4.4. Changes in dry weight (DW) and contents of carbon (C), nitrogen (N), and C/N ratio during embryonic development; mean, minimum and maximum values per individual ± SD. Note only eggs in Stage I and Stage II were encountered in this study.

Stage	DW (µg)	C (µg)	N (µg)	C/N (µg)	N
Stage I (mean)	17.30 ± 1.27	8.99 ± 0.56	1.69 ± 0.27	5.42 ± 0.74	34
(min-max)	13.47-19.95	7.34-10.03	1.40-2.50	3.44-6.07	
Stage II (mean)	17.23 ± 1.10	8.79 ± 0.65	1.67 ± 0.32	5.37 ± 0.63	20
(min-max)	15.19-19.20	7.66-9.82	1.26-2.90	3.32-6.10	

Table 4.5. The general linear model (GLM) of possible explanatory variables for variation in DW, C, N of *C. pagurus* eggs (Factors: chela loss, blackspot disease and chela loss*blackspot disease, Covariates: egg stage, egg volume and CW)) (n = 54).

Source	DW			C			N		
Factors	df	F	*P*	df	F	*P*	df	F	*P*
Chela loss	1	1.63	0.208	1	1.01	0.321	1	0.81	0.373
Blackspot disease	1	0.02	0.899	1	0.10	0.755	1	1.44	0.237
Chela loss* Blackspot disease	1	0.26	0.613	1	0.24	0.629	1	0.03	0.855
Covariates									
Egg stage	1	0.02	0.890	1	0.86	0.357	1	0.07	0.792
Egg volume	1	0.42	0.519	1	0.24	0.624	1	0.17	0.678
CW	1	0.17	0.685	1	0.22	0.643	1	3.29	0.076

Results compared in a wider European context

The size at which female brown crabs are first observed to carry eggs varies considerably across northern Europe and ranged from 113 to 144 mm CW (Figure 4.5). There appears to be a significant increase in the minimum size of ovigerous crabs with the smallest females occurring off Sweden, Norway and NE England, and the largest females occurring in western waters (Figure 4.5). Variation in the minimum size of egg bearing appears to be related to water temperature differences in the sampling areas (ANOVA: $F_{1,6} = 11.2$, $P = 0.02$).

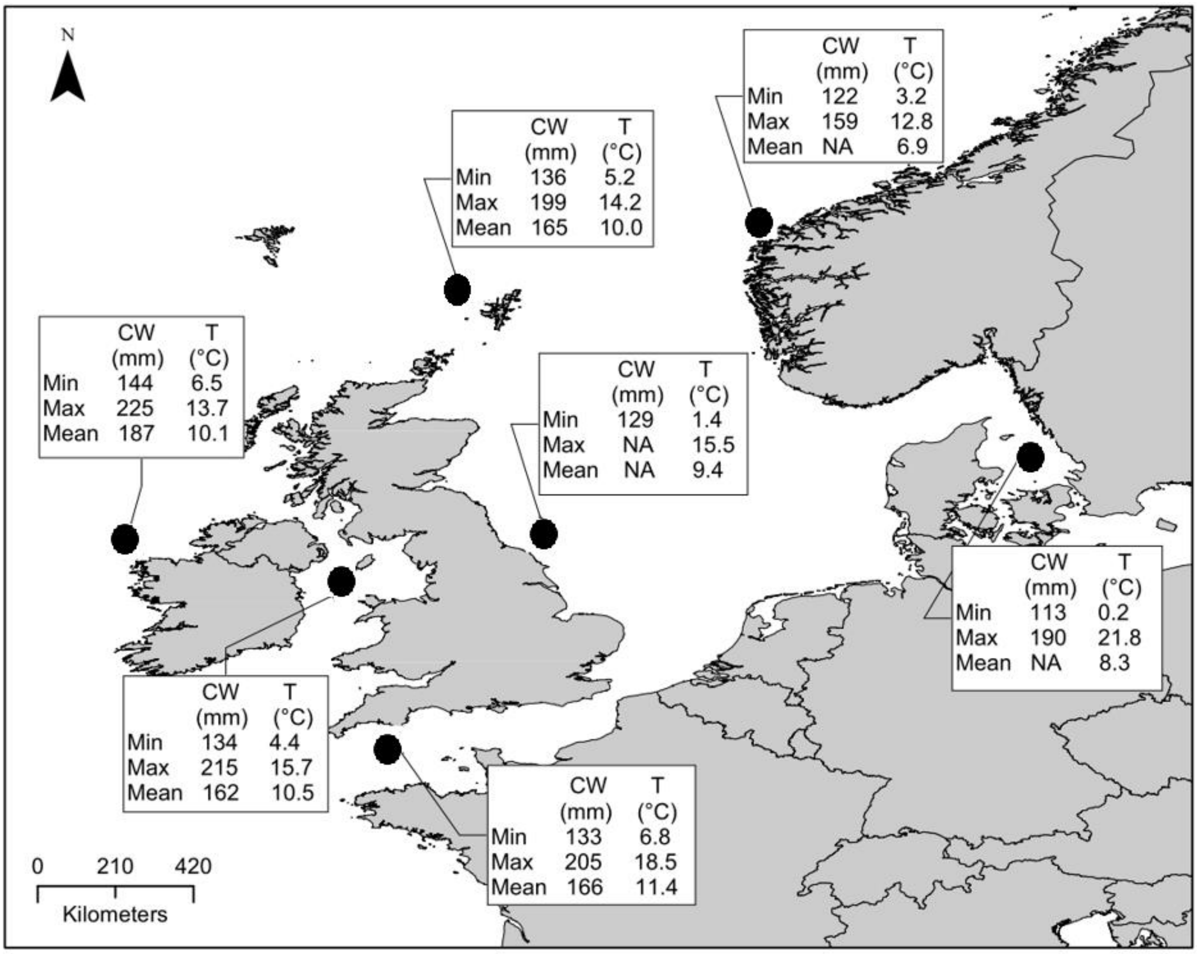

Figure 4.5. Body size measurements (minimum, maximum and mean) of ovigerous *C.pagurus* in different geographical areas (Yorkshire (Edwards, 1979); English Channel (Brown and Bennett, 1980); Donegal (Cosgrove, 1998); Shetland (Tallack, 2002); Norwegian waters (Woll et al., 2003); Skagerrak and the Kattegat (Ungfors, 2007); Isle of Man (This study)) and historical bottom water temperature values (minimum, maximum and mean). The annual bottom water temperature data (the period between 1965 and end of 2013, the depths between 3 and 100m) was modified from ICES data portal.

Figure 4.6 shows size-fecundity relationships of *C. pagurus* in the present study compared to other studies in different European locations. Fecundity increased significantly with body size in all of these studies (Tallack, 2002) except for Williamson (1900). The sample size in the Williamson (1900) study was too low for meaningful analysis. These studies included different methods (wet weight and dry weight).

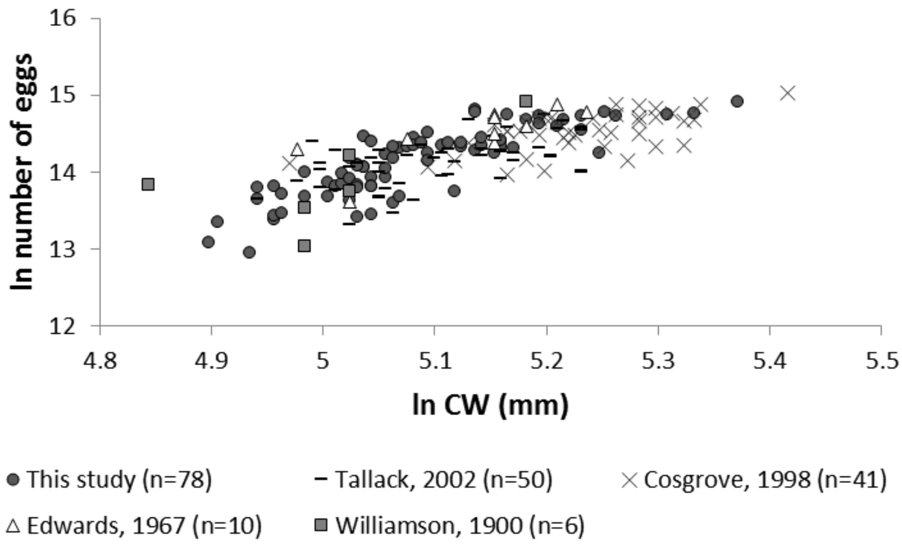

Figure 4.6. Comparison of size-brood fecundity estimates for *C. pagurus* from different geographical areas (Scotland (Williamson, 1900); England (Edwards, 1967); Donegal (Cosgrove, 1998); Shetland (Tallack, 2002); Isle of Man (This study)). Pooled data (n = 185, regression: y = 3.017x – 1.225, R^2 = 0.60).

4.5 Discussion

There is considerable diversity in benthic habitats found around the Isle of Man (Hinz et al., 2010), and the areas sampled during the present study generally consist of sandy, muddy and mixed gravelly habitats, providing suitable substratum in which ovigerous females can bury. Despite this high level of habitat variation there were no effects of sampling location on fecundity in the present study. Sampling female crabs that are incubating eggs is problematic. Edwards (1979) and Brown and Bennett (1980) sampled 23000 and 25000 females respectively and found <1% of animals bearing eggs in both cases. In the present study, 5795 pots were hauled in the Isle of Man from spring 2012 to summer 2013, but only 16 ovigerous females were found in these pots. For this reason the present study used bycatch of brown crab from scallop fisheries to supplement the sample size.

Based on previous published data and the present study, it appears that the minimum size at which female crabs are first observed to carry eggs varies significantly with minimum bottom seawater temperature. For the Isle of Man, the smallest female crab encountered with eggs was 134 mm CW which is above the minimum landing size of 130 mm CW. Thus future management may need to consider whether the current MLS is adequate to ensure that crabs have an opportunity to breed before they are removed by the fishery. As shown in other studies, female crab size was a strong predictor of egg carrying capacity which was strongly related to pleopod size and hence egg carrying capacity. The importance of the size and functioning of crab pleopods is demonstrated by observations that crabs with damaged pleopods carry smaller egg broods (Hankin et al., 1989). Thus protecting larger females by setting a higher MLS would seem a sensible management measure given the high survivorship of discarded crabs in pot fisheries. However, such measures need to be given careful consideration due to changes in moulting frequency as crabs become larger. Shields (1991) reported that the moulting probability, the number of eggs per brood and their survival rates decreased in older female crabs of the genus *Cancer*. More specifically, older *C. pagurus* individuals do not moult annually (Pearson, 1908; Hankin et al., 1985; Shields, 1991). This means that for a standard time period, larger females may have lower fecundity compared to more frequently moulting smaller females.

The loss of legs and chelae will affect normal behaviour during the period from autotomy to regeneration which may take several moults to achieve. Growth and reproduction may be affected due to changes in energy budget due to the loss of chelae or energy directed to the regrowth of limbs (Juanes and Smith, 1995; Lira and Calado, 2009). For example, in the grapsid crab *Cyrtograpsus angulatus* (Dana, 1851), females that lost at least half of their pereipods, had significantly lower fecundity (Luppi et al., 1997). In the present study although fecundity was not affected, egg volume decreased with increasing limb loss. Water quality, parasites, predators and damage are other important factors that can affect the ovigerous crabs, their eggs and the mortality of the early development stages of larvae (Samuel and Soundarapandian, 2009).

Maternal influences on offspring quality could be a significant source of variation in crustacean recruitment (Moland et al., 2010) and the energy content per egg usually depends upon egg size (Queellet and Plante, 2004). Moland et al. (2010) reported that large females of *Homarus gammarus* (Linnaeus, 1758) produced large eggs. However, Hines (1991) noted that egg size of *Cancer* crabs did not differ significantly with female size. The variation in egg size among similar sized females could be linked to heritable traits, their physiological condition and/or previous growth history (Moland et al., 2010). Additionally, inter annual temperature variation and regional variation in salinity can be considered other factors that influence egg size (Bas et al., 2007). For example, Graham et al. (2012) suggested that the egg diameter of the blue crab, *Callinectes sapidus* Rathbun, 1896, was larger in spring than summer/autumn. Similarly, Urzua et al. (2012) suggested that eggs of shrimp *Crangon crangon* (Linnaeus, 1758) are larger and heavier in winter than in summer. According to the results of present study, egg size did not correlated with the female body size but egg size decreased with increasing chela losses.

In the present study the first data was reported concerning biomass and elemental composition of *C. pagurus* eggs. Results here suggest the relationship between body size (CW) and initial egg biomass was not significant for DW, C and N. Weiss et al. (2009) noted that elemental composition (C, H, N) of zoea 1 larvae of *C. pagurus* varied significantly among the eight females. The present study showed that even though DW, C and N contents decreased relatively from early stages to late stage, the relationships were not significant. Previous studies indicated that elemental composition (C, H, N and DW) can changed during embryonic development stages of eggs or the time of larval of early juvenile development patterns (Calcagno et al., 2003; Anger and Moreira, 2004). Consequently, this study compares temporal and spatial variations in elemental composition of crab eggs. However, any significant differences in DW, C, and N contents in different sampling periods and areas could not be found. According to Torres et al. (2002), DW, lipid and protein contents of the zoea 1 larvae (*C. pagurus*) were affected by declined salinity. More importantly, results of this study suggest that elemental composition (e.g. N and C) did not increase with increased egg size.

In the present study there were no significant temporal or spatial differences in fecundity, egg size or the elemental composition of eggs. The patterns in sea water bottom temperature values had a similar trend at the Targets, Cypris and Resa sampling stations during the sampling period. This similarity in bottom temperature may explain the lack of spatial variation in fecundity around the Isle of Man. This is contrast with the finding that minimum bottom temperature affected the size of first egg bearing in brown crabs across northern Europe.

4.6 Conclusions

As for other studies, there was a strong relationship between fecundity and increasing crab size. The smallest size of an egg bearing female encountered was higher than the current minimum landing size, nevertheless the sample size in this and other studies is low due to problems associated with sampling egg bearing females. Egg volume was lower for crabs that had lost claws although the elemental composition (quality) of these eggs was not related to egg size. This also suggests that eggs size cannot be assumed to be an indicator of egg quality. While it is unclear whether fecundity is related to egg size, it is an issue that warrants further investigation due to the potential for damage sustained by crabs taken as bycatch in mobile fishing gear (Ondes et al., *unpublished*). Although declawing is not permitted in the Isle of Man, it is permitted in Scotland, England, Ireland and Wales and may have potential negative effects in these fisheries (Patterson et al., 2007).

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4.8 References

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CHAPTER 5 - QUANTIFICATION OF THE IMPACTS OF SCALLOP DREDGING AND TRAWLING ON THE BROWN CRAB FISHERY IN THE ISLE OF MAN

5.1 Abstract

The present chapter describes the characteristics of the by-catch of *C. pagurus* in king scallop dredges and queen scallop otter trawls in the Isle of Man, and determined the damage and immediate mortality associated with scallop dredges. Crab by-catch rates in dredges and trawls were 33 times higher in dredges. Based on dredge surveys, spatial and seasonal variations were observed, with the highest number of crabs found off the west coast of the Isle of Man in the autumn when berried females crabs were most frequently caught. In general, female crabs comprised 84% of the catch. Based on dredge surveys, the damage levels of crabs was high with 45% of crabs recorded as crushed or dead or with severe damage, whilst 24% of crabs exhibited missing limbs. Estimates of the potential mortality associated with scallop dredging led to a lower and upper estimate of possible crab by-catch mortality of 11t and 17t respectively which represented 2.2 – 3.4% of the commercial landings of brown crab for the Isle of Man. Heaviest mortalities of crabs occurred in November to the west of the Isle of Man when female berried crabs move offshore into deeper water. Extending the scallop dredge closed season to the end of November to the west of the Isle of Man would reduce mortality of female crabs at a critical stage of their reproductive cycle.

Keywords: *Cancer pagurus*, by-catch, damage, limb loss, mortality estimations, fishing impact, dredging, trawling.

5.2 Introduction

An ecosystem-based approach to fisheries management demands a clear understanding of the effects of fisheries on other components of the ecosystem in addition to the target species. In particular, mobile fishing gears, such as scallop dredges and trawls, have been shown to cause changes to the structure of benthic communities and habitats, and can be associated with high catches of by-catch species (Jennings and Kaiser, 1998; Kaiser, 2000; Queiros et al., 2006; Bellido et al., 2011). By-catches in mobile gear fisheries can sustain varying levels of mortality that vary among different metiers (Kaiser and Spencer 1995; Lindeboom and de Groot, 1998; Auster and Langton, 1999; Johnson, 2002; Matsuoka, 2008). The magnitude of the physical damage exerted upon by-catch species is determined by fishery-specific factors (e.g. tow duration, towing speed, fishing depth, gear type, weight of the gear, gear configuration, season, habitat type, the proportion of debris [dead shells, stones], catch size, composition, body size and body morphology of species) (Hill et al., 1996; Ball et al., 2000; Bergmann and Moore, 2001; Bergmann et al., 2001; Veale et al., 2001; Brown et al., 2005; Sartor et al., 2006; Milligan et al., 2009; Moreira et al., 2011; Policarpo, 2011). These factors affect the survivorship of the by-catch once it has been discarded which has important implications when estimated total mortality for a particular species (Hill et al., 1996; Veale et al., 2001; Policarpo, 2011).

As a result of their brittle exoskeleton and articulated appendages, crustaceans are known to be sensitive to direct physical contact with scallop dredges and bottom-fishing trawls (Eleftheriou and Robertson, 1992; Kaiser and Spencer, 1995; Bradshaw et al., 2000; Veale et al., 2000) such that the survival rate of crabs with even limited damage is low (Stoner, 2012). Although crustaceans can repair limited amounts of damage to their carapace and can regenerate damaged or lost limbs, this requires investment of energy resources and consequently reduces growth, and lengthens intermoult duration, foraging ability, and protection from predators (Bennett, 1973; Juanes and Smith, 1995; Mariappan et al., 2000). Some studies have investigated the damage level and mortality of crabs in scallop dredges (e.g. Hill et al., 1996; Jenkins et al., 2001; Veale et al., 2001). These studies reported the visible damage of crabs to consist of limb loss, carapace and abdominal cracks and crushed body-parts. There may be other forms of physical damage that cannot be ascertained from visual assessment in the field.

Cancer pagurus (brown crab) is one of the most important commercial fishery species in England and Wales in terms of its economic value (valued at > £15M at first sale in 2011) and in the Isle of Man it accounts for 1.1% of the value of landings worth nearly £0.5M (495t in

2012) (ICES, 2012; DEFA, 2012; FAO, 2015). Brown crabs are caught using parlour pots throughout the year in the Isle of Man. Brown crab co-occur in the same habitat as scallops and it has been noted that brown crabs consume scallops damaged as a result of dredge fisheries (Jenkins et al., 2004). Therefore, it is not surprising that brown crabs have been recorded in many studies as a by-catch species in scallop dredges (Hill et al., 1996; Hill et al., 1999; Bradshaw et al., 2000; Veale et al., 2000; Beukers-Stewart et al. 2001; Jenkins et al., 2001; Veale et al., 2001; Montgomery, 2008) and in trawls (Duncan, 2009). A previous study noted that this species was caught more often by scallop dredges rather than in a beam trawl (Kaiser et al., 1996). Given the large area of the continental shelf swept by towed mobile fishing gear, there is considerable potential for interactions between these gears and brown crabs. Thus it is important to quantify the amount and seasonal changes in by-catch of brown crab caught as bycatch in mobile fishing gears and to estimate the possible incidental mortality associated with these fishing activities.

The king scallop *Pecten maximus* (Linnaeus, 1758) and the queen scallop *Aequipecten opercularis* (Linnaeus, 1758) have been fished around the Isle of Man for about 70 and 40 years respectively (Hill et al., 1996). The fishing season for king scallops in Manx waters occurs between 1st of November and 31st of May, while queen scallops are fished throughout the year. The queen scallop fishery is prosecuted by trawls and dredges, however the trawl fishery operates from June to October when seawater temperatures are warm enough for active swimming by the scallops (Pers. Comm. P. Duncan, 2013). These two fisheries are the most important fisheries in Isle of Man (Murray et al., 2009). A total of 217 vessels were licensed in 2008-2009 during the scallop fishing season. Of these vessels, 142 may fish for scallops within 0 to 3 NM of the Isle of Man, although only around 50 to 100 vessels are likely to fish with considerable latent capacity in the fleet (Hanley et al., 2012). These two scallop fisheries fish approximately 46% and 17% (king and queen scallops respectively) of the seabed in the territorial waters of the Isle of Man.

Observations of brown crab elsewhere in the UK indicate that there is a directional reproductive migration of brown crab between offshore and inshore waters (Pearson, 1908; Edwards, 1979). As a result, scallop fisheries could be an important source of mortality for crabs at a critical time in their reproductive cycle. A questionnaire survey of fishers in the Isle of Man indicated that berried female crabs migrate offshore in the autumn at the beginning of the open season for the king scallop dredge fishery (Whiteley, 2009).

Information about the spatial and temporal distribution of fishing effort can play a fundamental role in underpinning ecosystem-based fisheries management (Jennings et al., 2000). In recent years vessel monitoring systems (VMS) have been used in order to describe fishing activities and impacts. VMS can enable us to determine the environmental impacts of fishing fleets (Murray et al., 2011; Lambert et al., 2012; Hinz et al., 2013). All vessels (irrespective of size) fishing in the scallop fishery within the territorial waters of the Isle of Man must be fitted with VMS. In this study, this information is used together with direct seasonal observations of crab bycatch from a total of 331 tows to assess the potential impact of the scallop fishery on the brown crab fishery around the Isle of Man.

5.3 Materials and Methods

Field observations

By-catch data collection

Three different sources of observations of the bycatch of brown crabs in scallop dredge and trawls were used for this study. Fishery-independent data were collected between 2009 and 2012 during scallop stock assessment surveys on board the R.V. Prince Madog (using commercial scallop dredges) in the northern waters of the Isle of Man (Figure 5.1, abbreviations in brackets). This survey enabled us to determine the spatial distribution and catch rate of crabs outside the normal scallop dredge open season in late May/June and September/October each year. In order to determine seasonal differences in crab by-catch during the king scallop fishing season (between November 2012 and May 2013), seasonal observations were made on board commercial scallop boats that fished in different areas around the Isle of Man (Figure 5.1). In addition to these direct observations during the scallop fishing season, data were also collected by volunteer scallop dredge fishermen using a crab by-catch form (Appendix 5.1). In order to estimate the amount of crab by-catch in the queen scallop otter trawl fishery, surveys were conducted aboard fishing vessels between June and October 2012 (during the queen scallop open season) (Table 5.1 and Figure 5.1). Thus, this study was able to compare the catch efficiency of scallop dredges versus otter trawls for brown crab and assess the impact of these different fisheries on the crab population.

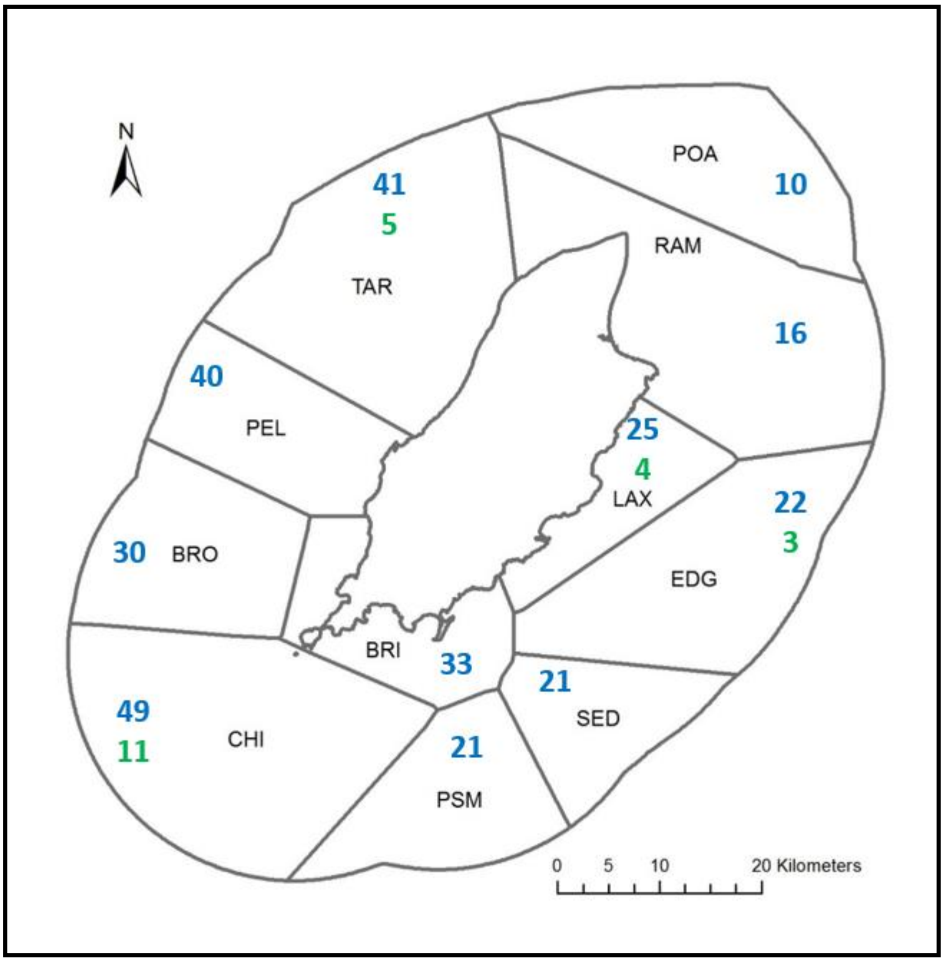

Figure 5.1. Location of the dredge and trawl survey areas in Manx waters. Site Codes: Bradda Inshore (BRI), Bradda Offshore (BRO), Chickens (CHI), East of Douglas (EDG), Laxey (LAX), Peel (PEL), Port St Mary (PSM), Ramsey (RAM), South East Douglas (SED), Targets (TAR). All sites were sampled for by-catches of brown crabs in scallop dredges, while Chickens (CHI), East Douglas (EDG), Laxey (LAX) and Targets (TAR) were sampled for a by-catches of brown crabs in otter trawls. Figures within fishing grounds indicate sample size (tow number) *n*; blue figures are dredge surveys, whereas green figures are otter trawl surveys.

Table 5.1. General information about the tows from which brown crab bycatch was estimated (fishing gear, tow number, minimum and maximum depth (m), minimum and maximum tow duration (min) and swept area (m^2). Scallop dredge surveys include a combination of three different sources of observations.

Fishing Gear	Tow (number)	Depth (m)	Tow Duration (min)	Swept Area (m^2)
Scallop dredges of R.V. Prince Madog	187	16-80	5-20	731-6872
Commercial scallop dredges	121	19-65	39-105	23224-86211
Trawl	23	24-60	46-117	60400-152200

For each tow the following characteristics were recorded for each brown crab found in the catch: sex, reproductive state of females (berried and non-berried), carapace width (CW), and moult stage (soft and hard). For each tow the start and haul position was recorded using GPS, the depth (m) was ascertained from the echo-sounder and tidally corrected, tow duration and the number of dredges used were also noted.

Damage assessment

Very few crabs were found in otter trawl catches, hence these crabs were not evaluated for damage analysis as the numbers were not considered to be statistically meaningful. For the dredge catches, in order to assess damage level of *C. pagurus*, a subsample (n=574) of crabs were evaluated for damage. For these crabs, the number of limbs lost, and the occurrence of carapace and abdomen damage were noted. Damage levels were evaluated under four categories, similar to those reported by Jenkins et al (2001) and Veale et al (2001) (Table 5.2 and Figure 5.2).

Table 5.2. Definition of the damage levels recorded for *C. pagurus* caught in scallop dredges around the Isle of Man.

Level	1	2	3	4
Damage Information	No visible damage to external structure	Legs missing	Major carapace/abdomen cracks	Crushed /dead

In order to estimate limb loss attributed to capture within a scallop dredge, comparable data were obtained from pot surveys in Manx waters (spring 2012, autumn 2012, winter 2012 and spring 2013). Animals were considered much less likely to lose limbs as a result of entry into pots and hence this provided a baseline against which to compare the damage sustained by crabs in the scallop dredges. When evaluating limb loss due to dredge operations, only new wounds with no melanisation were noted. A lack of melanisation indicated recent loss or damage. Again, for the pot fishery, old wounds with melanisation were also noted as this would indicate older wounds or past limb loss c.f. more recent injuries. When crabs autotomize or lose limbs or sustain wounds the resulting membrane over the wound becomes darker with increasing time post injury (Woll and Alesund, 2006; Figure 5.2b).

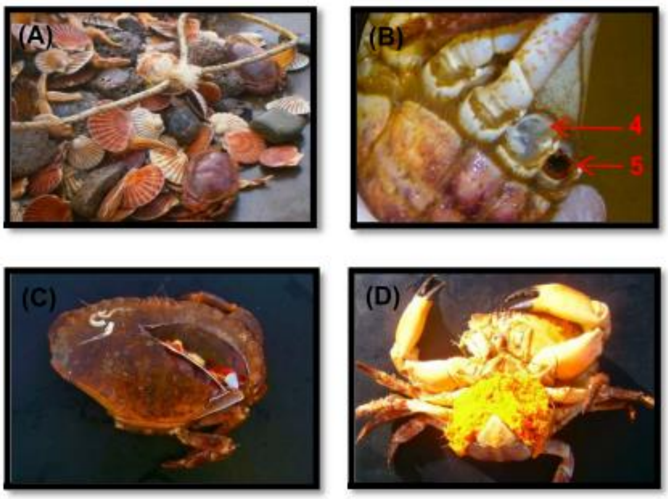

Figure 5.2. (A) The brown crab as a by-catch species in a typical scallop dredge catch, (B) Limb loss of pereipods 4 and 5, a light membrane represents a recent limb loss while a darker membrane represents an older injury, (C) Brown crab with carapace damage, limb loss and visible mature gonad prior to spawning, (D) Dead berried female crab (Photos by Fikret Ondes).

Fishing effort

Fishing effort data for the king scallop fishery was obtained from Vessel Monitoring System data (VMS) in Manx waters for the period between 2008 and 2013. This data provided information on the specific areas fished. The poll frequency included the vessel position, speed, course, a vessel identifier, date and time (Murray et al., 2013). From this information it was possible to ascertain the time (h) spent fishing in catch area (Figure 5.1).

Data analysis

The catch data of brown crabs was standardized to the number of animals caught per 1000 m^2 using the following approaches for the different fishing gears used.

For the otter trawl data, the method described by Courtney et al. (2007) was used such that the swept area per tow was calculated for each trawl two (equation 1).

1) Area Swept = F*NSF*D

Where F = footrope length (m), NSF = net spread factor (=0.75 (Sterling, 2005)) and D = distance trawled (converted to (m) when 1 nautical mile = 1852m).

The swept area per tow for each dredge tow and crab density per 1000 m^2 were calculated using equation 2 and 3.

2) Area Swept =Speed (2.5 knots)*nautical mile (1852m)*Time (hour)*Dredge number* Dredge width (0.76 m)
3) $\text{Density (individuals } 1000\text{m}^{-2}) = \dfrac{\text{catch x } 1000}{\text{area swept}}$

Protocol for calculating crab catches:

For each fishing area (Figure 5.1) the average number of crabs caught per 1000m^2 was calculated using the different sources of observations (fishery independent data based on direct observations of crab catches on the research vessel, observations made onboard scallop dredgers). If a dredge tow crossed two or more fishing areas the value for the number of crabs caught per 1000m^2 for that tow was allocated to each of the areas transected. The mean number of crabs caught for each area was only calculated for those months for which observations were available. Thus for months when no observations of crab by-catch were available no inference is drawn about the potential crab by-catch.

Based on the available data for fishing effort (expressed in hours fished) for each of the fishing areas, the number of crabs caught by fishing vessels for the months in which by-catch observations were available was computed. Two possible levels of bycatch were computed assuming that all vessels fished with either a total of 16 dredges or a total of 10 dredges. These limits were used as it was not possible to differentiate allocate the time fished to the different vessels. The number of dredge reflects the legal limit of the number of dredges that can be used by vessels fishing either within 3 nm or 12 nm and it was assumed that all vessels used a full compliment of dredges (which may not be true in all cases). It is assumed that all vessels towed their dredges at a speed of 2.5 knots which is generally considered to be the mean fishing speed for scallop dredges (Lambert et al., 2013; Murray et al., 2013).

Thus for scallop dredgers fishing 16 dredges in month *m* with fishing effort *t* hours and a mean crab by-catch (numbers) of *c* per 1000m^2 the total estimated crab by-catch equals:

*Crab by-catch = c * t*(2.5 x 1852 x 16 x 0.76) / 1000

For scallop dredges fishing 10 dredges in month *m* with fishing effort *t* hours and an mean crab by-catch (numbers) of *c* per 1000m^2 the total estimated crab by-catch equals:

*Crab by-catch = c * t*(2.5 x 1852 x 10 x 0.76) / 1000

The number of crabs caught was then converted to a value of weight using the mean individual weight of all crabs (0.61kg = 0.00061t) encountered in all survey tows that used scallop dredges.

Statistical analyses

As the data did not conform to the assumption of parametric tests, non-parametric tests were applied to the data. The Kruskal-Wallis test was used to test spatial and seasonal patterns of crab and berried female numbers per 1000 m^{-2}. A Kolmogrov-Smirnov test was used to test for differences in the size-distribution of male and female crabs in scallop dredges. A Mann-Whitney U-test was performed to evaluate differences that might occur in the damage level of crabs in relation to sex, moult stage, and female reproductive status (berried and non-berried). In order to compare differences in the standardized catches of crabs that occurred in dredges and trawls, a *t*-test was used. In order to compare the number of limbs lost by crabs in scallop dredges compared with pot fisheries (scale varied from 0 to 10), a Mann-Whitney U-test was used. A x^2 contingency test was used to examine the vulnerability of loss of pereipods. A Spearman's rank correlation was used to examine the correlation between carapace width and mean damage level. All analyses were undertaken using the statistical software SPSS 20.0.

5.4 Results

By-catch data

A total of 1291 *C.pagurus* were collected from scallop dredges during the 308 tows. For scallop dredges, the average crab catch rate was calculated as 0.201 (± 0.019 SE) crabs per 1000m^2 swept. A total of 16 *C.pagurus* specimens were collected via trawls from 23 tows, and crab catch rate was calculated as 0.006 (± 0.001 SE) crabs per 1000 m^2 towed. Crab catch rates in dredges and trawls were statistically significant such that trawl catches rates were only 3% of those for dredges (t = 2.74, df = 329, P = 0.006). Given small magnitude of the trawl catches these were not considered further in the analyses.

Dredge bycatches were highly skewed towards female crabs (84%) c.f. male crabs (11%) (Kolmogrov Smirnov test, Z = 0.527, P < 0.001). The gender of the rest of the sample could not be identified owing to damage sustained in the dredge and hence these individuals were recorded as an indeterminate sex. Of a total of 422 female crabs examined from dredge catches, 24% of the crabs were berried while 76% of the females were not berried. Crabs in the bycatch varied in size from 73 mm up to 220 mm of which 96% of crabs were larger than the minimum landing size (MLS=130mm) (Figure 5.3). The average carapace width was 164 and 149 mm for females and males, respectively.

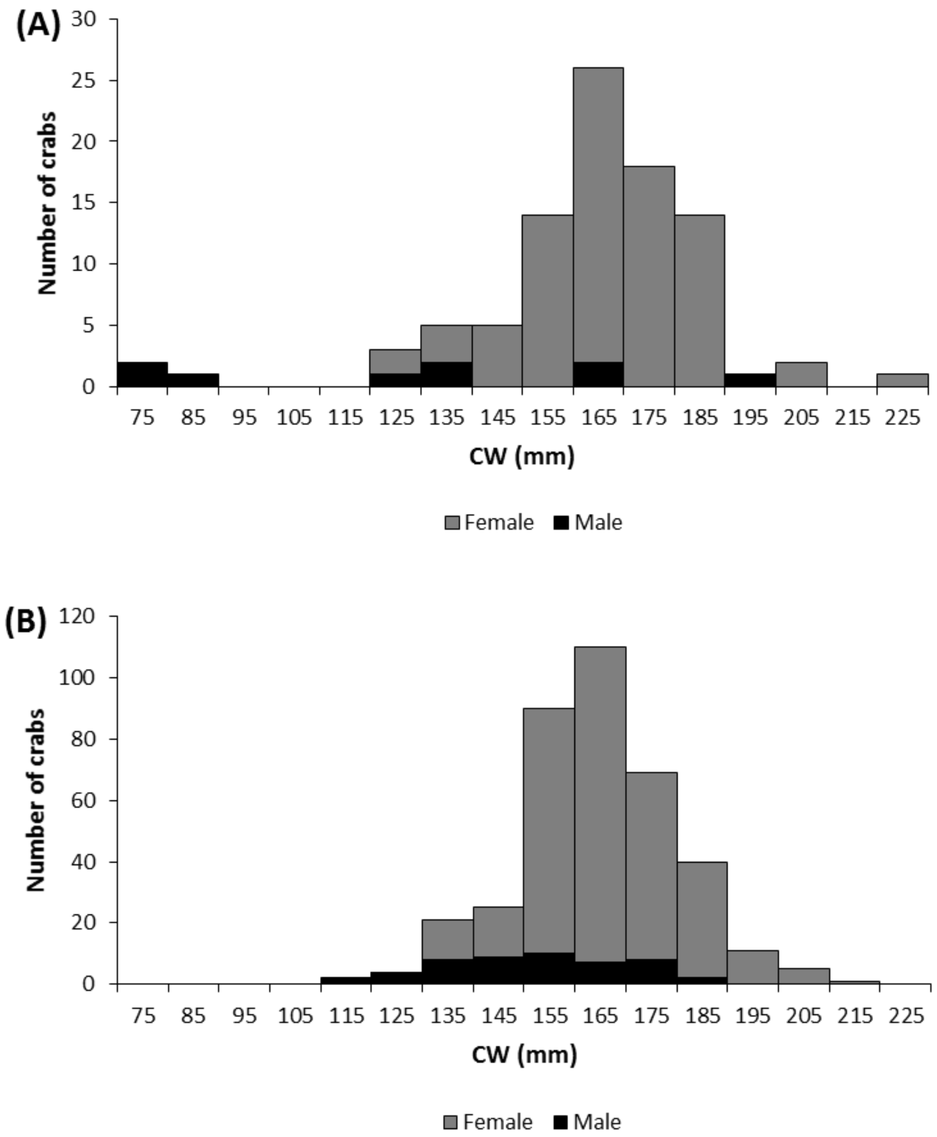

Figure 5.3. Size distribution of female and male *C.pagurus* caught by dredges fished from A) RV Prince Madog between 2009 and 2013 in Manx waters, B) commercial fishing vessels between 2012 and 2013 in the Isle of Man. The smaller size classes of crab caught by the RV Prince Madog is probably linked to the fact that two of the four dredges used are 'queen scallop dredges' which have smaller belly rings and a smaller tooth spacing on the dredge bar.

Spatial patterns in crab distribution and catches

Crab by-catches in scallop dredges varied significantly among the different fishing grounds (Table 5.3). Similarly, berried female number in dredges varied except for the data which was collected by the research vessel but this may be related to the short tow duration used (Table

5.3). The number of *C. pagurus* caught by scallop dredges was highest on grounds to the west of the Isle of Man, particularly in the Bradda Offshore, Targets and Peel fishing areas (Figure 5.4). In contrast the catches of *C. pagurus* in dredges was lowest on the South East Douglas, East Douglas, Laxey and Ramsay fishing grounds. The highest number of berried females was observed on the west coast fishing grounds (Figure 5.4). Male crabs accounted for low by-catch numbers irrespective of location (Figure 5.4 a, b).

Table 5.3. Statistical tests (Kruskal-Wallis) for spatial variation in the mean crab number per 1000 m^{-2} caught on different fishing grounds around the Isle of Man using three different survey techniques.

Source	df	Chi-square of all crabs	*P*-value	Chi-square of berried females	*P*-value
R.V. Prince Madog surveys	10	57.11	< 0.001	8.84	0.574
Direct observations with commercial boats	6	28.32	< 0.001	29.11	< 0.001
Fishermen’s forms	5	24.28	< 0.001	18.36	0.003
Pooled data	10	86.28	< 0.001	56.25	< 0.001

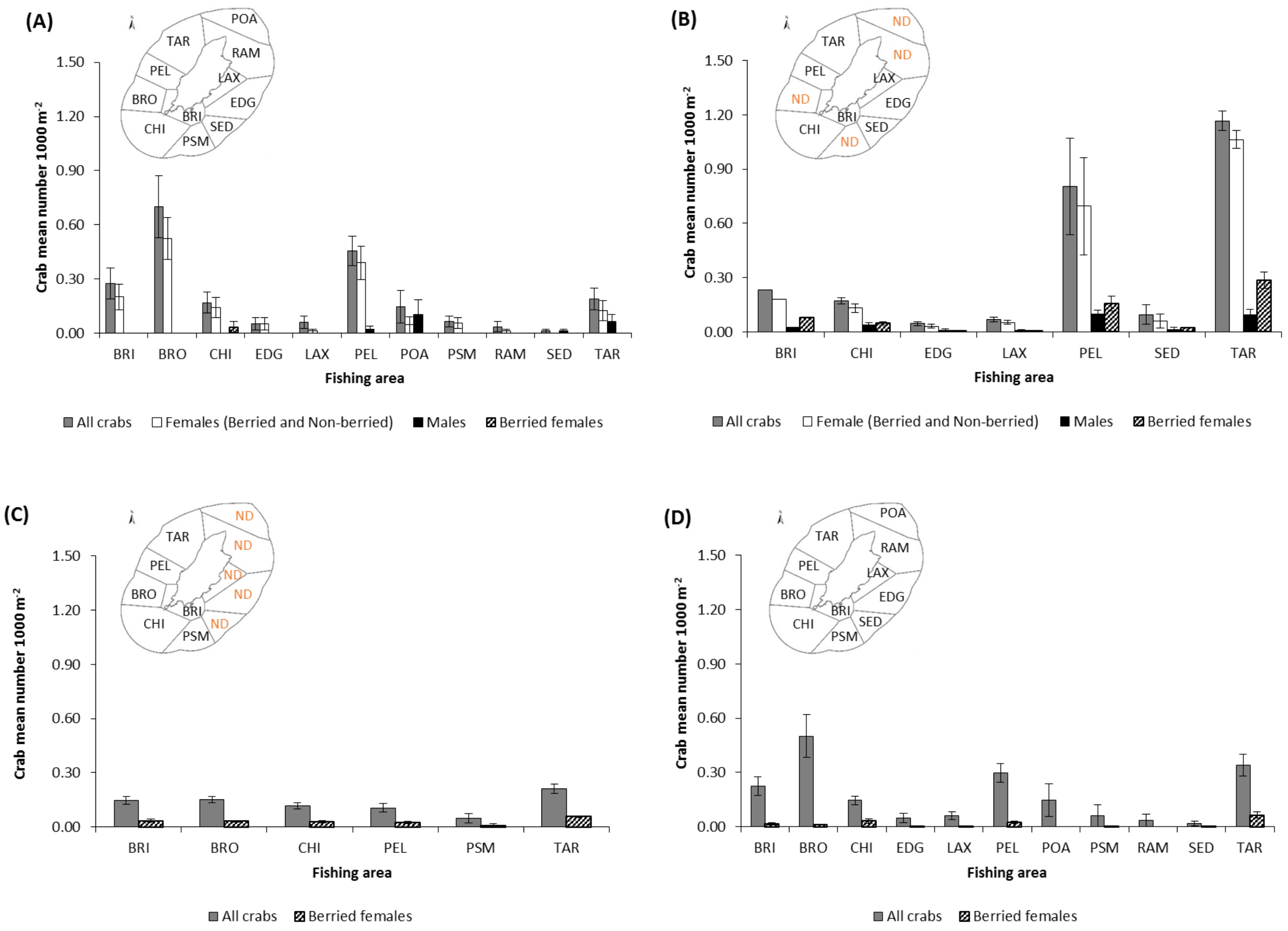

Figure 5.4. Spatial variation in density (mean number per 1000m^2 ±SE) of crab and berried females captured by; A) research boat (187 tow), B) direct observations (35 tow), C) fishermen forms (86 tow) and D) total (308 tow) king scallop during surveys on fishing grounds around the Isle of Man. For site codes see Figure 5.1. The abbreviation: ND; no data.

Seasonal patterns in crab distribution and catches

Results of Kruskal-Wallis test shows that the mean number of crabs caught as by-catch changed seasonally for the different sources of data (Table 5.4). When the different sources of data were considered together it appears that the catches of female crabs start to increase in the early autumn and peak in the late autumn/early winter. Catches of male crab were low throughout the year (Figure 5.5). In addition, table 5.5 shows details about the mean fishing effort (h) and mean crab number 1000m^{-2} in different fishing grounds during fishing season.

Table 5.4. Statistical tests (Kruskal-Wallis) for monthly variation in the mean crab number per 1000 m^{-2} estimated from three different survey types in the Isle of Man.

Source	df	Chi-square of all crabs	*P*-value of all crabs	Chi-square of berried females	*P*-value of berried females
R.V. Prince Madog surveys	3	13.80	0.003	2.28	0.516
Direct observations with commercial boats	2	9.27	0.010	4.36	0.113
Fishermen’s forms	3	24.84	< 0.001	19.06	< 0.001
Pooled data	7	44.34	< 0.001	170.74	< 0.001

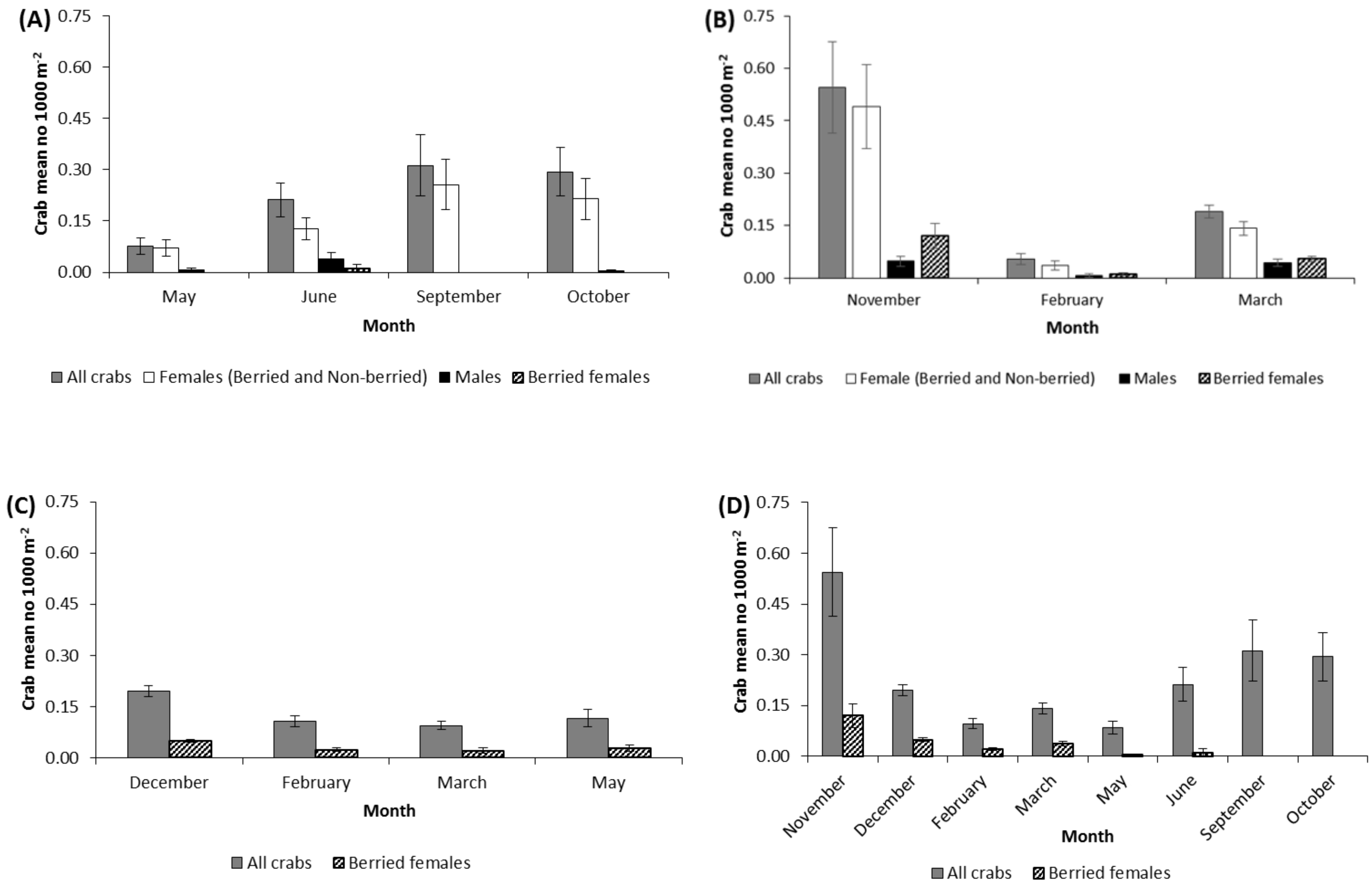

Figure 5.5. Seasonal variation in density (mean number per $1000m^2$ ±SE) of crab and berried females which came from different data sources; A) research vessel (187 tows), B) direct observations on board fishing vessels (35 tows), C) fishermen's forms (86 tows) and D) combined surveys (total 308 tows) during the entire study on fishing grounds around the Isle of Man.

Table 5.5. Spatial and temporal information of mean tow time (h) of scallop dredging in the Isle of Man for the 6 years pooled data for the period 2008-2013. The data was obtained from the vessel monitoring system (VMS). Spatial and temporal information of mean crab no 1000m^{-2} and no of total tow which were calculated using the different sources of observations (fishery independent data based on direct observations of crab catches on the research vessel, observations made onboard scallop dredgers).

		Fishing Season						
Area	**Characteristic**	November	December	January	February	March	April	May
BRI	Mean fishing effort (h)	188	169	163	170	235	193	154
	Mean crab no. 1000m^{-2}	ND	0.237	ND	0.109	0.233	ND	0.203
	No. of tows	0	4	0	9	1	0	6
BRO	Mean fishing effort (h)	34	33	59	25	33	22	17
	Mean crab no. 1000m^{-2}	ND	0.153	ND	ND	ND	ND	0.129
	No. of tows	0	11	0	0	0	0	6
CHI	Mean fishing effort (h)	334	316	265	231	322	217	167
	Mean crab no. 1000m^{-2}	ND	ND	ND	ND	0.131	ND	0.089
	No. of tows	0	0	0	0	17	0	19
EDG	Mean fishing effort (h)	174	175	149	107	171	117	67
	Mean crab no. 1000m^{-2}	0.085	ND	ND	0.038	ND	ND	0
	No. of tows	1	0	0	5	0	0	6

Table 5.5 continue. Spatial and temporal information of mean tow time (h) of scallop dredging in the Isle of Man for the 6 years pooled data for the period 2008-2013. The data was obtained from the vessel monitoring system (VMS). Spatial and temporal information of mean crab no 1000m^{-2} and no of total tow which were calculated using the different sources of observations (fishery independent data based on direct observations of crab catches on the research vessel, observations made onboard scallop dredgers).

		Fishing Season						
Area	**Characteristic**	November	December	January	February	March	April	May
LAX	Mean fishing effort (h)	90	147	107	68	116	72	81
	Mean crab no. 1000m^{-2}	0.067	ND	ND	ND	ND	ND	0
	No. of tows	9	0	0	0	0	0	6
PEL	Mean fishing effort (h)	123	59	116	96	81	29	22
	Mean crab no. 1000m^{-2}	1.062	ND	ND	0.106	0.289	ND	0.312
	No. of tows	2	0	0	21	1	0	3
POA	Mean fishing effort (h)	44	35	71	38	34	57	17
	Mean crab no. 1000m^{-2}	ND	ND	ND	ND	ND	ND	0
	No. of tows	0	0	0	0	0	0	3
PSM	Mean fishing effort (h)	38	49	135	150	321	243	213
	Mean crab no. 1000m^{-2}	ND	ND	ND	ND	0.085	ND	0.055
	No. of tows	0	0	0	0	1	0	8

Table 5.5 continue. Spatial and temporal information of mean tow time (h) of scallop dredging in the Isle of Man for the 6 years pooled data for the period 2008-2013. The data was obtained from the vessel monitoring system (VMS). Spatial and temporal information of mean crab no 1000m^{-2} and no of total tow which were calculated using the different sources of observations (fishery independent data based on direct observations of crab catches on the research vessel, observations made onboard scallop dredgers).

		Fishing Season						
Area	**Characteristic**	November	December	January	February	March	April	May
RAM	Mean fishing effort (h)	39	25	14	11	15	13	8
	Mean crab no. 1000m^{-2}	ND	ND	ND	ND	ND	ND	0
	No. of tows	0	0	0	0	0	0	6
SED	Mean fishing effort (h)	65	238	130	134	105	120	29
	Mean crab no. 1000m^{-2}	ND	ND	ND	0.097	ND	ND	0
	No. of tows	0	0	0	2	0	0	6
TAR	Mean fishing effort (h)	507	164	171	119	55	44	11
	Mean crab no. 1000m^{-2}	1.166	0.212	ND	ND	ND	ND	0.218
	No. of tows	6	16	0	0	0	0	6

Limb loss, damage and mortality

A total of 574 *C. pagurus* specimens were examined to determine differences of damage levels from dredge surveys. For the animals that were examined, 31% of the crabs were intact, and 34% and 24% of all crabs had carapace and abdomen damage respectively. In addition, 55% of all crabs had missing limbs. The ratios of each pair of limbs missing were, in general, bilaterally symmetrical for the 3rd and 5th pereipods (Table 5.6). In general, all limbs were equally vulnerable to loss as a result of dredging (chi-square = 0.204, P = 0.98).

Table 5.6. Percentage of *C. pagurus* with missing appendages (Chela and P2-5: pereiopod 2-5) and carapace damage (CD) and abdomen damage (AD) (n = number of individuals)

n	Intact	CD	AD	Percentage of appendages missing					
574	31%	34%	24%	Position	P1 (Chela)	P2	P3	P4	P5
				Right	13%	11%	13%	17%	17%
				Left	15%	12%	13%	18%	17%

Thirty percent of collected crabs were recorded as a crushed or dead. There was no significant difference between females and males, and between berried and non-berried females and the damage level sustained (Table 5.7, 5.8). There was no correlation between the mean damage score and in crab body size (CW) (rho = 0.06, P = 0.181). However, there was a statistically significant relationship between moult stage and damage level (Table 5.9) such that crabs with a softer or less thick shell sustained greater levels of damage. The mean damage score was determined as 2.5 (± 0.1 SE).

Table 5.7. Mean damage level for male and female crabs (n = number of individuals; SE = Standard error; U = value of the Mann-Whitney U-test; X^2 = chi-square from Kruskal-Wallis test; P = significant level).

Sex	*n*	Mean damage level	Median	±SE	U	X^2	df	*P*
Combined	541	2.36	2	0.05				
Females	481	2.39	2	0.06	13130.50	1.396	1	0.237
Males	60	2.17	2	0.14				

Table 5.8. Mean damage level was determined for berried and non-berried females (n = number of individuals; SE = Standard error; U = value of the Mann-Whitney U-test; P = significance level)

Egg bearing	*n*	Mean damage level	Median	±SE	U	*P*
Berried	102	2.49	2	0.12	15416.00	0.379
Non-berried	320	2.38	2	0.07		

Table 5.9. Mean damage level was determined for soft and hard crabs (n = number of individuals; SE = Standard error; U = value of the Mann-Whitney U-test; P = significance level)

Moult Stage	*n*	Mean damage level	Median	±SE	U	*P*
Soft	44	2.91	2	0.18	6554.00	0.005
Hard	396	2.35	2	0.06		

Mortality estimates of crabs in the catches

Table 5.10 shows the mortality estimates of brown crabs in 11 fishing grounds during fishing season (7 month). However, this table also included cells for which there were no observations of crab by-catch. In other words, in the worst case scenario, the estimations in current study may only represent 33.8 % of total catches. The highest crab by-catch estimations were found in November around Targets. The predicted crab by-catch generally decreased in May (last month of fishing season) for many fishing grounds. When the lowest and highest estimate of possible crab by-catch (10 or 16 dredges) is considered, approximately 23 or 37 tonnes crab were caught of which 45% (level 3 and 4 damage) would be killed. This would result in an estimated crab by-catch mortality of c.11 or 17 tonnes per annum (= 2.2 - 3.4% of total commercial catches).

Table 5.10. Mortality estimates of crabs in the catches assuming 100% and 45% mortality based on 10 and 16 dredges (upper and lower limits) in 11 fishing grounds during the fishing season. The data include both number of crab by-catch (N) and estimated weight (W(t)).

		Fishing Season													
		November		**December**		**January**		**February**		**March**		**April**		**May**	
Area	**Characteristic**	**N**	**W (t)**	**N**	**W (t)**	**N**	**W (t)**	**N**	**W (t)**	**N**	**W (t)**	**N**	**W (t)**	**N**	**W (t)**
BRI	10 dredges, 100%	ND	ND	1409	0.86	ND	ND	652	0.4	1927	1.18	ND	ND	1100	0.67
	10 dredges, 45%	ND	ND	634	0.39	ND	ND	293	0.18	867	0.53	ND	ND	495	0.3
	16 dredges, 100%	ND	ND	2255	1.38	ND	ND	1043	0.64	3083	1.88	ND	ND	1760	1.07
	16 dredges, 45%	ND	ND	1015	0.62	ND	ND	469	0.29	1387	0.85	ND	ND	792	0.48
BRO	10 dredges, 100%	ND	ND	178	0.11	ND	ND	ND	ND	ND	ND	ND	ND	77	0.05
	10 dredges, 45%	ND	ND	80	0.05	ND	ND	ND	ND	ND	ND	ND	ND	35	0.02
	16 dredges, 100%	ND	ND	284	0.17	ND	ND	ND	ND	ND	ND	ND	ND	123	0.08
	16 dredges, 45%	ND	ND	128	0.08	ND	ND	ND	ND	ND	ND	ND	ND	56	0.03
CHI	10 dredges, 100%	ND	ND	ND	ND	ND	ND	ND	ND	1484	0.91	ND	ND	523	0.32
	10 dredges, 45%	ND	ND	ND	ND	ND	ND	ND	ND	668	0.41	ND	ND	235	0.14
	16 dredges, 100%	ND	ND	ND	ND	ND	ND	ND	ND	2375	1.45	ND	ND	837	0.51
	16 dredges, 45%	ND	ND	ND	ND	ND	ND	ND	ND	1069	0.65	ND	ND	377	0.23
EDG	10 dredges, 100%	520	0.32	ND	ND	ND	ND	143	0.09	ND	ND	ND	ND	0	0
	10 dredges, 45%	234	0.14	ND	ND	ND	ND	64	0.04	ND	ND	ND	ND	0	0
	16 dredges, 100%	833	0.51	ND	ND	ND	ND	229	0.14	ND	ND	ND	ND	0	0
	16 dredges, 45%	375	0.23	ND	ND	ND	ND	103	0.06	ND	ND	ND	ND	0	0

Table 5.10 continued. Mortality estimates of crabs in the catches assuming 100% and 45% mortality based on 10 and 16 dredges (upper and lower levels) in 11 fishing grounds during the fishing season. The data include both number of crab by-catch (N) and estimated weight (W(t)).

		Fishing Season													
		November		December		January		February		March		April		May	
Area	Characteristic	N	W (t)	N	W (t)	N	W (t)	N	W (t)	N	W (t)	N	W (t)	N	W (t)
LAX	10 dredges, 100%	212	0.13	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	0	0
	10 dredges, 45%	95	0.06	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	0	0
	16 dredges, 100%	339	0.21	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	0	0
	16 dredges, 45%	153	0.09	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	0	0
PEL	10 dredges, 100%	4596	2.8	ND	ND	ND	ND	358	0.22	824	0.5	ND	ND	242	0.15
	10 dredges, 45%	2068	1.26	ND	ND	ND	ND	161	0.1	371	0.23	ND	ND	109	0.07
	16 dredges, 100%	7354	4.49	ND	ND	ND	ND	573	0.35	1318	0.8	ND	ND	386	0.24
	16 dredges, 45%	3309	2.02	ND	ND	ND	ND	258	0.16	593	0.36	ND	ND	174	0.11
POA	10 dredges, 100%	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	0	0
	10 dredges, 45%	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	0	0
	16 dredges, 100%	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	0	0
	16 dredges, 45%	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	0	0
PSM	10 dredges, 100%	ND	ND	ND	ND	ND	ND	ND	ND	960	0.59	ND	ND	412	0.25
	10 dredges, 45%	ND	ND	ND	ND	ND	ND	ND	ND	432	0.26	ND	ND	186	0.11
	16 dredges, 100%	ND	ND	ND	ND	ND	ND	ND	ND	1536	0.94	ND	ND	660	0.4
	16 dredges, 45%	ND	ND	ND	ND	ND	ND	ND	ND	691	0.42	ND	ND	297	0.18
RAM	10 dredges, 100%	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	0	0
	10 dredges, 45%	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	0	0
	16 dredges, 100%	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	0	0
	16 dredges, 45%	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	0	0

Table 5.10 continue. Mortality estimates of crabs in the catches assuming 100% and 45% mortality based on 10 and 16 dredges (upper and lower levels) in 11 fishing grounds during the fishing season. The data include both number of crab by-catch (N) and estimated weight (W(t)).

		Fishing Season													
		November		December		January		February		March		April		May	
Area	**Characteristic**	**N**	**W (t)**	**N**	**W (t)**	**N**	**W (t)**	**N**	**W (t)**	**N**	**W (t)**	**N**	**W (t)**	**N**	**W (t)**
SED	10 dredges, 100%	ND	ND	ND	ND	ND	ND	457	0.28	ND	ND	ND	ND	0	0
	10 dredges, 45%	ND	ND	ND	ND	ND	ND	206	0.13	ND	ND	ND	ND	0	0
	16 dredges, 100%	ND	ND	ND	ND	ND	ND	732	0.45	ND	ND	ND	ND	0	0
	16 dredges, 45%	ND	ND	ND	ND	ND	ND	329	0.2	ND	ND	ND	ND	0	0
TAR	10 dredges, 100%	20802	12.69	1223	0.75	ND	ND	ND	ND	ND	ND	ND	ND	84	0.05
	10 dredges, 45%	9361	5.71	551	0.34	ND	ND	ND	ND	ND	ND	ND	ND	38	0.02
	16 dredges, 100%	33283	20.3	1957	1.19	ND	ND	ND	ND	ND	ND	ND	ND	135	0.08
	16 dredges, 45%	14977	9.14	881	0.54	ND	ND	ND	ND	ND	ND	ND	ND	61	0.04

5.5 Discussion

The results of this study demonstrated that crab catch rates were considerably higher in dredges compared to otter trawls. Otter trawling for queen scallops only occurs in the summer which coincides with the king scallop closed season. Thus scallop dredging is most intense in the winter period when female crabs are to be caught in elevated numbers to the west of the Isle of Man. Similarly, Kaiser et al. (1996) reported that this species was caught more often by scallop dredges rather than in a beam trawl. The capture frequency of *C. pagurus* per tow in the Isle of Man queen scallop trawl fishery was found to be 0.29 crab/tow (Duncan, 2009), whilst a similar catch rate of 0.70 crab/tow was found in the present study. The different catchabilities for edible crabs for each type of gear no doubt relates to different modes of operation. The teeth on the scallop dredges are more likely to dig out crabs that are buried in the sediment, whereas both beam and otter trawls are more likely to catch only those crabs that are active on the surface of the seabed. Furthermore, the otter trawl fishery in the Isle of Man is subject to a dawn – dusk curfew which avoids the period when edible crabs are most active, i.e. at night (Skajaa et al., 1998).

Migration, spatial and seasonal patterns

Numerous studies have examined the movement and migration of brown crab in northern Europe (Williamson, 1900; Meek, 1913; Mistakidis, 1960; Mason, 1962; Gundersen, 1976, 1977; Edwards, 1979; Bennett and Brown, 1983; Latrouite and Le Foll, 1989; Hall et al., 1991; Skajaa et al., 1998; Ungfors et al., 2007). Previous studies reported that *C. pagurus* exhibited a seasonal migration between inshore and offshore areas; in the spring they move inshore, while in the autumn they move into deeper and warmer offshore areas (Pearson, 1908; Meek, 1913; Edwards, 1979; Nichols et al., 1982; Ungfors et al., 2007, 2008). Furthermore, adult females tended to migrate longer distances than males and immature females (Bennett and Brown, 1983; Latrouite and Le Foll, 1989; Edwards, 1979; Pawson, 1995; Skajaa et al., 1998; Ungfors, 2007, 2008; Bannister, 2009). Due to the annual offshore/inshore migration of brown crab, a large portion of those caught in autumn consist of large female crabs in the English Channel (Brown and Bennett, 1980). Nevertheless, these studies are based largely on trap based sampling which has the problem that only those crabs that are actively feeding will be sampled by this technique. The current study therefore provides additional observations that give insights in to the distribution of crabs that do not depend on trap dependent data.

In the current study, in terms of gender 84% were female and 11% were male. This sex bias may be related to habitat preferences exhibited by the different sexes, their migration activities and fishing season. For example, a relatively large number of crabs were collected around the west coasts of island and according to White (2011) these areas are characterized by sand and sand-mud sediments which is the sediment type in which berried females prefer to bury themselves (Woll, 2003). The number of crabs caught in commercial dredges peaked in November which concurs with the observations of Veale et al. (2001) who reported that, brown crabs are more abundant in dredges in October than June in Manx waters.

With respect to the spatial distribution of brown crab, in the current study the highest catches were recorded around the west coasts of island (BRO, TAR and PEL), while the lower catch records were determined around the south and east coasts (Figure 5.4, Table 5.10). More importantly, berried females exhibited the high abundance around TAR, CHI and PEL in comparison with other fishing areas, and they were not recorded in the northern fishing grounds RAM and POA. These observations of the distribution and timing of catches of female crabs indicated that post-mated female crabs move into deeper water to the west of the Isle of Man during the early to late Autumn.

Limb loss, damage and mortality

Like many decapod crustaceans, limb loss of *C. pagurus* may occur owing to physical contact with fishing gear, stress during the fishing operation or interactions with other species (e.g. autotomy). Not surprisingly, the significant difference were found between the limb loss ratio in scallop dredges and pots (Table 5.11). The most likely explanation for the observed limb loss and damage to *C.pagurus* in dredge is the mechanical trauma that occurs from direct contact with the gear and the catch contents. In contrast, for crustacean retained in pots interactions between other species are the most likely explanatory factor of limb loss.

A lack of melanisation indicated recent loss or damage. Again, for the pot fishery, old wounds with melanisation were also noted as this would indicate older wounds or past limb loss c.f. more recent injuries.

Table 5.11. Limb loss prevalence of *C. pagurus* taken by commercial pot and scallop dredge. When evaluating limb loss due to pot fishery, old wounds with melanisation were noted as this would indicate older wounds or past limb loss, whilst for the dredge operations, only new wounds with no melanisation were noted.

Pot fishery		Dredge fishery	
Limb loss ratio	*n*	Limb loss ratio	*n*
23 %	960	55 %	574

*Pearson Chi-square = 157.156[a], $P < 0.001$

However, the appendages of decapod crustaceans play a crucial role for some of their activities (e.g. feeding, walking, burrowing, swimming, mate protection and sensory reception) (Mariappan et al., 2000; Tallack, 2002). In case of limb loss, growth rate of decapods is reduced and intermoult duration is extended (Bennett, 1973; Bennett 1995; Juanes and Smith, 1995). In addition, limb damage causes a negative effect on foraging efficiency, prey handling and mating success (Mariappan et al., 2000; Patterson et al., 2009). In particular, the loss of chelipeds reduces efficiency in capturing hard and large size prey and this may result in alterations in diet (Bender, 1971; Juanes and Hartwick 1990; Smith and Hines 1991; Juanes and Smith, 1995). In order to regenerate chelipeds energy may be diverted away from reproduction and growth (Mariappan et al., 2000). On the other hand, owing to damage or limb loss in decapod crustaceans that exhibits high vulnerability to their predators and agonistic individuals (Juanes and Smith, 1995; Mariappan et al., 2000; Bergman and Moore, 2001).

The present study demonstrates the proportions of 4 damage levels. Among them, the most frequent damage was of level 1 (a good condition), while level 2 (leg missing) and level 3 (carapace and abdomen cracks) exhibited 24% and 15% respectively. Moreover, 30% of crabs exhibited level 4 (crushed and dead crabs) (Figure 5.6). Based on these results it may be reasonable to assume that 31% of crabs in the by-catch survive (level 1) while 45% (level 3 + 4) have a high probability of death or die as a result of capture in dredges.

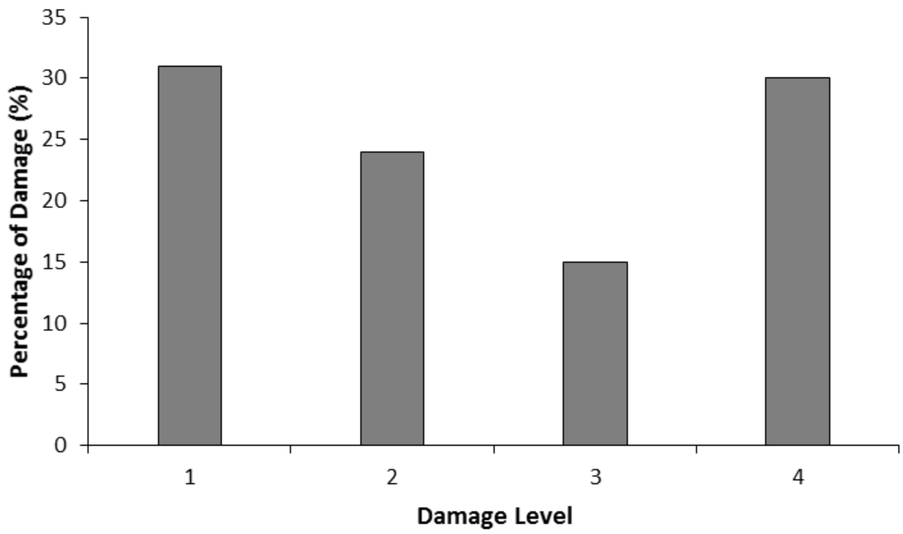

Figure 5.6. The proportions of the 4 damage levels (*n* = 574). Damage levels; 1) no visible damage to external structure, 2) Legs missing, 3) Major carapace or abdomen cracks, and 4) Crushed or dead.

Missing or damaged limbs frequently result in low survival rates (McVean and Findlay, 1979; Kennelly et al., 1990; Juanes and Smith, 1995; Bergman and Moore, 2001). The percentage of crabs that survive the loss of one cheliped was approximately 30-50% (Mistakidis, 1959; Tallack, 2002). Another example is that of the *Liocarcinus* spp. Where individuals that exhibited damaged carapace and/or >50% limb loss died within 2 days after the trawl operation (Kaiser and Spencer, 1995). Veale et al. (2001) used post-capture laboratory observations and reported that 18% of severely injured (major carapace cracks) *C. pagurus* died. Nevertheless, other species of crab have been reported to have high post-capture mortality as a result of capture in towed fishing gear such as trawls and dredges (Stevens, 1990; Bergman and Moore, 2001; Stoner et al., 2008; Stoner, 2012). In addition to the mortality of crabs landed on deck as part of the by-catch, additional incidental mortality also occurs for those individuals that are in contact with fishing gear but that remain on the seabed (Jenkins et al., 2001).

The catch by the dredge fishery in comparison with the commercial crab fleet

In the Isle of Man, around 50 to 100 vessels are likely to fish king scallop (Hanley et al., 2012). Fishing effort in the king scallop fishery consistently has the highest values in November (when crab by-catch appears to be highest), whilst the smallest values are generally found in May (Appendix 5.2). This study indicates that the lower and upper estimate of possible crab by-catch assuming 45% mortality are 11t and 17t per annum. The amount of by-catch was spatially variable and highest off the west coast of the Isle of Man (particularly Targets) in November. Given commercial landings of crab by the pot fleet amounted to 495t in 2012 the estimated by-catch mortality of brown crab associated with scallop fishing may range from 2.2 to 3.4 percent of commercial landings of crab.

5.6 Conclusions

This study shows the impact of scallop dredges on the brown crab population by spatial and seasonal trends. Late summer-early autumn female crabs migrate to the offshore areas. Thus, especially female crabs (both berried and non-berried individuals) are threatened by scallop dredges around the North-West coast of the island (Targets) in November. For the same area and period, the fishing effort of scallop dredges peaked according to the VMS data (Appendix 5.2). Similarly, according to commercial crab catches data, female crabs are abundant in autumn in offshore areas (Chapter 2). However, soft crabs and berried females are not captured in the Isle of Man pot fishery. Even, berried individuals rarely enter the pots (Chapter 4).

This study suggests that extending the scallop dredging closed season to the end of November to the west of the Isle of Man would afford protection for female crabs that have moved into offshore deeper water at a critical point in their reproductive cycle. Opening the scallop dredging closed season at the beginning of December would also coincide with the peak in scallop sales value prior to the Christmas period.

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CHAPTER 6 - FISH AND INVERTEBRATES BY-CATCH IN THE CRAB POT FISHERY IN THE ISLE OF MAN

6.1 Abstract

This study aimed to determine non-target fish and invertebrate species composition in crustacean pots and to assess spatial and temporal differences in catches in the waters around the Isle of Man. The data were collected using fishery independent surveys and a questionnaire study. The results indicated that a total of 5 taxonomic groups and 43 by-catch species were found. The dominant by-catch species was velvet crab *Necora puber*. This study also showed that the IUCN red list species, classified as vulnerable (cod *Gadus morhua*, haddock *Melanogrammus aeglefinus*) and near threatened (edible sea urchin *Echinus esculentus*), were found in pots. Moreover, four by-catch species (common whelk *Buccinum undatum*, small spotted catshark *Scyliorhinus canicula*, ballan wrasse *Labrus bergylta* and European conger *Conger conger*) were generally kept by fishermen as bait or for commercial sale. Some damaged individuals of sessile species such as dead's man finger *Alcyonium digitatum*, snakelocks anemone *Anemonia viridis* and sea chervil *Alcyonidium diaphanum* were rarely found in the pots due to "dragging". The catch per unit effort for all of the bycatch species was low particularly in comparison to towed bottom gear fisheries around the Isle of Man. CPUE of by-catch composition showed spatial variations. Both results of fishery independent data and questionnaire study suggested that the by-catch rates varied during the seasons with a peak in spring which declined into autumn and winter. The by-catch composition did not decrease significantly with an increasing target species catch. Additionally, there was a negative correlation between crab and lobster catches. In conclusion, crustacean pots were determined to be selective gears due to use of escape gaps in this fishery.

Keywords: by-catch, crustacean pot fishery, Isle of Man, Irish Sea

6.2 Introduction

By-catch, the incidental capture of non-target species in fishing gear, has become a major issue in global fisheries management and conservation for the last 30 years (Kelleher, 2005; Soykan et al., 2008). By-catch can also include under-sized individuals of the target species that must be returned to the sea. By-catch mortality is of most concern for organisms that have slow growth (late maturity) and low reproductive rates (Hall et al., 2000; Soykan et al., 2008). Such organisms are typically defined as endangered, vulnerable or threatened species and include fish, birds, reptile and mammals (Dayton et al., 1995; Zollett, 2009; Harden and Williiard, 2012; IUCN, 2015). The issues related to the by-catch composition of mobile fishing gears (e.g. trawls and dredges) and some static gears such as long-lines are well studied (Auster and Langton, 1999; Kelleher, 2005; Lokkeborg, 2005). In contrast, trap fisheries have been little studied to date in relation to by-catch due to the general perception that the environmental effects of these fisheries is minor compared to other fishing gears (Eno et al., 1996; Eno et al., 2001). However, in Europe, there is now a move to ban discards of target species and as such it will be necessary for all fisheries to quantify and report their by-catches. For this reason there is an urgent need to gather evidence on the by-catch associated with pot fisheries in the UK and more widely in Europe. In particular, it is important to report the catch amounts of endangered and quota species. Based on reports of target and non-target (commercial and non-commercial) species' catch amounts in crustacean pots, the seasonal or regional closures or pot limitation may be considered to provide more sustainable fisheries management.

Pots are one of the most commonly used fishing gears in the British Isles to catch brown crab *Cancer pagurus,* European lobster *Homarus gammarus* and common whelk *Buccinum undatum* (Gray, 1995; Eno et al., 2001). Pots are generally assumed to be environmentally friendly fishing gears due to their associated low energy use, low habitat impact (e.g. Eno et al. 2001; Coleman et al. 2013), high selectivity (in terms of species and size) and high rate of live by-catch (Jennings and Kaiser, 1998; Furevik et al., 2008). However, the loss of pots due to bad weather or interactions with other fisheries can lead to "ghost fishing" and additional mortality for some species (Jennings and Kaiser, 1998; Bullimore et al., 2001; Kaiser and Jennings, 2002; Kaiser, 2014). Additionally, pots and traps can damage the some sessile organisms such as corals and sponges and benthic habitats (Jenkins and Garrison, 2013).

Previous studies have shown that survey design (e.g. fishery dependent or fishery independent surveys), environmental factors (e.g. season, fishing areas, substratum type, animal behaviour) and fishery-specific factors (e.g. pot design, soak time) can affect the estimated by-catch rate in pots and traps (Roosenburg and Green, 2000; Brock et al., 2007; Butler and Heinrich, 2007; Hart and Crowder, 2011; Harden and Williard, 2012; Page et al., 2013). Hence these factors are important considerations when attempting to estimate the losses associated with by-catch in pot fisheries. Mitigation measures that reduce by-catch can be effective, such as the introduction of escape panels that allow undersized individuals and other species to leave pots (Brown, 1982; Frusher and Gibson, 1998). Seasonal closures can also be used to alleviate the incidence of by-catch (Pascoe, 1997; Harden and Williard, 2012; Lewison et al., 2013). Both measure require quantification of their effectiveness prior to implementation.

The present study focused on the Isle of Man pot fishery for which little information exists on composition of catches. In the Isle of Man, brown crab *Cancer pagurus*, and European lobster *Homarus gammarus* are targeted using the same pot gear. Landings of both brown crab and European lobster have increased markedly over the last 20 years (crab landing has risen from 52t in 1994 to 453 t in 2013, whereas lobster landing has risen from 3 t in 1993 to 41 t in 2013) (FAO, 2015). The pot fishing occurs around most of the island within 3 nm (with the possible exception of the NE coast), and out to the territorial sea boundary (12 nm) off the central-west and southwest coasts. The minimum landing size of brown crab and European lobster are 130 mm carapace width and 87 mm carapace length respectively. Pots are fitted with escape gaps (80 mm wide x 45 mm high) to reduce catches of undersized individuals. The typical soak time is 1 or 2 days but can be longer during periods of poor weather. There are no spatial or seasonal closures in the Isle of Man pot fishery.

The goals of the present study were (1) to determine non-target fish and invertebrate species composition in the Isle of Man pot fishery, (2) to quantify patterns in the spatial and temporal catch of these non-target species, and (3) to highlight catches of species of conservation importance or those that might be relevant to the EU landings obligation.

6.3 Materials and Methods

By-catch composition using fishery independent data (FID)

Fishery independent surveys were conducted between spring 2012 and summer 2013 on the main fishing grounds for the brown crab around the Isle of Man, Irish Sea (Figure 6.1 a, b). In some seasons, the extent of the area over which fishing occurred was reduced due to limited fishing activity and bad weather. The hauled pot numbers were 184, 685, 660, 316, 136 and 508 respectively in each of the sampling seasons. Around the north coast of the island there were no active fishermen which is in part related to the unsuitable tidal conditions for the use of traps. To provide spatial and temporal comparisons of catch ratio, data were standardised to reporting areas of c. 75 km^2 using the grid squares, which subdivide the 37E5 (ICES) rectangle (Figure 6.1b). Individual fishing locations were recorded from the GPS systems of the fishing vessels used during the surveys. Commercial fishing pots, which were fitted with mandatory escape gaps, were lifted across depths ranging between 2 m and 65 m. Soak time varied from 24 hours to 288 hours and pots were mainly baited with small-spotted catshark, cod, haddock, herring and pollack.

During the field work, both target and non-target species were quantified aboard the fishing vessels during 12 sampling trips. All by-catch species were identified (to species level when possible). Lobster and brown crabs were not counted as part of the by-catch. Subsamples of bycatch species were collected in order to assess their mean body-size. Animals were measured for their total length (fish), carapace length or width (crabs), carapace length with rostrum (lobsters), total shell length (gastropods and bivalves), mantle length (cephalopods) and diameter (echinoderms) (Tonks et al., 2008). According to the mean body size, animals were classified into 2 classes. Animals that were bigger than the pot mesh size (45 mm), were categorised as “by-catch species”, whilst animals that were smaller than mesh size, were categorised as “incidental species”. Incidental species sometimes occurred both inside and outside the pots.

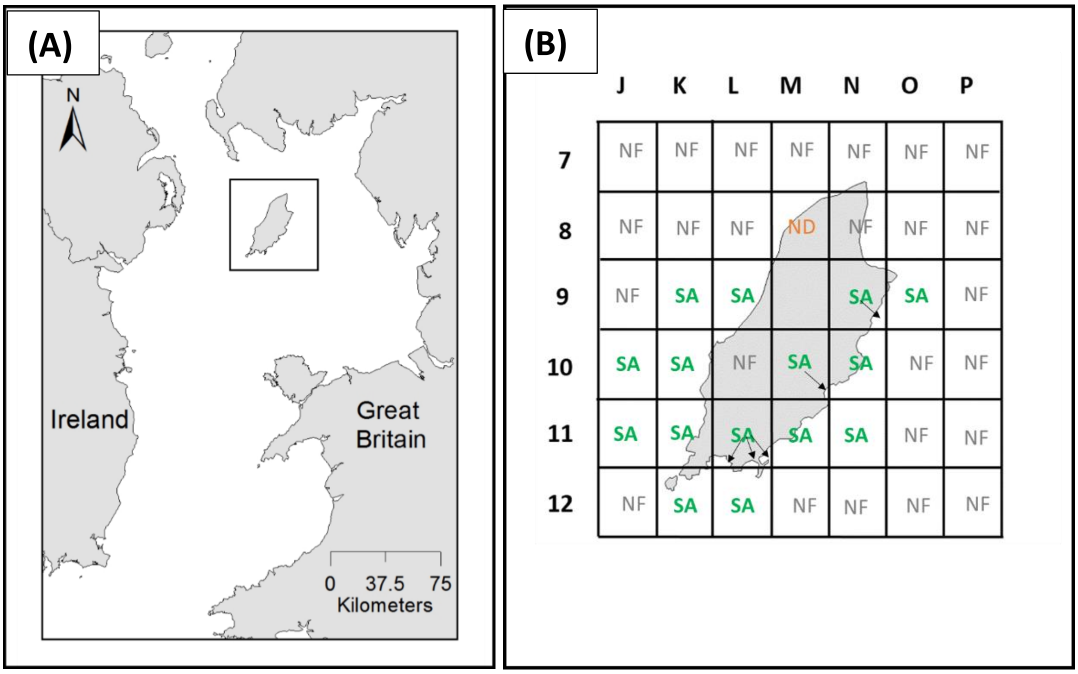


Figure 6.1. A, location of the Isle of Man in the northern Irish Sea (ICES subdivision VII A). B, study area subdivided into 42 areas of approximately 75 km² with reference grid. Grid showing alpha-numeric coordinates for ICES statistical rectangle 37E5. The abbreviation: NF; no commercial fishing using pot gear, ND; no data, SA; sampling area. The no-fishing areas were defined from the questionnaire study undertaken by Whiteley (2009) and DEFA (2013).

Local ecological knowledge (LEK)

Local ecological knowledge (LEK) was collected through the use of face-to-face questionnaires in July 2013. Interviews were undertaken with fishermen that were owners of fishing vessels and that actively fished brown crab. A total of 10 interviews were conducted out of a population of 40% commercial pot fishers. The questionnaire aimed to gather basic information on by-catch composition in crustacean pot fisheries, and the seasonal patterns that might occur in the Isle of Man. The questionnaire form included both the common name of potential non-target species with photographs to aid identification.

Environmental data

In addition to the pot by-catch survey data and habitat data, marine environmental data for the year 2008 around the Isle of Man (Figure 6.1b) obtained from Bangor University (Murray et al., 2009; Lambert, 2011). The data included bottom water temperature, chlorophyll-a in the sediment, seasonal chlorophyll-a in the water column, sediment grain-size, kurtosis, PEA (potential energy anomaly) (Murray et al., 2009) and bed shear stress (Lambert, 2011). From these data-layers, the mean values of each of these environmental variables were calculated for each statistical areas defined in Figure 6.1b. Although there is a mismatch between the year in which these data layers were generated and the collection of the bycatch data, they represent the most comprehensive spatial data for the environmental variables.

Catch per unit effort (CPUE)

The catch of bycatch species per unit effort (CPUE) was calculated using equation 1 and standardised to numbers per 100 pots.

Equation 1: $CPUE = \frac{total\ individuals\ per\ string\ of\ pots}{total\ number\ of\ pots\ per\ string} \times 100$

Data analyses

Statistical analyses were carried out using Primer v.6, SPSS v.20 and STATA v.11. To test all data for normality and homogeneity of variance, a Kolmogorov-Smirnov K-S test and Levene's test were used respectively (Field, 2005; Becerra-Jurado et al., 2014) and either parametric or non-parametric tests were applied accordingly. Spatial and seasonal trends in the CPUE of by-catch species were examined using the Kruskal-Wallis test. A pairwise comparison technique was used to test for seasonal and spatial differences in the mean CPUE of the most abundant by-catch species. To test the effect of soak time a linear regression was used in order to test the relationship between CPUE of by-catch species and soak time. As lobsters and brown crab are predators, the number of these animals within a trap may determine the likelihood of trap entry of other incidentally caught species. A quantile regression (75th) was used to test the relationship between the number of crabs per pot and lobster per pot. A quantile regression (75th) was also used to test the relationship between the number of target species (crabs and lobsters) per pot and the total number of by-catch species per pot.

To understand patterns in the 'community' of animals retained in pots a multivariate analysis approach was used to examine similarities in catch composition with location. The mean CPUE of bycatch species per statistical area (averaged across seasons) was square root transformed and a resemblance matrix calculated using the Bray-Curtis index of similarity. The resemblance matrix was used to generate a dendrogram and MDS ordination plot to show the relative similarity between catch composition with location. The DIVERSE programme was used to calculate summary community metrics. Autocorrelation among environmental factors was checked using a draftsman's plot and if correlations of 0.95 were encountered, two of the variable (depth and bottom salinity) was eliminated from further analysis accordingly. The BEST analysis was used to explore which environmental variables contribute most to any patterns observed within the data. K-dominance curves were plotted for bycatches for inshore and offshore stations to see if patterns in bycatch composition differed for these two areas. For inshore areas, Spearman's rank correlation was used to test the relationships among mean bottom temperature (BT) and variables: sample size (n), number of species (S) and Shannon-Wiener diversity index (H'(loge)).

Bycatch species that might be of concern from a fisheries management and conservation perspective were ascertained by consulting the online IUCN red list catalogue. These species were highlighted in the analysis in addition to identifying those species that will become an important consideration under the data collection framework (DCF) of the European Commission.

6.4 Results

By-catch composition using fishery independent data (FID)

In total, 2489 pots were lifted from which a total of 17 fish species (220 specimens) and 26 invertebrate species (868 specimens) were caught (Figure 6.2a). The bycatch of Pisces accounted for the highest number of species and Crustacea was the most abundant group accounting for 55 % of the total number of animals retained by pots (Figure 6.2b). Velvet swimming crab (*Necora puber*) was the most commonly observed species, accounting for 34% in number of all by-catch species, and had a mean CPUE (±SE) of 17.56 ± 2.82 indiv. 100 pots^{-1}. Small spotted catshark *Scyliorhinus canicula* and squat lobster *Galathea* spp. were the next most commonly caught by-catch species, with a mean CPUE of 4.65 ± 1.41 and 4.58 ± 1.13 indiv.100 pots^{-1} respectively. Other invertebrate species (spiny starfish *Marthasterias glacialis*, European edible sea urchin *Echinus esculentus* and common starfish *Asterias rubens*) had lower mean CPUE values (Figure 6.3a). The most common fish species retained in the pot gear were determined as small-spotted catshark *Scyliorhinus canicula,* ballan wrasse *Labrus* *bergylta,* European conger *Conger conger,* butterfish *Pholis gunnellus,* pollack *Pollachius pollachius* and rockling *Gaidropsarus vulgaris* (Figure 6.3b).

Mean CPUE (±SE) of total by-catch was 46.50 ± 4.46 indiv. 100 pots^{-1}. The mean CPUE of by-catch was not significantly affected by soak time (Linear regression, r = 0.153, P = 0.12).

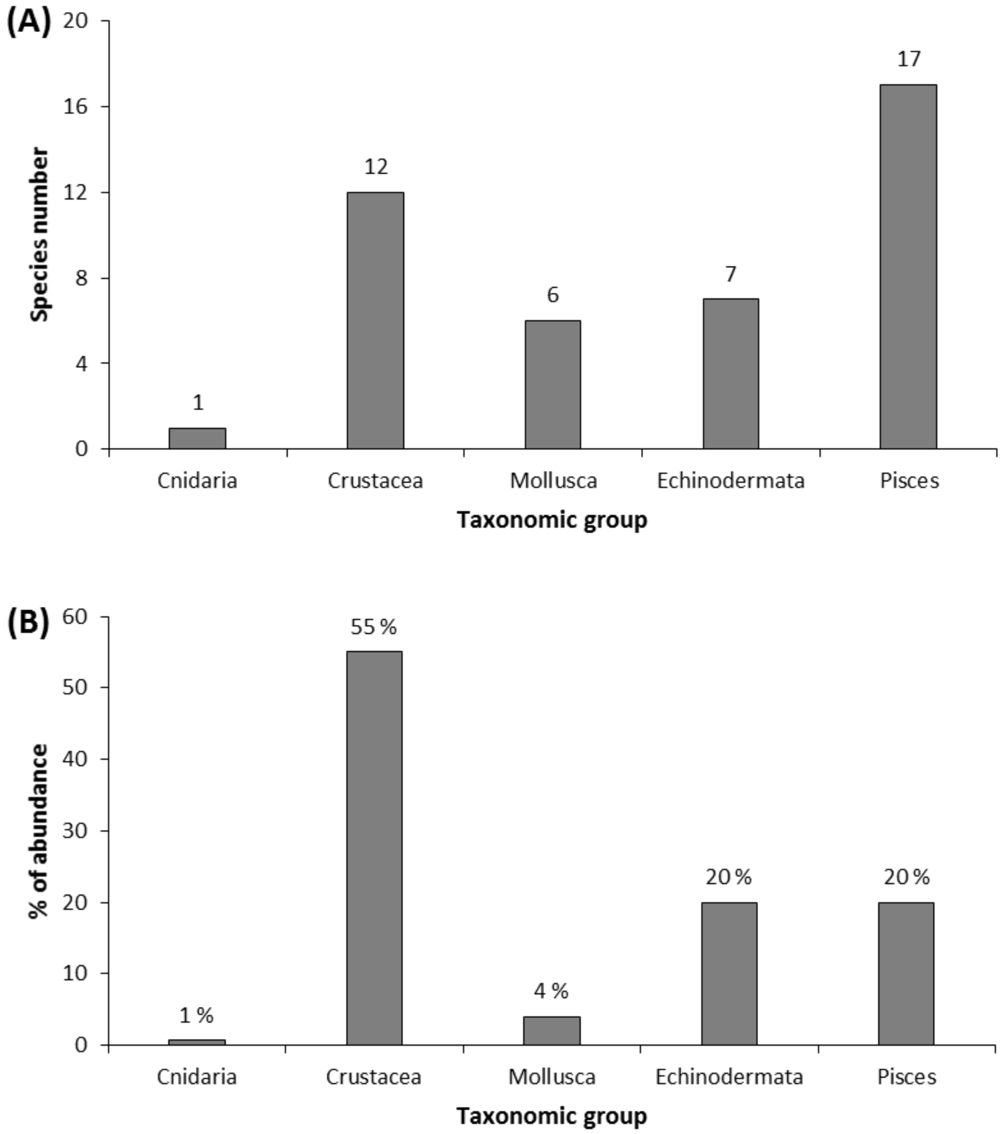
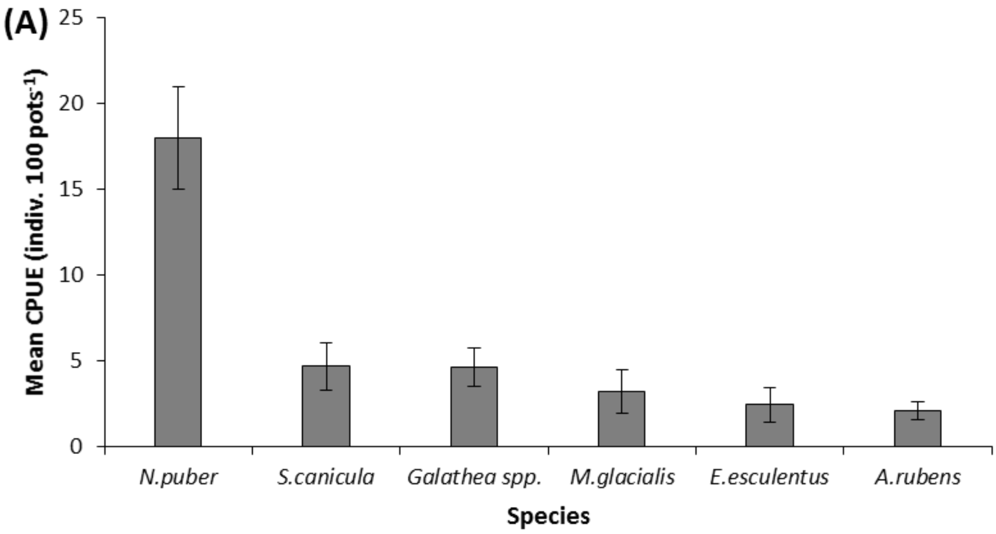


Figure 6.2. (A) By-catch composition by major taxonomic group and numbers of species, (B) % abundance of by-catch species according to their taxonomic groups.



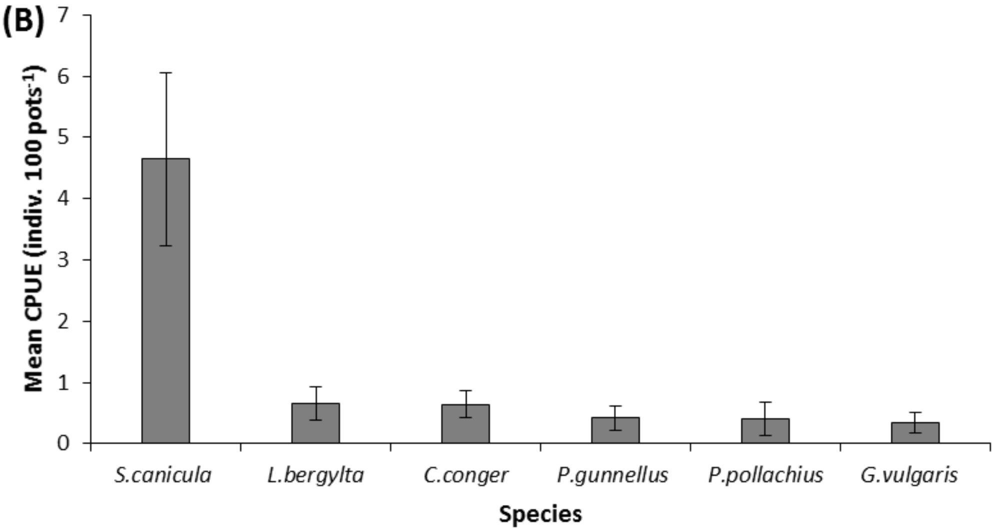


Figure 6.3. (A) Mean CPUE (± SE) of the six most abundant by-catch species (fish and invertebrates), (B) Mean CPUE (± SE) of the most six most abundant fish species.

Spatial variation

The mean CPUE of the total by-catch per pot differed significantly between statistical areas (Kruskal-Wallis, Chi-square = 26.65, df = 14, P = 0.02). The highest mean (± S.E.) CPUE was recorded in K11 with 135 ± 96 indiv. 100 pots^{-1}, whilst the lowest value was in M10 with 8 ± 8 indiv. 100 pots^{-1} (Figure 6.4).

The dendrogram and MDS shown in Figure 6.5 illustrates the similarity between the statistical areas in terms of mean CPUE of by-catch species. The offshore and inshore areas showed a difference in terms of species dominance (Figure 6.6). Table 6.1 shows that the results of the DIVERSE analysis. According to the BEST analysis, a bottom temperature was the best explained the observed differences in catch composition in pot gear among different statistical areas (rho = 0.43).

The most abundant six by-catch species exhibits the spatial variations in CPUE (Figure 6.7). Among them, *M. glacialis* exhibited high CPUE values around the west coast of the island, whereas *E. esculentus* mainly showed the highest mean CPUE values around the east coast. There were statistically significant differences between sampling areas and the CPUE of *N. puber*, *S. canicula and M. glacialis*, whilst there were no significant differences for *Galathea* spp., *E. esculentus* and *A. rubens* (Table 6.2).

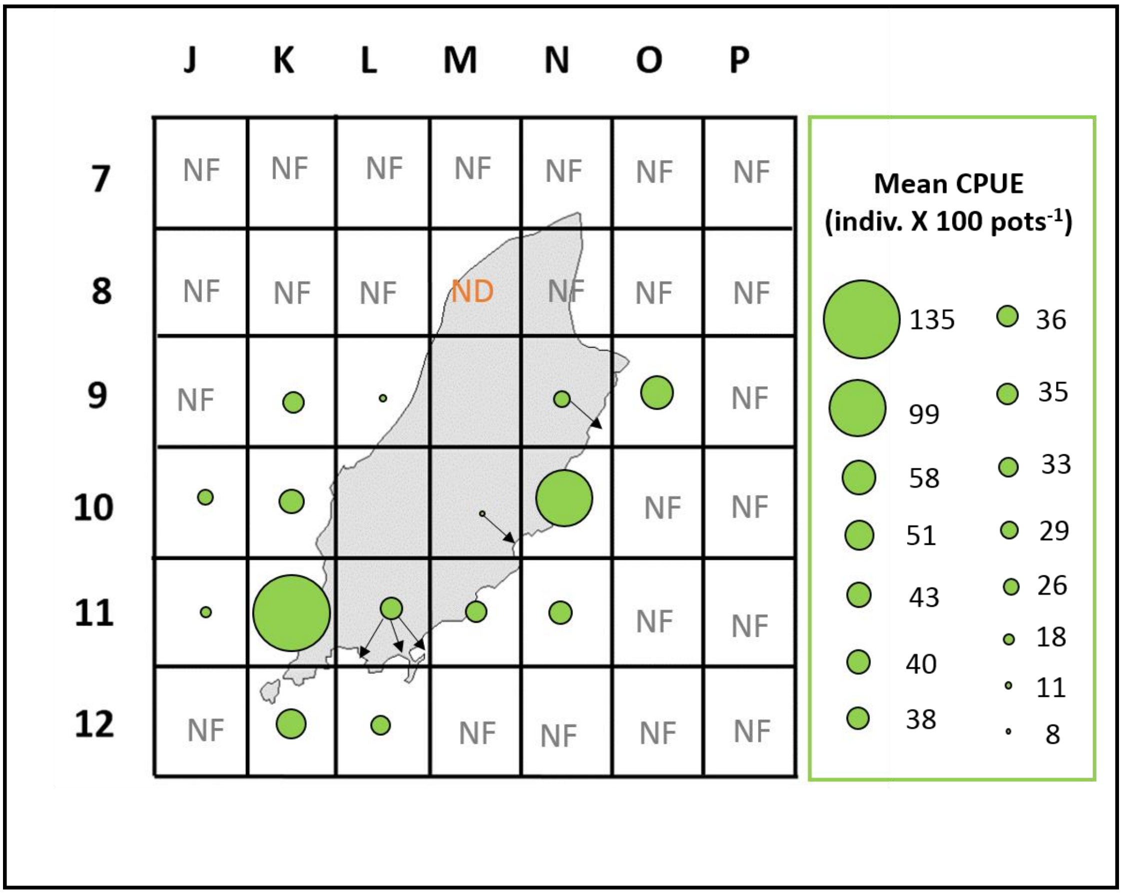


Figure 6.4. Mean CPUE for all by-catch species in each of the statistical areas. The abbreviation: NF; no commercial fishing using pot gear, ND; no data.

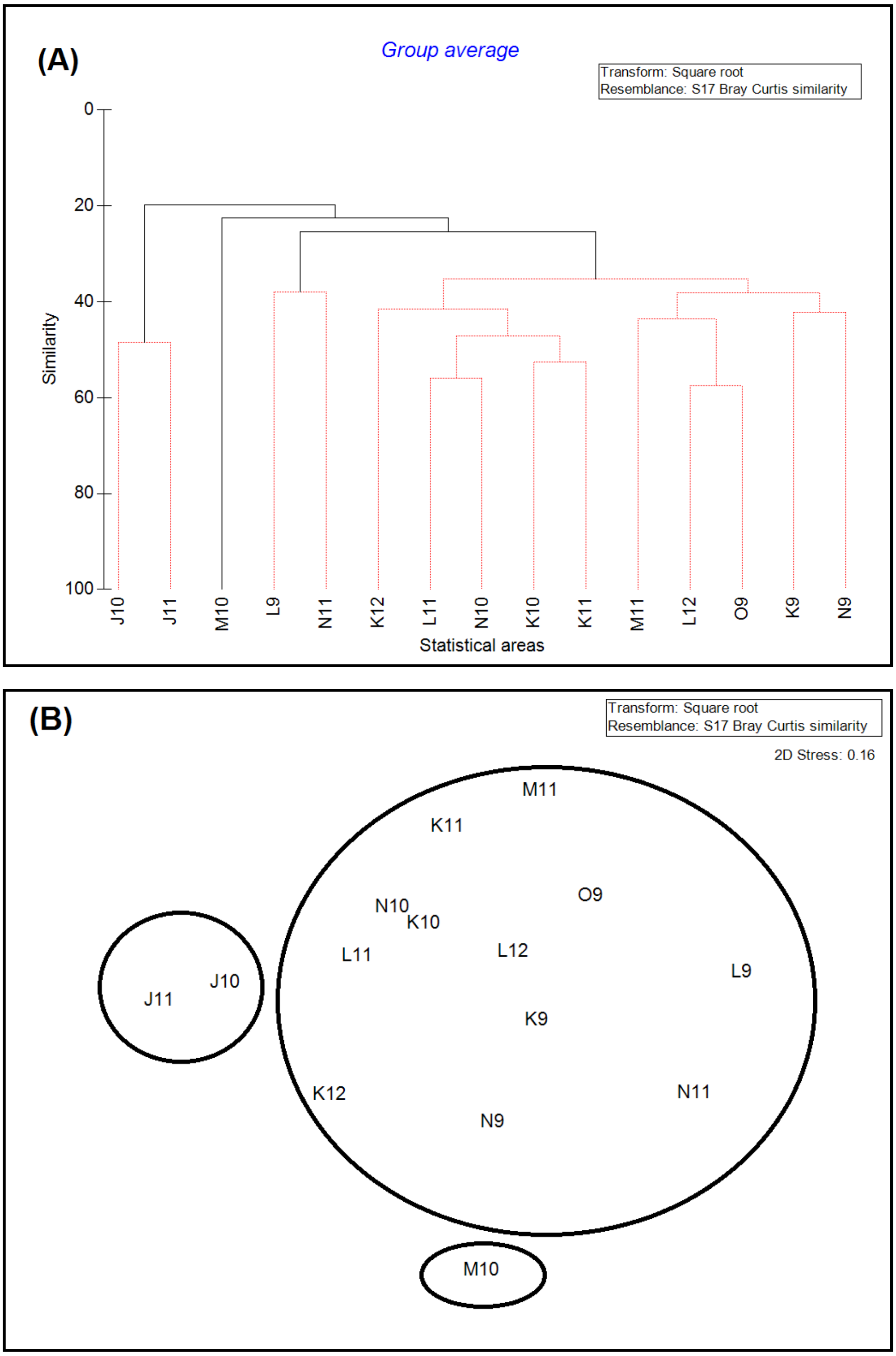


Figure 6.5. (A) Dendrogram and (B) MDS ordination plot showing the similarity in bycatch composition for each of the different statistical areas for standardised pot catch data. The data were derived from 2489 hauled pots.

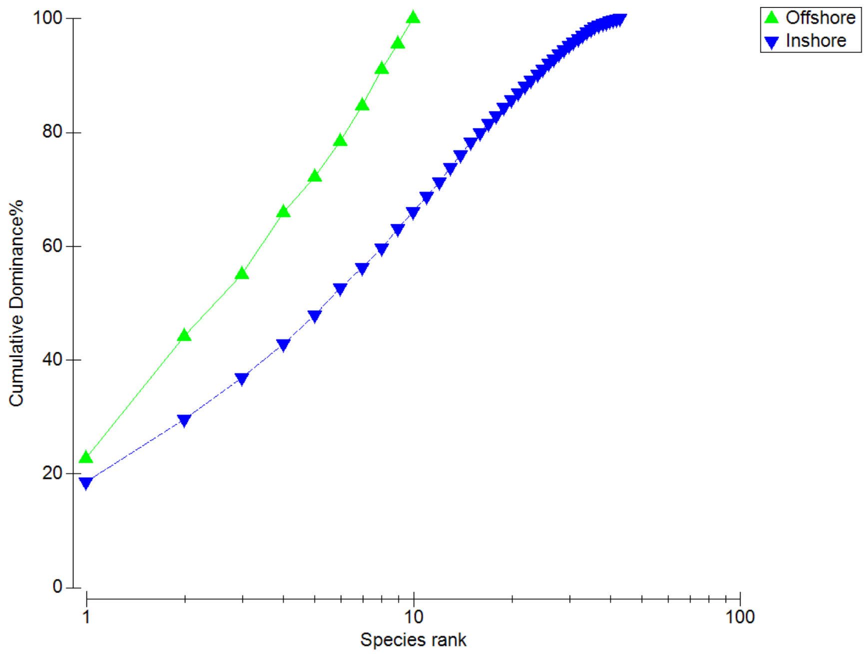


Figure 6.6. Cumulative K-dominance curves for of all by-catch (mean CPUE) species in offshore (J10 and J11) and inshore (other statistical areas) stations.

Table 6.1. Results of DIVERSE (Univariate Diversity Indices) analysis related to spatial trends in CPUE (indiv. 100 pots^{-1}) (n, sample size; S, number of species; H' (loge), Shannon-Wiener diversity index; 1- Lambda', Simpson diversity) and environmental variable; BT (mean bottom temperature), which exhibited the best fit.

Ground	**Statistical Area**	**n**	**S**	**H'(loge)**	**1-Lambda'**	**Mean BT (ºC)**
Offshore	J10	14	8	2.048	0.934	13.868
Offshore	J11	8	5	1.486	0.850	14.090
Inshore	K10	29	33	3.237	0.982	14.577
Inshore	K11	25	11	1.916	0.815	14.660
Inshore	K12	14	6	1.546	0.801	14.710
Inshore	K9	16	11	2.208	0.924	14.698
Inshore	L12	22	23	2.886	0.974	14.470
Inshore	L9	7	5	1.588	0.920	15.215
Inshore	M11	21	18	2.729	0.964	14.713
Inshore	N10	34	16	2.62	0.944	14.917
Inshore	N11	13	5	1.52	0.823	14.867
Inshore	N9	14	7	1.9	0.911	14.930
Inshore	O9	26	13	2.516	0.951	14.860

*For inshore areas, Spearman's rank correlation shows the relationships among Mean BT and variables: S (r = -0.61, *P* = 0.05), H' (loge) (r = -0.54, *P* = 0.09).

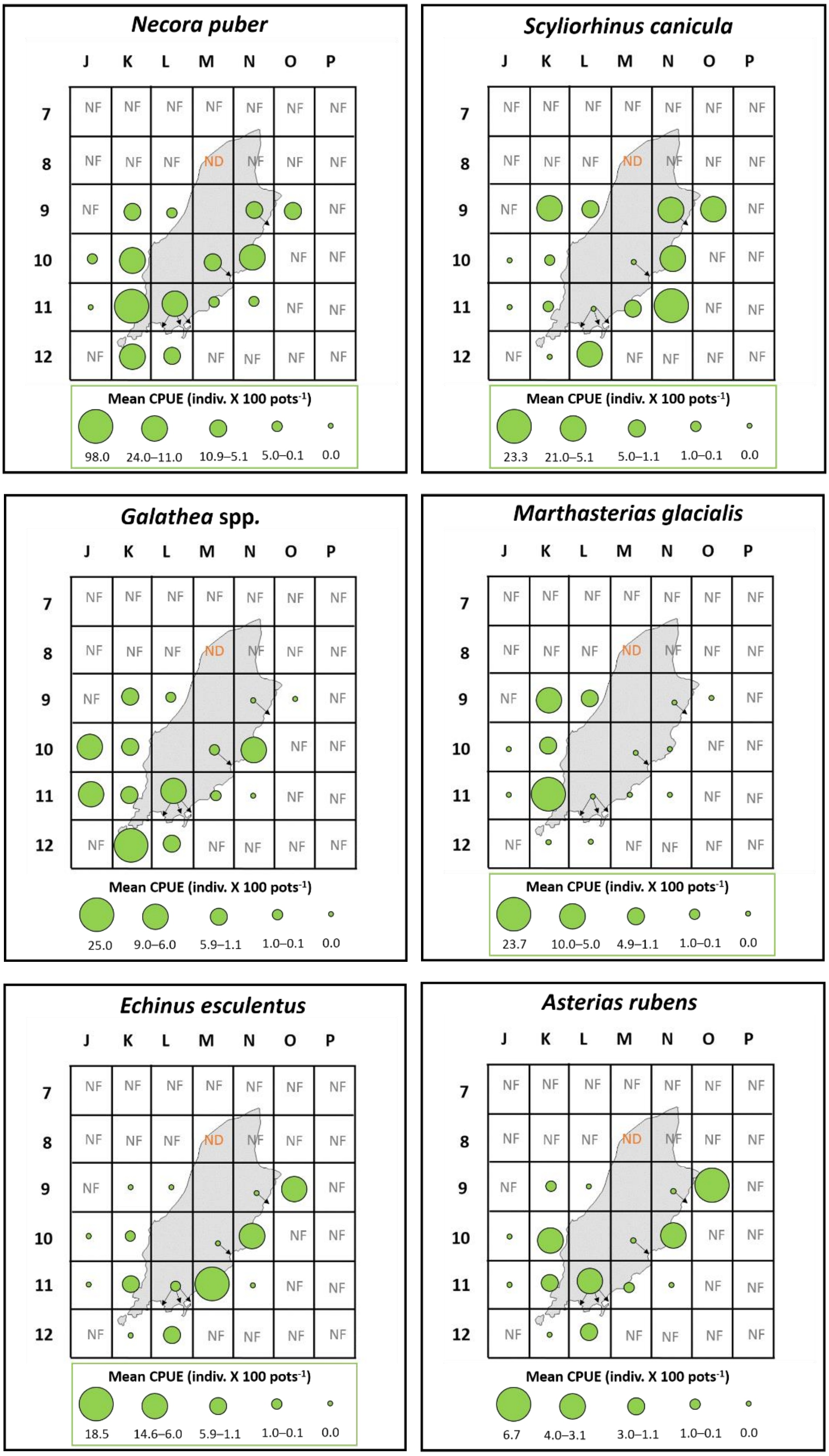


Figure 6.7. Spatial differences in mean CPUE of the six most abundant by-catch species (*N. puber, S. canicula, Galathea* spp., *M. gracialis, E. esculentus* and *A. rubens*). The abbreviation: NF; no commercial fishing using pot gear, ND; no data.

Table 6.2. Spatial differences of the mean CPUE of the most abundant 6 by-catch species using the Kruskal-Wallis test (df = 14). Pairwise comparisons of the mean CPUE for the different statistical areas for the six most abundant by-catch species.

Species	n	Chi-square	*P* value General data	Statistical areas	*P* value Pairwise comparisons
Necora puber	369	30.286	0.007	J11 vs. K11	0.015
				M11 vs. K11	0.003
				L12 vs. K12	0.001
Scyliorhinus canicula	135	39.027	< 0.001	K12 vs. O9	0.013
				L11 vs. O9	0.005
				K11 vs. O9	0.048
				K10 vs. O9	0.011
Galathea spp.	99	19.963	0.131		
Marthasterias glacialis	84	36.729	0.001	L12 vs. K10	0.001
Echinus esculentus	62	21.523	0.089		
Asterias rubens	49	12.992	0.527		

Seasonal variation

The highest and lowest mean CPUE values were determined as 81 ± 26 indiv. 100 pots^{-1} and 26 ± 4 indiv. 100 pots^{-1} in spring 2012 and autumn 2012 respectively (Figure 6.8). There was a marginal significant difference in the by-catch CPUE among the different sampling seasons, with the CPUE highest in spring and summer of 2012 and 2013 (Kruskal-Wallis test, Chi-square = 10.50, df = 5, P = 0.06). Figure 6.9 indicates the seasonal variations in CPUE of the six most common by-catch species. Among them, *N. puber*, *M. glacialis*, *E. esculentus* and *A. rubens* reached the peak CPUE in spring, whereas *Galathea* spp. and *S. canicula* were the most abundant in summer. There were statistically significant differences between sampling seasons and the CPUE of *N. puber, M. glacialis, E. esculentus* and *A. rubens* (Table 6.3).

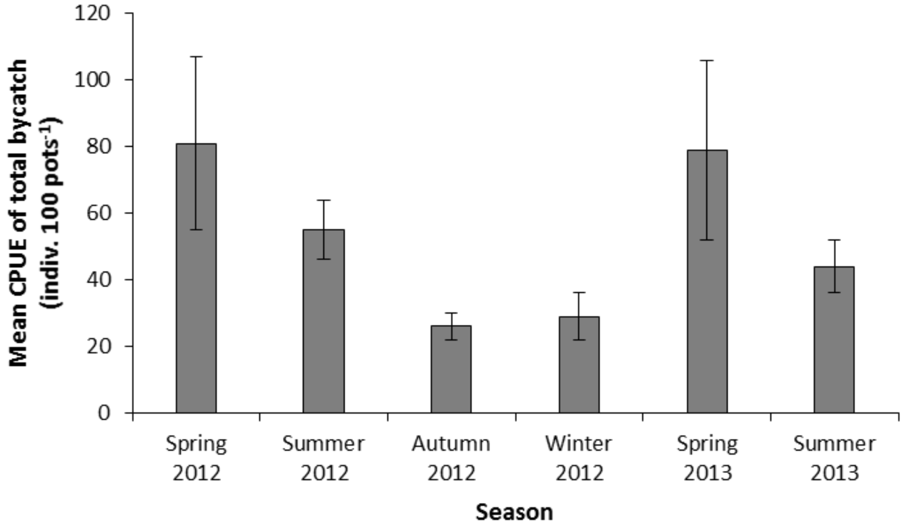


Figure 6.8. Mean (±SE) CPUE of by-catch species (indiv. 100 pots^{-1}) in each of the sampling seasons.

Table 6.3. Seasonal differences of the mean CPUE of the most abundant 6 by-catch species using the Kruskal-Wallis test (df = 5).

Species	**n**	**Chi-square**	***P* value**
Necora puber	369	14.65	0.012
Scyliorhinus canicula	135	10.23	0.069
Galathea spp.	99	6.07	0.299
Marthasterias glacialis	84	17.83	0.003
Echinus esculentus	62	31.65	< 0.001
Asterias rubens	49	11.48	0.043

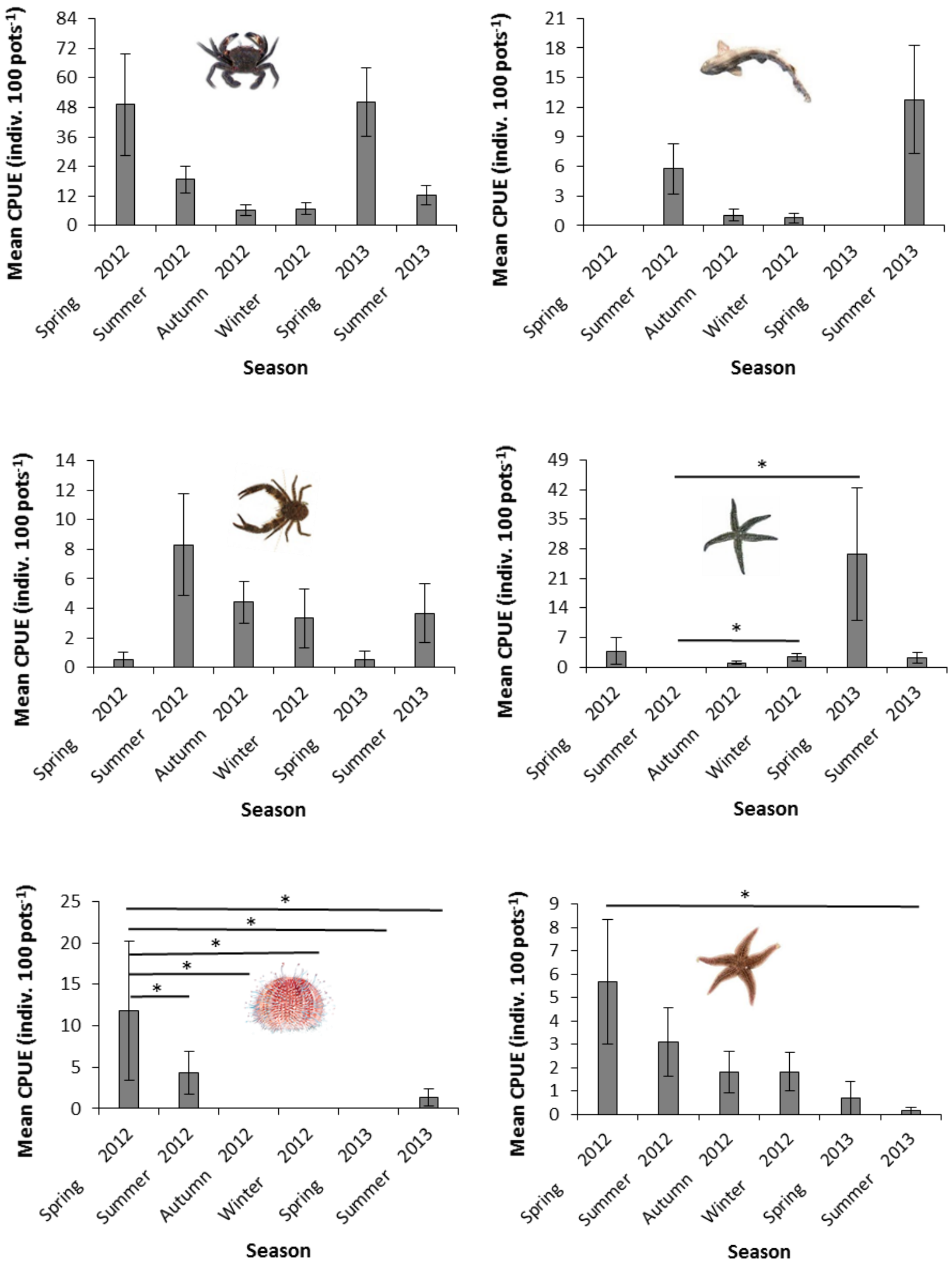
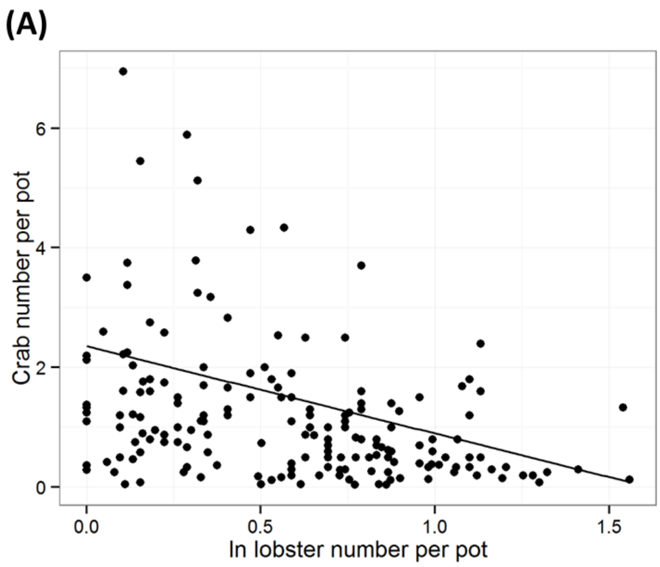


Figure 6.9. Seasonal variations in mean (±SE) CPUE of the six most abundant by-catch species (*N.puber, S.canicula, Galathea* spp., *M.glacialis, E.esculentus* and *A. rubens*). Black lines indicate a significant difference among seasons (Pairwise comparisons, non-parametric tests), The significance level: * = 0.05.

Comparison of CPUE values of crab, lobster (target species) and by-catch species

There was a significant negative relationship between crab and lobster number per pot (75th quantile regression, coef. = -0.46, $P = 0.001$) (Figure 6.10a). However, there was no significant relationship between the target species (crab and lobster) number per pot and the total by-catch number (75th quantile regression, coef. = -0.09, $P = 0.629$) (Figure 6.10b).



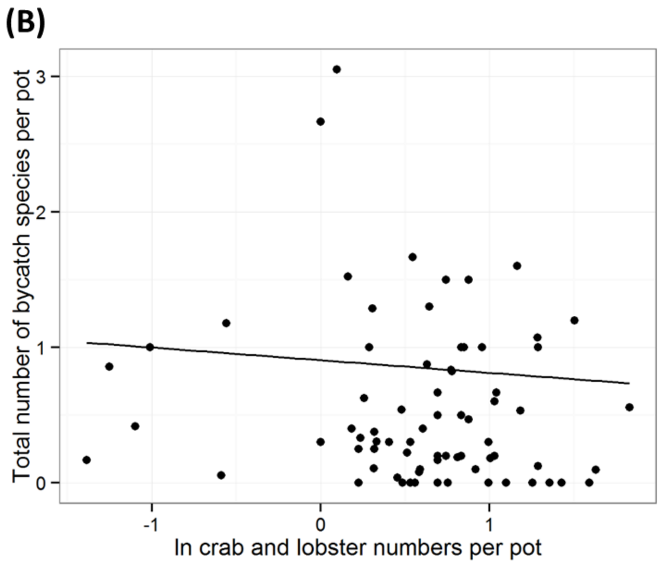


Figure 6.10. (A) The relationship between crab number per pot and ln lobster number per pot (n = 2406 hauled pot from 176 strings), (B) the relationship between total number of by-catch species per pot and ln target species (crab and lobster) number per pot (n = 1068 hauled pot from 78 strings).

The IUCN red list and quota species

The results of this study show that the bycatch in crab traps included ten fish and one invertebrate species that are listed on the IUCN red list (Table 6.4). Among them, cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*) are categorised as vulnerable, whereas edible sea urchin (*Echinus esculentus*) is near threatened species. The former two species and whiting would also need to be considered important in relation to the EU landings obligations as these species are quota species. Small-spotted catshark (*Scyliorhinus canicula*) and edible sea urchin (*Echinus esculentus*) had the highest CPUE compared with other species. Other by-catch or incidental species of this study have not been evaluated in the IUCN red list yet.

Table 6.4. IUCN Red list species, their global status and mean CPUE values of these species from the current study.

Species	**IUCN Red List-Global Status**	**Mean CPUE (number/pot)*100 ± SE**
Cod (*Gadus morhua*)	Vulnerable	0.28 ± 0.14
Haddock (*Melanogrammus aeglefinus*)	Vulnerable	0.10 ± 0.07
Edible sea urchin (*Echinus esculentus*)	Near threatened	2.40 ± 1.01
Small-spotted catshark (*Scyliorhinus canicula*)	Least Concern	4.65 ± 1.41
Ballan wrasse (*Labrus bergylta*)	Least Concern	0.66 ± 0.27
Pollack (*Pollachius pollachius*)	Least Concern	0.41 ± 0.27
Rockling (*Gaidropsarus vulgaris*)	Least Concern	0.34 ± 0.17
Long-spined scorpion (*Taurulus bubalis*)	Least Concern	0.20 ± 0.11
Whiting (*Merlangius merlangus*)	Least Concern	0.10 ± 0.06
Poor cod (*Trisopterus minutus*)	Least Concern	0.08 ± 0.08
Common dab (*Limanda limanda*)	Least Concern	0.03 ± 0.03

***Information about the IUCN Red List- Global Status:** Extinction status of the aquatic species (except for mammals, warm-water reef building corals and freshwater crabs) have not been evaluated comprehensively in the IUCN Red List-Global Status yet. Basically, the IUCN red list consist of the several categories depending on species' extinction levels. They are ranged from the highest level to lowest level; *extinct*, *extinct in the wild*, *critically endangered*, *endangered*, *vulnerable*, *near threatened*, *least concern*, *data deficient* and *not evaluated*. Animal species that have been evaluated to have a low risk of extension are classified as "Least Concern". A species is "Near Threatened" when it has been evaluated against the criteria but does not qualify for Critically Endangered, Endangered or Vulnerable now, but is close to qualifying for or is likely to qualify for a threatened category in the near future. "Vulnerable" species are considered to be facing a high risk of extinction in the wild (IUCN, 2015).

Incidental species

In this study a total of 25 species were recorded as an incidental species whose body sizes were smaller than 45 mm (mesh size) or those species recorded from the presence of damaged body parts (Appendix, 6.2). Incidental species were represented by 6 taxonomic groups of which Crustacea were the most commonly encountered followed by Mollusca, Echinodermata and Cnidaria (Figure 6.11).

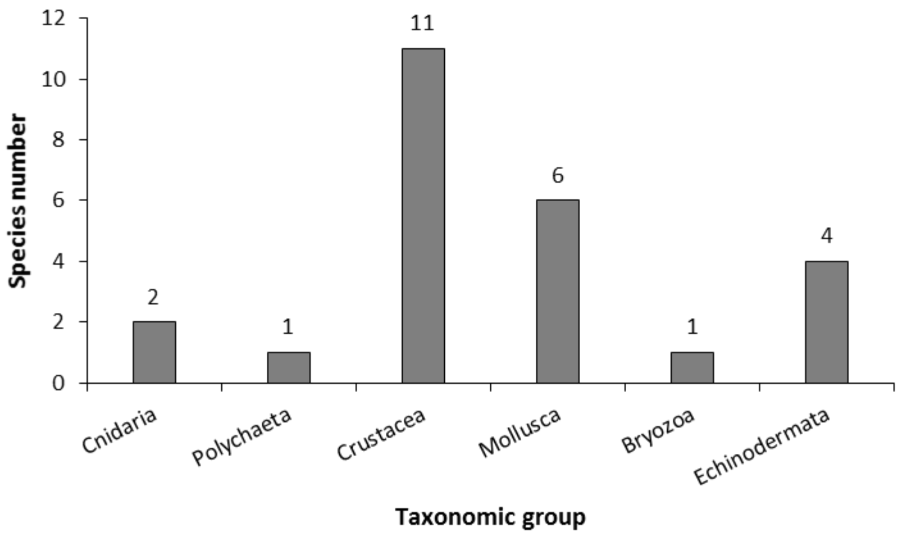


Figure 6.11. Incidental species composition by major taxonomic group and numbers of species.

Local ecological knowledge (LEK)

According to the questionnaire study all the fish and invertebrate species found during the fishery independent surveys, were also encountered by fishermen. Pot fishers reported encountering two other by-catch species (plate fish *Bothus lunatus* and blennies, Blenniidae) in crustacean pots. Half of the fishermen reported that the peak season for the occurrence of by-catch species in pots is spring and other 5 fishermen estimated the peak season to be early summer. Furthermore, some species exhibit a strong seasonal increase in by-catch abundance. For example, fishermen reported that the common jellyfish *Aurelia aurita*, spiny spider crab *Maja squinado*, European conger *Conger conger* and Atlantic cod *Gadus morhua* occurred with the highest abundance in summer, whilst curled octopus *Eledone cirrhosa* peaked in spring. The latter species was also considered to suppress lobster catches due to its status as a predator of Crustacea.

6.5 Discussion

The present study has provided some useful insights into the potential for fish and invertebrate by-catch in crustacean pots in the Northern Irish Sea. A total of 43 by-catch species were encountered in crustacean pots fished around the Isle of Man. Perhaps not surprisingly, Crustacea were the most abundant taxonomic group represented by 12 by-catch species. Elsewhere, Frusher and Gibson (1998) investigated by-catch in the Tasmanian rock lobster fishery. They found 33 finfish species, 9 crustacean species, 21 mollusc species and 7 echinoderm species in pots which did not have escape gaps. They also reported that escape gaps reduced catches of the most finfish and invertebrates by over 80%. Similarly, Brock et al. (2007) evaluated the by-catch composition in the South Australian rock lobster fishery and determined a total of 40 by-catch species. Recently, Page et al. (2013) reported the by-catch in the commercial blue crab pot fishery in Georgia. They reported that there were 26 finfish species and 15 invertebrate species in pots. While the number of species that occur in pots may be different due to the habitat structure, biodiversity of sampling areas, the feeding behaviours of local species and technical characteristics of pots, there are striking similarities in the number and types of organisms encountered in these different studies.

The current study also demonstrates that the number of by-catch species retained by pots around the Isle of Man is relatively low in pots in comparison with other fishing gears such as trawls and scallop dredges. For example, Duncan (2009) and Boyle (2012) found 96 and 93 by-catch species respectively in the Isle of Man queen scallop trawl fishery. Similarly, Craven et al. (2012) reported 50 fish species in the by-catches of scallop dredges in the same location (invertebrates were not recorded in this study).

In the present study, the most abundant by-catch species was the velvet crab *N. puber* that accounting for 34% in number of all by-catch species. Although *N. puber* is a target species in some fisheries (Tallack, 2002), it was not commercially exploited in the Isle of Man because of the lower catch of this species and the small body size of animals encountered. Henderson and Leslie (2006) investigated the survival rates of *N. puber* specimens, which were collected by pots. They reported that the mortality of *N. puber* is low (only 4 crab from a total of 167 dead during the study).

It is clear from this study that the mean CPUE of the total by-catch per pot differed significantly between fishing grounds. The total number of by-catch species in inshore areas is high in comparison with the offshore areas. Habitat structure may be a reason of the CPUE differences in statistical areas particularly for inshore waters where the habitat diversity is highest (Table 6.5). In particular, around the west coasts of the island some fishing grounds exhibited relatively high by-catch diversity (K10) and high CPUE (K11). It is interesting to note that K11 encompasses the Port Erin 'closed area' which has been protected from fishing for over 20 years. The highest mean CPUE values of the six most common by-catch species differed depending on sampling areas. For example, *E. esculentus* were commonly found around the east coast where the main habitats are sand, mixed gravel, mixed maerl and *Modiolus* beds (Table 6.5), which are commonly preferred by *E. esculentus* (Parr and Ager, 2003). Bottom temperature was the single factor that had the best fit with the species composition of bycatches in the different areas around the Isle of Man. Thus, a combination of habitat type and environmental conditions (temperature) may be the key determinants of bycatch composition.

Table 6.5. Dominant substrate types of different sampling areas which were identified from image analysis and sediment particle size analysis (Modified from Hinz et al., 2010; White, 2011).

Sampling area	Dominant substrate types
J10	Fine sand to mud
J11	Fine sand to mud, mixed sand, mixed gravel
K9	Mixed sand, muddy sand
K10	Mixed sand, mixed stone
K11	Mixed sand, mixed gravel
K12	Mixed gravel, mixed stone, rock
L9	Mixed gravel, mixed sand, mixed stone
L11	Rock
L12	Mixed gravel, mixed stone, rock
M10	Mixed maerl
M11	Mixed gravel, mixed maerl, modiolus bed
N9	Sand
N10	Mixed maerl
N11	Mixed maerl
O9	Sand

The highest mean CPUE of by-catch species was found in spring 2012 and the lowest mean CPUE was in autumn 2012 in the Isle of Man. The seasonal catch rates varied depending upon the species. For example, *N. puber* and *M. glacialis* exhibited the highest CPUE in spring months, whereas the CPUE of *S.canicula* and *Galathea* spp. peaked in summer. The catch rate of *N. puber, M. glacialis, E. esculentus* and *A. rubens* showed the statistically significant gap between the sampling seasons. Understanding these seasonal fluctuations in bycatch would help mitigate the occurrence of these catches if was thought that mortality occurred as a result of retention in pots. However, most of these species would survive capture once returned to the sea assuming they did not sustain injuries or damage.

There was a significant negative relationship between crab and lobster catches such that as lobster numbers increased within pots, the associated catch of brown crabs declined. As lobster predate brown crabs this is probably a predator avoidance response. A similar relationship was reported by Addison (1995) in English waters. Soak time did not appear to influence by-catch abundance, however there was not means of ascertaining whether predation within the pots was a factor that might have affected this finding. Similarly, there was no significant relationship between the soak time and crab catches in the Isle of Man (see Chapter 2).

In this study, a total of 242 specimens were recorded from 11 species that are listed in the IUCN red-list. Among them, cod and haddock are categorised as 'vulnerable', while the edible sea urchin is a 'near threatened' species. Another 8 fish species (*Scyliorhinus canicula, Labrus bergylta, Gaidropsarus vulgaris, Pollachius pollachius, Taurulus bubalis, Merlangius merlangus, Trisopterus minutus* and *Limanda limanda*) were identified as a 'least concern' species. All of these fish species had very low abundance in pots (except for *Scyliorhinus canicula*). All of the specimens were alive at the time of removal from pots. Small spotted catshark *Scyliorhinus canicula*, ballan wrasse *Labrus bergylta* and European conger *Conger conger* were kept by fishermen to use as bait. Similarly, common whelk *Buccinum undatum* specimens were kept for the commercial sale. As Europe moves towards fully reported fisheries, the information reported in the present study will provide important evidence on the potential effect of pot fisheries on by-catch species and will highlight those species which are likely to be utilised for purposes such as bait or as a secondary commercial catch.

The physical impacts of pots and traps on benthic species have rarely been evaluated (Eno et al., 1996; Eno et al., 2001; Hawkins et al., 2007; Heifetz et al., 2009; Coleman et al., 2013); in particular, the corals, sponges, bryozoans and similar sessile organisms have the greatest propensity to be affected by trap fisheries (Shester and Micheli, 2011). Both Eno et al. (2001) and Coleman et al. (2013) reported that crustacea potting seems to have no detectable effect on benthic species in field experiments to study the effects of the physical effects of potting on benthic fauna. In the current study, some sessile species such as *Alcyonium digitatum, Anemonia viridis* and *Alcyonidium diaphanum* occurred occasionally in the pots as damaged individuals that presumably had been dragged off the seabed. The rarity of the latter events would suggest that physical impact on the seabed is not an important issue for this fishery.

The phenomenon of "ghost fishing" is considered to be another impact of pot or trap fishing on marine ecosystems. Bullimore et al. (2001) examined the mortality rate and the number of animals caught by fleets of crustacean pots in Wales in order to understand the impacts of lost pots. Spider and brown crabs were reported as dominant species in lost pots; velvet crab, lobster, ballan wrasse, dogfish and triggerfish were found in pots with lower abundance. Each pot killed a minimum of 6.06 brown crabs and 0.44 lobsters per pot per year. More importantly, these lost pots can continue to fish for many months in spite of the consumed bait (Bullimore et al., 2001). However, the effects and frequency of the ghost fishing are still poorly understood in European fishing grounds. Pantin et al. (2015) estimated the number of lost pots in the Wales crustacean fishery using the questionnaire study. They reported that a total of 1167 pots are lost each year according to 44 brown crab fishermen's responses. In the Isle of Man, ghost fishing is considered as a rare situation (pers. comm. Manx fishers) due to limited and decreased fishing activity in winter and bad weather. Furthermore, the compulsory use of escape gaps reduces further the potential for ghost-fishing for smaller size-classes of animals.

6.6 Conclusions

By-catches may cause a variety of adverse on populations, food-web and conservation consequences (Revill et al., 2005). Thus, the determination of the diversity of by-catch species, their catch per unit effort values and by-catch reduction techniques play a vital role for sustainable fisheries management and protection of natural resources. The major findings of this research were that, the by-catch abundance is low in the Isle of Man pot fishery and it varied between inshore and offshore waters. By-catch composition consists of a total of 43 species, however 25 incidental species also entered the pots. There is a direct relationship between lobster and crab abundance within the pots which is indicative of the predator-prey relationship between the two species, but this factor may also need to be considered if using pot catches to assess the status of the two species (estimates of true crab abundance may be under-estimated if lobsters are dominant in catches). Two vulnerable (cod and haddock) and one near threatened (edible sea urchin) species were found in pots, however the CPUE for these species was low. In summary, this study shows that the Isle of Man crab pots selective fishing gears that generate relatively few discards and bycatch.

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CHAPTER 7 - A DESCRIPTION OF ISLE OF MAN RECREATIONAL BROWN CRAB FISHERIES

7.1 Abstract

In addition to commercial crab fisheries, recreational fisheries was evaluated using government return forms (2007-2012) to ensure a full understanding of the total exploitation rate of brown crab *Cancer pagurus* in the Isle of Man. The main aims of this study are to present an overview of the recreational brown crab fisheries and to compare recreational catch rates with commercial catch rates in the Isle of Man. While this study contributes to the assessment of the brown crab fisheries, it is clear that recreational fishing contributed only a small percentage of total mortality and is not at present an issue for concern provided the data submitted on catch return forms is accurate.

Keywords: *Cancer pagurus*, brown crab, recreational fisheries, CPUE, fishery dependent data, returned and retained crabs, the total exploitation rate, Isle of Man.

7.2 Introduction

Recreational fisheries are commonly defined as the fishing of aquatic animals that do not constitute the fisher's primary resource to meet basic nutritional needs and are not generally sold or otherwise sold on export, domestic or black markets (FAO, 2012). More specifically this activity can be considered as a kind of sport in many countries that provides food, and improves well-being (Murray-Jones and Steffe, 2000; Pitcher and Hollingworth, 2002). Even though recreational fishermen do not undertake this activity for income and employment purposes, their interactions with aquatic environments cannot be ignored. Thus, not only commercial fisheries but also recreational fisheries have the potential to negatively affect fish and shellfish stocks and aquatic habitats (Cooke and Cowx, 2006). However, recreational fisheries are often considered to have minimal impact on the wider ecosystem and are considered relatively sustainable compared with commercial fisheries (Pitcher and Hollingworth, 2002; Bucher, 2006; Levin et al., 2006). However, in contrast to commercial fisheries, recreational catches are not monitored in the detail afforded to commercial catches (Aas, 2008; Lloret et al., 2008; Hilborn and Hilborn, 2012). There are some limited examples where governments have monitored recreational fisheries by implementing management policies, which include logbooks and return forms which provide insights into catch and effort.

In order to determine ecological, economical and social impacts, and the magnitude of recreational fisheries, certain fishery-specific factors must be considered (e.g. active fishermen numbers, lifted trap/pot numbers, catch amount, and fishing effort). This fishery-dependent information (logbooks or return forms) can improve our understanding of stock status and hence inform effective management of marine resources (Morgan and Burgess, 2005). As such, it is important to consider recreational fisheries together with commercial fisheries to ensure a fuller understanding of the total exploitation rate of marine species (Cooke and Cowx, 2006). Currently, it is not clear to what extent recreational catches affect the status of species that are commercially exploited (Sumaila, 2002; Arnason , 2009; Arnason and Pearse , 2009; Hanna, 2009).

The brown crab, *Cancer pagurus* Linnaeus, 1758, has been harvested in commercial quantities in the Isle of Man, for 75 years. However, the crab production has been recorded since 1983. Moreover, recreational harvesting of crustacean species (crab and lobster) is becoming more popular around the island. Recreational shellfish pots have been licenced annually by the Department of Environment, Food and Agriculture (DEFA) since 2007. Licence holders are restricted to 5 pots per person, and a maximum daily catch of 5 brown crabs (ICES, 2012). Recreational fishermen report catch amounts on hobby fishing return forms. There is no season or area closure for recreational pot fisheries, but the landing of berried females or male or female crabs that are smaller than the minimum landing size (130 mm) is not permitted. In 2012 there were 27 licenced commercial vessels and 78 recreational licences (DEFA, 2013).

In addition to commercial crab fisheries (Chapter 2), recreational fisheries have been monitored using government return forms (2007-2012) to ensure a full understanding of the total exploitation rate of brown crab in the Isle of Man. To date, no studies have been undertaken on the recreational catch rates of *C. pagurus* in Northern Europe.

7.3 Materials and Methods

The Isle of Man has a coastline of 160 km, claims 12 nm of territorial waters and is located in the Irish Sea between Northern Ireland, Scotland, England, Ireland and Wales (Figure 7.1). The Department of Environment, Food and Agriculture (DEFA) (Isle of Man) collates and maintains records of recreational catches. The general information regarding recreational pot fishing includes lifted pot numbers, retained crabs and returned crab numbers. There data were extracted from "The Isle of Man Government Hobby Fishing Return Forms" for the period between 2007 and 2012. Commercial catch survey data obtained during 2012 was used to determine the average weight of crabs that were larger than the minimum landing size (MLS) [Chapter 2, 669.3±254.7 g (n = 1753)] which was the value used to estimate the total weight of crabs retained by hobby pots.

Catch per Unit Effort (CPUE) data (kg pot^{-1} trip^{-1}) ± (SD) of brown crab data from commercial fisheries logbooks and recreational crab fisheries return forms (2007- 2012) were compared to ensure a full understanding of total exploitation rate of brown crabs around the Isle of Man. The Spearman's correlation was used to test the relationship between CPUE of commercial and CPUE of recreational crab fisheries. Statistical analyses were performed with SPSS software (Version 20). The level of significance used was 95% for the statistical tests ($P<0.05$).

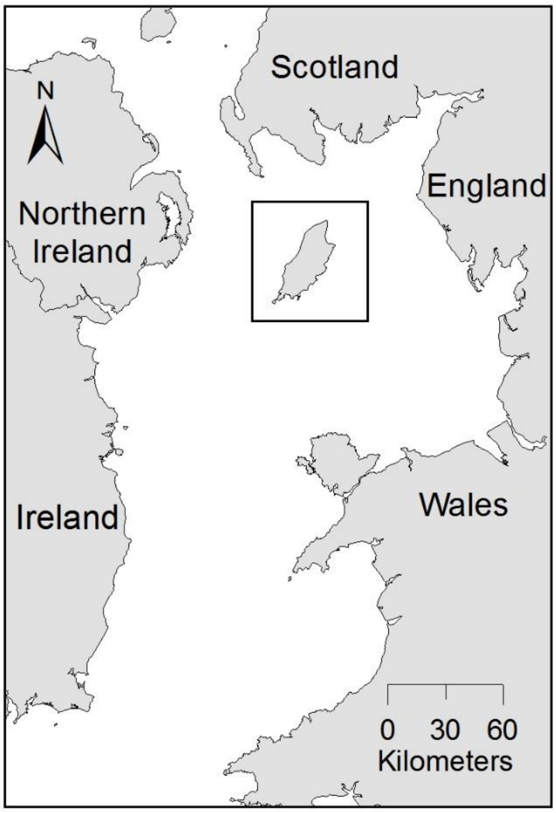

Figure 7.1. Location of the Isle of Man in Northern Irish Sea (ICES subdivision VII A).

7.4 Results

The returned percentage of annual licenced hobby fishermen's forms varied between 66% and 75% for the period 2007-2012. The average (± SE) number of pots lifted per year by active hobby fishermen was 51 ± 2, and the average (± SE) number of retained and returned crabs were 13 ± 1 and 30 ± 4 respectively, for 2007 – 2012 (Figure 7.2a). The annual percentage of the total catch returned to the sea varied between 62% (2012) and 74% (2009) in recreational fisheries (Figure 7.2b). The total annual weight of crabs taken by the hobby pot sector is estimated at between 0.604 t (2012) and 0.871 t (2009) per annum. The CPUE of commercial fisheries is higher than the CPUE of recreational fisheries for each years (Figure 7.2c). Total annual landings of all brown crab on the Isle of Man varied between 198.7 t and 554.7 t, of which 0.1 – 0.4% consisted of recreational landings and 99.6 – 99.9% consisted of commercial landings. There was no significant correlation between the CPUE of commercial fisheries and CPUE of recreational fisheries (Spearman's correlation, P = 0.468).

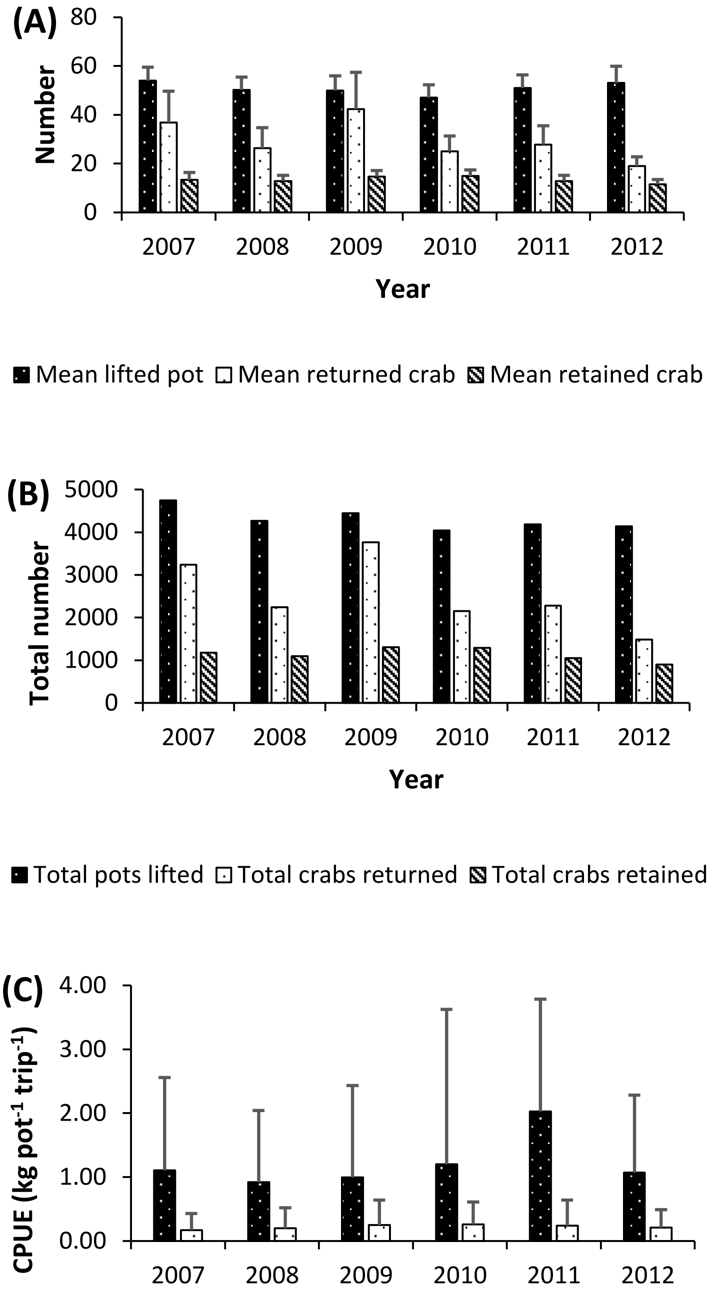

Figure 7.2 (A) Mean number (± SE) of lifted pots, returned and retained crabs between 2007 – 2012, (B) The total lifted pot number, total returned and total retained crabs between 2007- 2012, (C) CPUE (kg pot^{-1} $trip^{-1}$) ± (SD) of brown crab data from commercial fisheries logbooks and recreational crab fisheries return forms (2007- 2012). The active commercial boat numbers were counted as 17, 15, 18, 23, 25, and 27 respectively for the period 2007-2012, whilst the licenced active hobby fishermen numbers were 88, 85, 89, 86, 82, and 78 respectively.

7.5 Discussion

Fishing activity, whether commercial or recreational, influences fish and shellfish population structure (Pauly et al. 2002; Post et al. 2002; Arlinghaus and Cowx, 2008). However, recreational fisheries are often considered to have minimal impact on commercially exploited populations compared with commercial fisheries (Levin et al., 2006). In the present case-study recreational crustacean fishermen can use only five pots per day and generated a very small proportion of the total catch in comparison to the contribution of commercial fishers. Consequently, this study suggests that the restricted pot number in recreational fisheries on the Isle of Man has been an effective limitation on the contribution of recreational fisheries to total crab mortality.

7.6 References

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CHAPTER 8 - GENERAL DISCUSSION

General discussion

To achieve an ecosystem based approach to fisheries management it is necessary to have a full understanding of the life history traits, reproductive ecology and mortality of the exploited species, interactions with other fisheries and the wider ecosystem effects of fishery (Jennings and Kaiser, 1998; Jennings et al., 2001). The aims of this thesis were to focus on filling critical knowledge gaps about the brown crab fishery in the Isle of Man. In this context, this study set out to:

1) Understand the catch per unit effort (CPUE) of brown crab and how this was altered by environmental and fishery specific factors (Chapter 2).
2) To compare the scientific and the commercial CPUE to understand how well scientific data reflected catches in the commercial fishery (Chapter 2).
3) Estimate the total exploitation rate using both commercial and recreational fisheries data (Chapter 7).
4) Determine the ecological parameters relevant to understanding and managing brown crab population, with particular focus on population structure (sex and size distribution, migration patterns), relative growth and reproduction (Chapters 2,3 and 4).
5) Quantify the impacts of scallop dredging and trawling on the brown crab population. In addition to quantifying the by-catch density of the brown crab in dredges, the amount of damage, limb loss and mortality rates were ascertained based on direct observations. Moreover, the aim was to predict the mortality rates of crabs in different fishing grounds and periods during the fishing season based on vessel monitoring system (VMS) data (Chapter 5).
6) Understand the wider ecosystem effects of the crab fishery by quantifying the spatial and seasonal changes in non-target fish and invertebrate species by-catch. To highlight catches of species of conservation importance or those that might be relevant to the EU landings obligation (Chapter 6).

Both fisheries dependent data (FDD) and fisheries independent data (FID) showed that the highest mean CPUE was recorded in autumn and off the west coast of the island. More importantly, the monthly mean CPUE increased with increasing monthly mean bottom temperature. This observation emphasises the importance of taking account of water temperature (rather than a specific time period) if developing a standardized annual survey of CPUE for crab fisheries. Similarly, the catchability of some other crustacean species (e.g.

Carcinus maenas, Panulirus cygnus) increased with increasing water temperature (Murray and Seed, 2010; Green et al., 2014). In addition, in the current study CPUE also increased with increasing depth and pot volume, thus these two factors also need to be accounted for if using fishery dependent data to monitor trends across time. The comparison of commercial and scientific data to estimate CPUE is rare in the literature (Petitgas et al., 2003), however the use of fisher derived data is increasingly important given the reduction in public funding for scientific monitoring. Results in Chapter 2 indicated that there was a strong correlation between the scientific CPUE and commercial CPUE. This suggests that fishermen's logbooks can be considered as a reliable source to estimate CPUE. Nevertheless, commercial estimates of CPUE do not provide information on the composition of the catch in terms of the composition of undersized individuals and males and females. This information still requires either the use of direct observations by observers or through the use of cameras (Hold et al. 2015).

Commercial fishers often report negative interactions with hobby fishers and consider that they contribute considerable additional fishing pressure on stocks (Pantin et al. 2015). This study is first to determine the total exploitation rate of brown crab using both commercial and recreational fisheries data. The annual landings of all brown crab on the Isle of Man varied between 198.7t and 554.7t between 2007 and 2012. However, only 0.1 - 0.4% of these landings consisted of recreational landings, hence it would appear that the legislative limitations on hobby fishing in the Isle of Man effectively limit the contribution of recreational fisheries to total crab mortality (Chapter 7).

C. pagurus exhibits a reproductive migration in many areas of the Europe (Ungfors, 2008). In the autumn/early winter ovigerous females migrate to deeper water where they remain hidden and half buried in the sand, gravel or silt (Nichols et al., 1982; Naylor et al., 1999; Woll, 2003). However, Woll (2003) also reported that all ovigerous females do not migrate from inshore to offshore. The observations reported in this thesis support the existence of migration pattern around the Isle of Man that is related to reproduction. Although many ovigerous females were found in offshore areas, several egg-carrying females were also observed in inshore areas of the Isle of Man (Chapters 4 and 5). Additionally, it should be noted that it is very difficult to determine the egg-carrying period of female *C. pagurus*, because ovigerous specimens of this species do not enter pots (or rarely enter) (Edwards, 1979). In addition to the pot surveys, ovigerous females were observed in the by-catch of scallop dredges. Based on these observations it appears that there is a north-south migration of female crabs from spring to autumn, with mating occuring somewhere to the south – south west of the Isle of Man. The mated females then appear to migrate offshore to the west where they extrude their eggs and they peak in abundance in November based on by-catch observations in the scallop dredge fishery (Chapter 5). Further insights into the precise movement of crabs around the island would be gained from a tagging study.

Based on gonad maturity, fifty percent of females were mature at 108 mm CW, whereas 50% of males were mature at 89 mm CW (Chapter 3). Ovigerous crabs varied in size from 134 to 215 mm CW and each individual carried an estimated 0.4-3.0 million eggs. Fecundity was related to animal size. In addition, egg volume was lower for crabs that had lost claws although the elemental composition (quality) of these eggs was not related to egg size. Importantly, the variation in the minimum size of egg bearing appears to be related to water temperature differences in the sampling areas of Europe (Chapter 4). Thus an increase in the minimum landing size of crabs in this fishery could increase the reproductive output of the population. In general, the size distribution of crabs landed in the fishery was well above the current MLS of 130 mm CW which indicates that the fishery is fished at a moderate level at present levels of fishing.

Another important and novel finding was in Chapter 5 when ovigerous crabs migrated to the offshore areas, they were vulnerable to the scallop dredges. In particular, these egg-carrying females were common around the North-West coast of the island in November. Interestingly, for the same area and season, the fishing effort of scallop fisheries peaked according to the vessel monitoring system (VMS). Thus, this situation increases the possibility of mortality of ovigerous females. With respect to the damage assessment of the brown crab caused by scallop dredges: 31% of crabs were recorded as undamaged (a good condition), whereas 24% and 15% of crabs showed leg missing and abdomen and or carapace cracks respectively. Lastly, 30% of crabs were found as crushed and dead. However, the incidental mortality was reported by Jenkins et al. (2001), who collected data by scuba-diving after the fishing operations. Chapter 5 also provides the estimations of crab by-catch and mortality for each fishing grounds throughout the fishing seasons using fishing effort data (VMS). The highest estimated crab by-catch was generally calculated for the first month of the fishing season (November), whilst the smallest estimated crab by-catch was often found in the last month of the fishing season (May). On the other hand, commercial landings of brown crab in the Isle of Man was 495t in 2012. Estimates of the potential mortality associated with scallop dredging led to a lower and higher estimate of possible crab by-catch mortality of 11t and 17t respectively (assuming 45%

mortality of the crab by-catch), which represented 2.2 - 3.4% of the commercial landings of brown crab for the Isle of Man.

Crab pots are generally considered as selective fishing gears with low rates of discards (Chapter 2) and by-catch (Chapter 6). The thesis has provided important insights into the catch per unit effort (CPUE) of the by-catch species in the brown crab fishery, and has contributed to an understanding of the seasonal and spatial patterns of these by-catch species in baited pots. A total of 43 by-catch species were found in crustacean pots lifted around the Isle of Man. Among them, the velvet swimming crab *N. puber* was the most abundant by-catch species, accounting for 34% of all the by-catch species. Other crab species such as spiny spider crab *Maja squinado* and common shore crab *Carcinus maenas* were rarely found in pots. The mean CPUE of the total by-catch per pot differed significantly between statistical areas; the highest by-catch CPUE was recorded around the west coast in K11, which is an area that has been closed to scallop dredging for over 20 years. This study suggests that a combination of habitat type and seawater temperature may be key determinants of by-catch composition while seasonal effects were less important. This means that if by-catch issues became more important at some point in the future (due to the rebuilding of commercial fish stocks) it may be possible to mitigate by-catch issues through the use of spatial management.

There was a significant negative correlation in catch combination between the two target species (brown crab and lobster); when lobster numbers increased in pots, crab numbers decreased which may be due to a possible predator avoidance response. However, there was no significant relationship between by-catch composition and target species (a combination of crab and lobster) composition. A total of 11 by-catch species were listed in the IUCN red list. Among them, the edible sea urchin (near threatened species) and the small spotted catshark (least concern species) were found with relatively high numbers in comparison with other species. Two vulnerable and economically important species, the common cod and haddock, were rarely found in pots which is an important finding in light of the EU landings obligation (EP, 2015) which will affect pot fisheries in 2019.

Limitations of the study

Understanding the ecological trends requires sampling during long time periods. In this study, the population data were collected over a period of 1.5 years. This period provided sufficient time to understand seasonal and spatial characteristics, such as sex ratio, size distribution, and reproductive migration patterns. However, it was not possible to undertake a stock assessment of brown crab based on the data collected in this relatively short time-scale. The fishing fleet of Isle of Man crab fishery is relatively small (about 27 active fishermen) and many of them do not fish all year round. However, in this study, the data was mainly collected from commercial boats during normal fishing hours. Thus, the sampling regime was limited by the constraints of fishermen's activities and behaviours. For example, fishermen do not fish around the north coast of the island due to low crab density, but as a result there are no data presented for this area in the thesis (Chapter 2; Figure 2.1). Furthermore, the frequency of sampling was limited by seasonal patterns in fishermen's behaviour which resulted in a lower sampling effort in the winter (Chapter 2; Figure 2.1) particularly on the east coast due to fishermen primarily targeting lobster which tend not to feed in winter.

Recommendations for future research and management proposals

In summary, according to the findings of the scientific and commercial CPUE, discard and by-catch rates, sex ratio, fecundity and size at maturity, the Isle of Man crab stock is successfully managed using some tools (Chapter 2). Moreover, the commercial fisheries logbooks and recreational fisheries return forms are a reliable data source. However, the brown crabs (especially ovigerous females) are threatened by the scallop fisheries industry in November although the contribution of by-catch mortality is relatively low in comparison with commercial landings of brown crab. The major recommendations are:

- Opening the scallop dredging season at the beginning of December in the area of the Targets scallop would help to protect ovigerous crabs around the west of the island and when opened would coincide with the peak in scallop sales value prior to the Christmas period.
- The brown crab is also used as a bait in the Isle of Man whelk fishery. It should be recorded all these crab catches (to avoid mis-reporting information).

- The MLS should continue to use 130mm CW although an increase to 135 mm would increase the reproductive output of the population and confer further protection and protection from outside fishermen who might tend to land any crab >130 mm.
- The prohibition of the landing berried crabs and de-clawing contributes to the protection of crab stocks.
- The data from catches of brown crab with basic characteristics (e.g. sex and CW) should be recorded by commercial fishermen using on-board cameras (Hold et al., 2015) to help monitor crab populations in the long term.
- Fecundity of the brown crab was determined as high in Manx waters. However, the larval mortality period of this species is known to be long in the other fishing grounds of Europe (Ungfors, 2008). Thus, the mortality rate of crab larvae should be investigated in further research.
- Based on the new approach of the European Commission, with respect to the data collection framework (DCF), it is considered imperative to record the by-catch species (at least commercially important species) in addition to target species, using fishermen's logbooks. Thus, this thesis provides an important source to assess the list of major by-catch species, which may be useful to prepare specific data sheets/forms for the Isle of Man Government.

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APPENDICES

Appendix 2.1. General Questionnaire Relate to the Brown Crab Ecology & Fishery

Boat name:

Fishing ground:

Date:

1- When does moulting occur in the brown crab (tick all months applicable)? In other words, when do you encounter with soft crabs?

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec

2- Which do you think are the peak moulting month(s) for male and female crabs?

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Male												
Female												

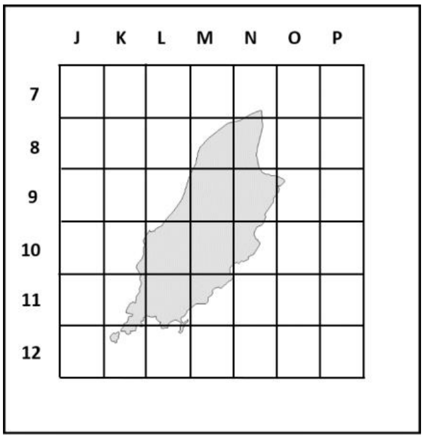
3- When do you encounter with berried brown crab in the pots (tick all months applicable)?

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec

4- Which do you think are the peak month(s) for observation of berried crabs?

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec

5- Do you think where the spawning areas are?



6- When do you encounter highest number of undersize crab?

Sex	Autumn	Winter	Spring	Summer
Male				
Female				

7- Migration patterns?

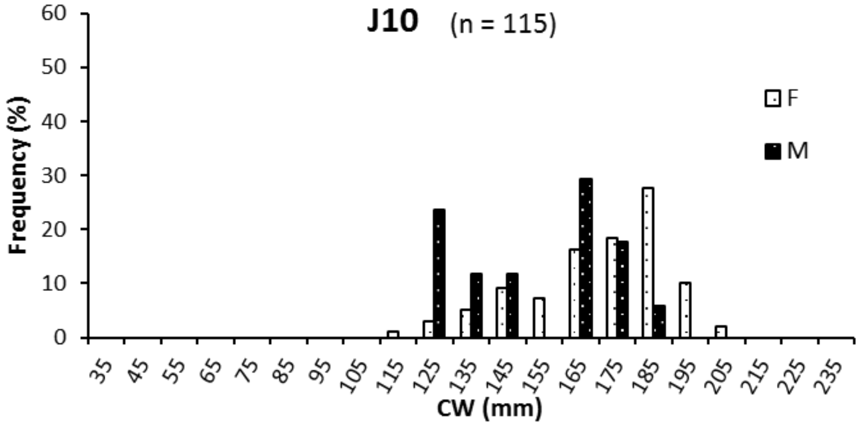
8- What kind of species do you use as a bait? Also amount for each per pot? (gr)

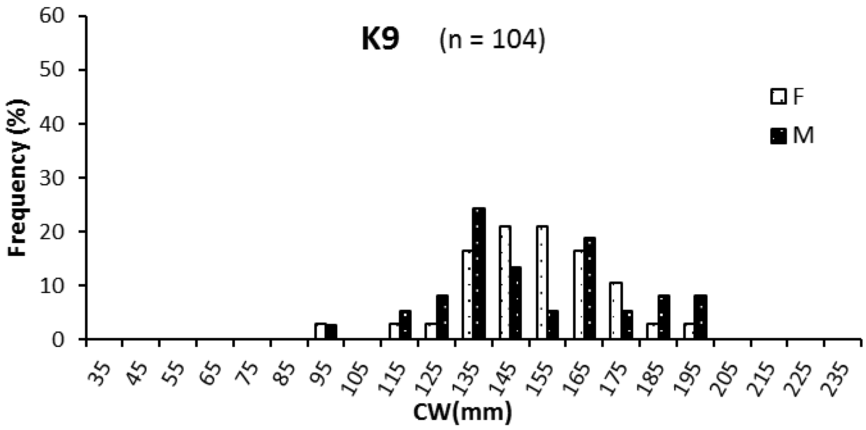
9- What is your average soak time (i.e. frequency of pot clearing) during the seasons?
Note: please report hours or days (e.g. 72 h or 3 day)

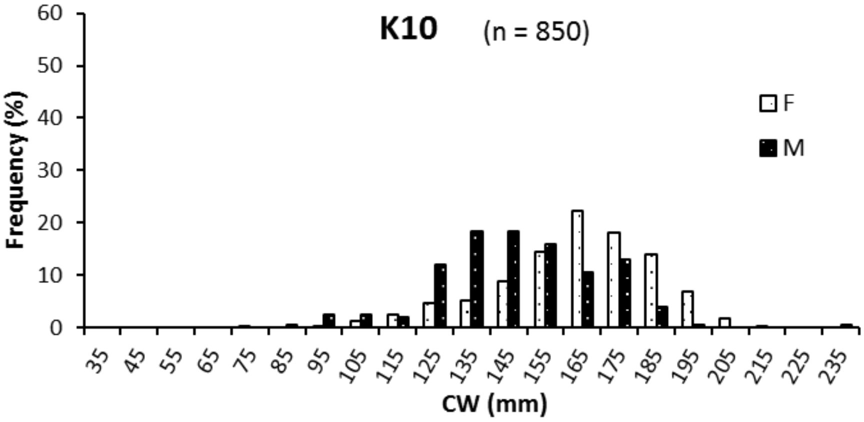
Autumn	Winter	Spring	Summer

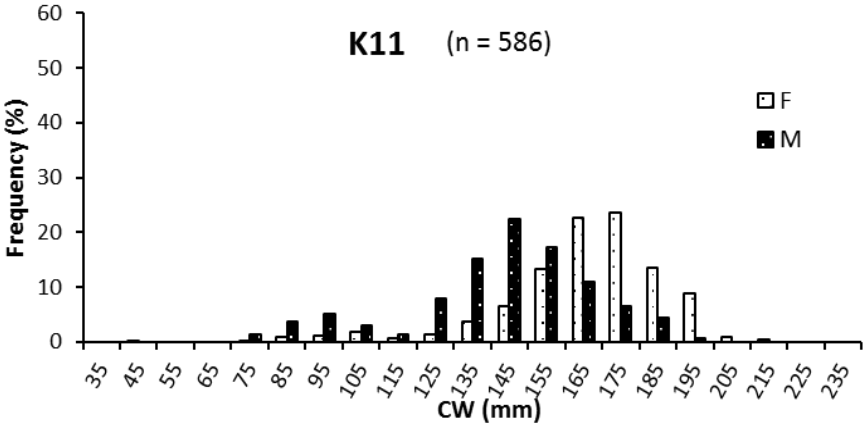
10- How many different pots do you use? And please report their sizes.

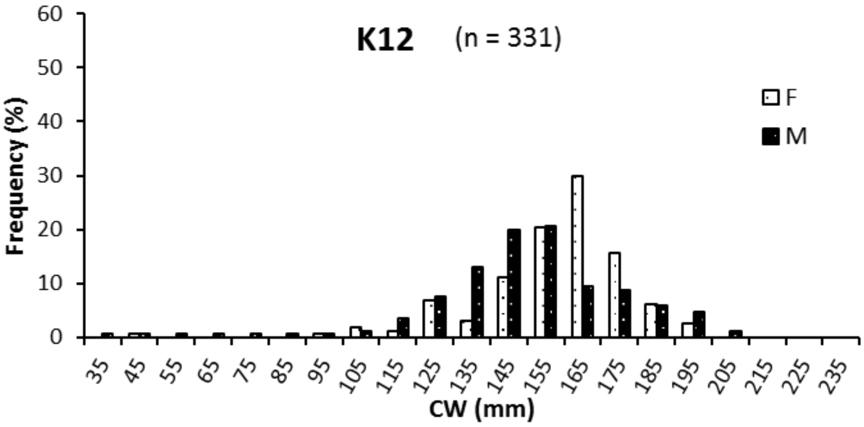
Appendix 2.2. Size (CW) - frequency distribution of female and male *C. pagurus* in 2012 and 2013 in the different fishing statistical areas.

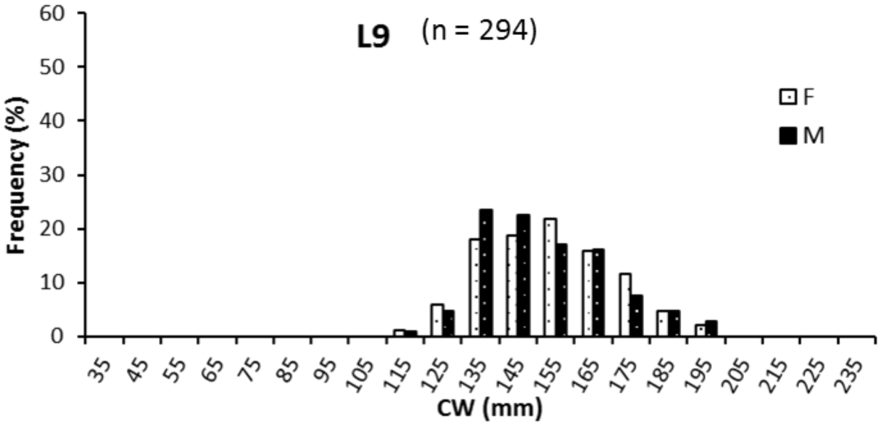


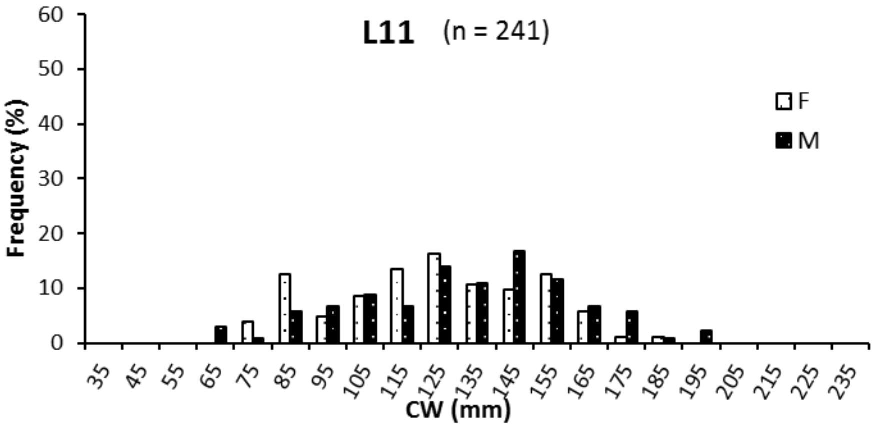


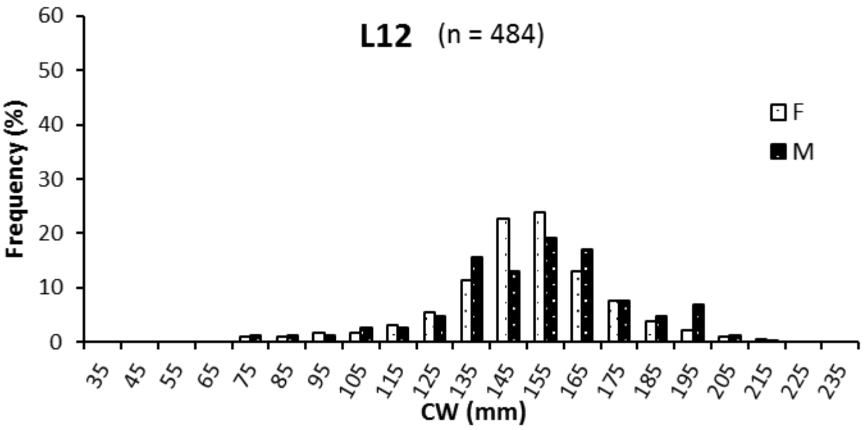

K10 (n = 850)
Frequency (%)
CW (mm)
F
M
0
10
20
30
40
50
60
35 45 55 65 75 85 95 105 115 125 135 145 155 165 175 185 195 205 215 225 235


K11 (n = 586)
Frequency (%)
CW (mm)
F
M
0
10
20
30
40
50
60
35 45 55 65 75 85 95 105 115 125 135 145 155 165 175 185 195 205 215 225 235


K12 (n = 331)
Frequency (%)
CW (mm)
F
M
0
10
20
30
40
50
60
35 45 55 65 75 85 95 105 115 125 135 145 155 165 175 185 195 205 215 225 235


L9 (n = 294)
F
M
Frequency (%)
CW (mm)
0
10
20
30
40
50
60
35
45
55
65
75
85
95
105
115
125
135
145
155
165
175
185
195
205
215
225
235


L11 (n = 241)
F
M
Frequency (%)
CW (mm)
0
10
20
30
40
50
60
35
45
55
65
75
85
95
105
115
125
135
145
155
165
175
185
195
205
215
225
235


L12 (n = 484)
F
M
Frequency (%)
CW (mm)
0
10
20
30
40
50
60
35
45
55
65
75
85
95
105
115
125
135
145
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165
175
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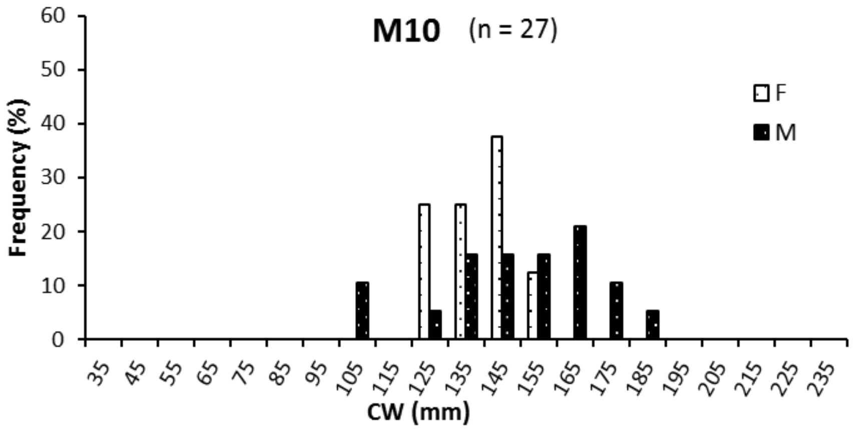
195
205
215
225
235


M10 (n = 27)
F
M
Frequency (%)
CW (mm)
0
10
20
30
40
50
60
35
45
55
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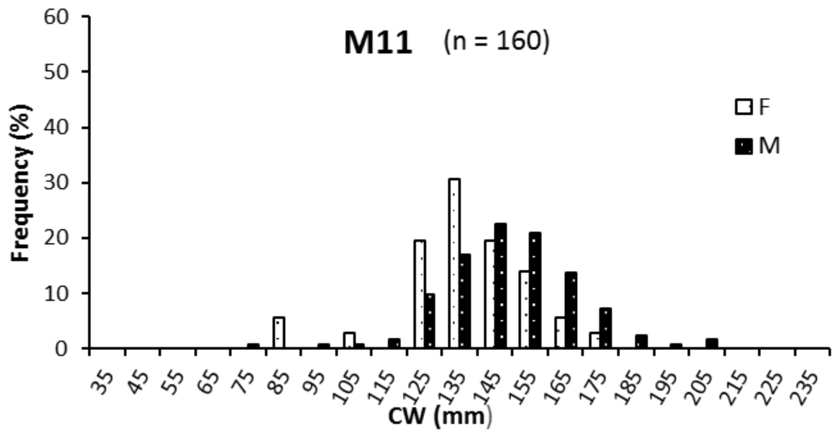
M11 (n = 160)
F
M
Frequency (%)
CW (mm)
0
10
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30
40
50
60
35
45
55
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75
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95
105
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125
135
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205
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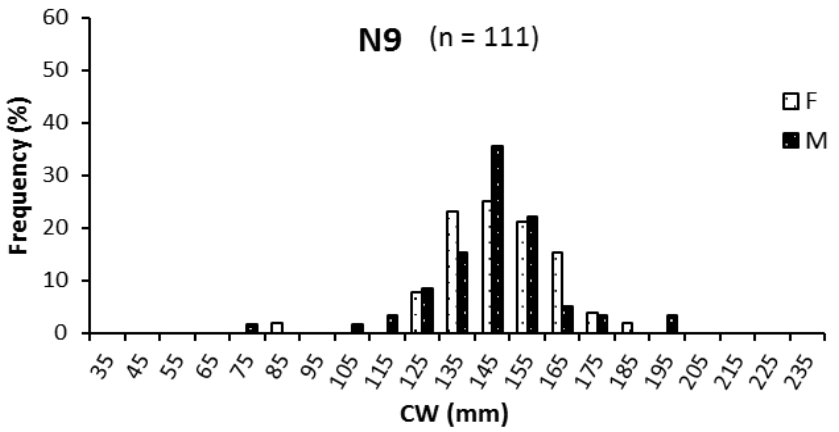
235


N9 (n = 111)
F
M
Frequency (%)
CW (mm)
0
10
20
30
40
50
60
35
45
55
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75
85
95
105
115
125
135
145
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195
205
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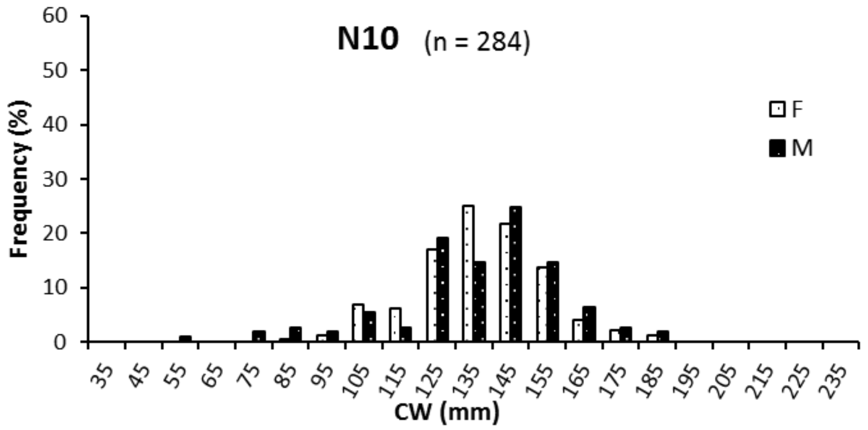
225
235


N10 (n = 284)
Frequency (%)
CW (mm)
F
M
0
10
20
30
40
50
60
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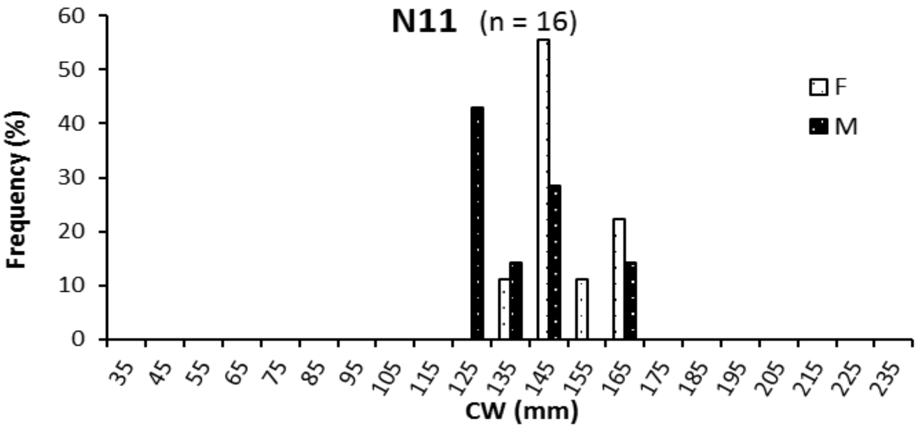
N11 (n = 16)
Frequency (%)
CW (mm)
F
M
0
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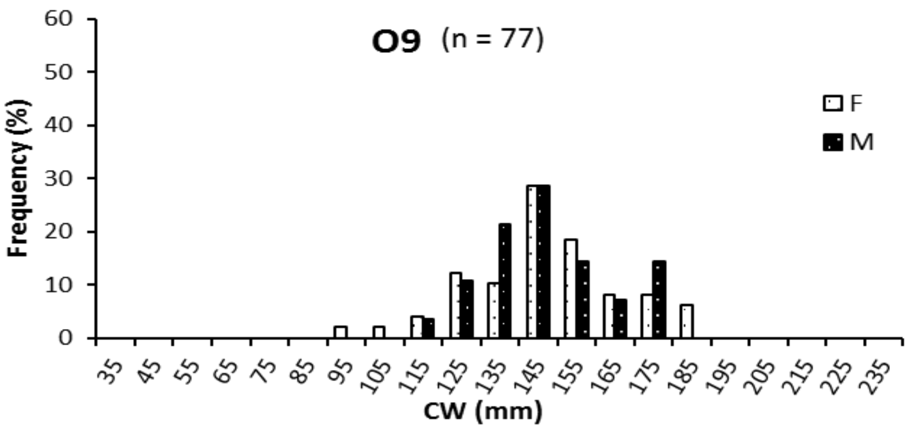
O9 (n = 77)
Frequency (%)
CW (mm)
F
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0
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Appendix 5.1. Fishermen's waterproof forms to collect data related to the crab catches in commercial scallop dredges.

Attention FIKRET ONDES

Bangor University – Brown Crab Monitoring Program

Vessel Name:	
Date:	
Number of dredge per side:	

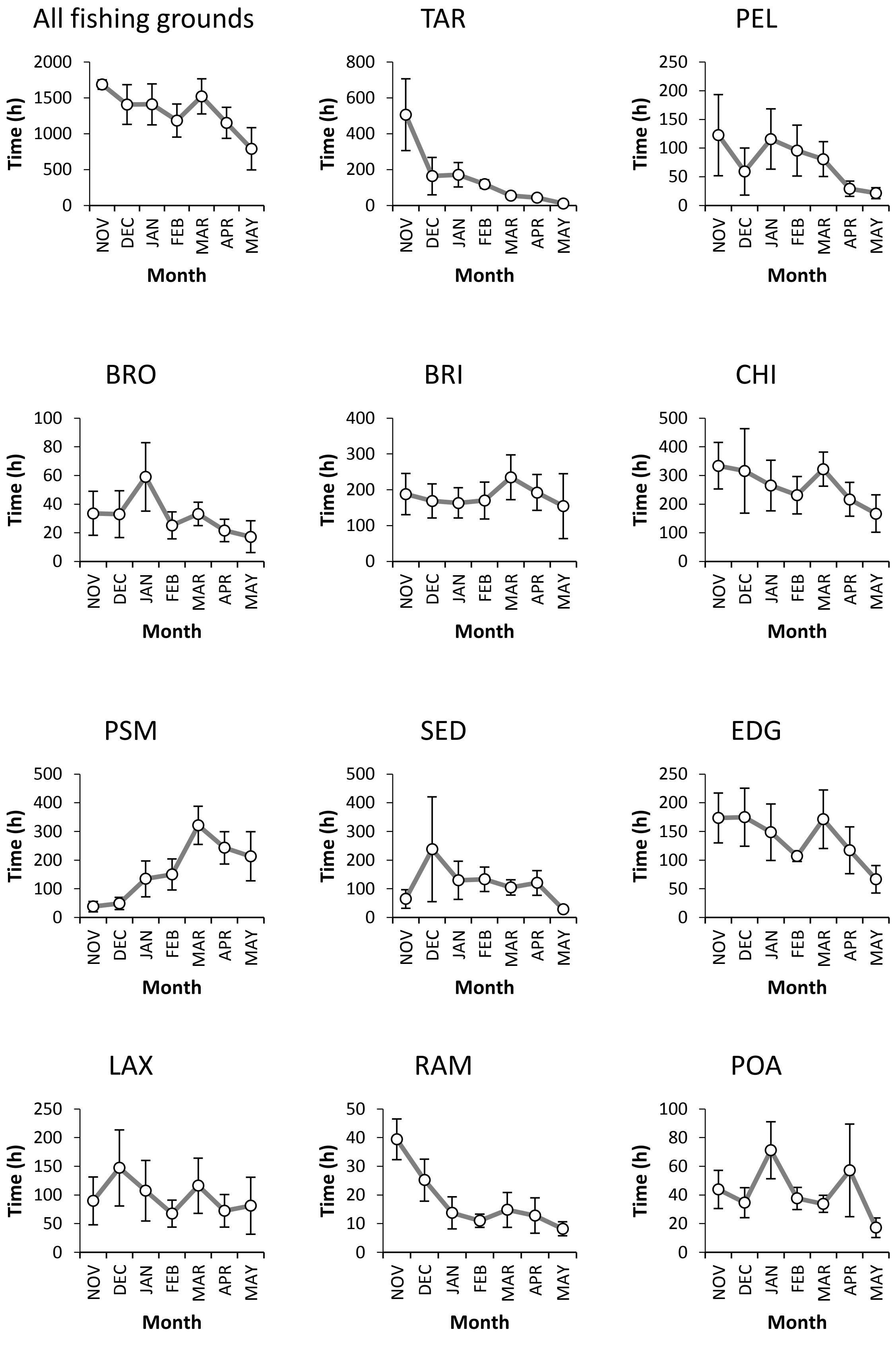
Tow Number	Tow Duration (hours, min)	Tow Coordinates	Depth (m)	Brown crab number per tow (except for berried crabs)	Berried crab number per tow	Bags of scallop per tow
1						
2						
3						
4						
5						
6						
7						
8						
9						
10						

Please return completed forms with your daily LOG SHEETS – Thank you

Or mail to: DEFA, Thie Slieau Whallian, Foxdale Road, St John's, IM4 3AS, Peel, Isle of Man

Email: fikretegesu@hotmail.com , Tel: 07624341472

Appendix 5.2. The mean tow time (h) ± SE of scallop dredging in the Isle of Man for the 6 years pooled data for the period 2008-2013. The data was obtained from the vessel monitoring system (VMS).



Appendix 6.1. By-catch species (mean body size > 45 mm) list.

Common name	Scientific name
Cnidaria	**Cnidaria**
Common jellyfish	*Aurelia aurita* (Linnaeus, 1758)
Crustacea	**Crustacea**
Circular crab	*Atelecyclus rotundatus* (Olivi, 1792)
Common shore crab	*Carcinus maenas* (Linnaeus, 1758)
Great spider crab	*Hyas araneus* (Linnaeus, 1758)
Squat lobster	*Galathea* spp.
Wrinkled Swimming crab	*Liocarcinus* sp.
Swimming crab	*Liocarcinus depurator* (Linnaeus, 1758)
Spiny spider crab	*Maja squinado* (Herbst, 1788)
Plated lobster	*Munida rugosa* (Fabricius, 1775)
Velvet crab	*Necora puber* (Linnaeus, 1767)
Prawn	*Palaemon* sp.
Common prawn	*Palaemon serratus* (Pennant, 1777)
Pink shrimp	*Pandalus montagui* Leach, 1814
Mollusca	**Mollusca**
Sea hare	*Aplysia punctata* (Cuvier, 1803)
Common pelican's foot	*Aporrhais pespelicani* (Linnaeus, 1758)
Common whelk	*Buccinum undatum* Linnaeus, 1758
Slender spindle shell	*Colus gracilis* (da Costa, 1778)
Curled octopus	*Eledone cirrhosa* (Lamarck, 1798)
King scallop	*Pecten maximus* (Linnaeus, 1758)
Echinodermata	**Echinodermata**
Common starfish	*Asterias rubens* Linnaeus, 1758
Cushion starfish	*Asterina gibbosa* (Pennant, 1777)
Sand star	*Astropecten irregularis* (Pennant, 1777)
Common sun star	*Croasster papposus* (Linnaeus, 1767)
European edible sea urchin	*Echinus esculentus* Linnaeus, 1758
Bloody Henry Starfish	*Henricia oculata* (Pennant, 1777)
Spiny starfish	*Marthasterias glacialis* (Linnaeus, 1758)
Pisces	**Pisces**
European conger	*Conger conger* (Linnaeus, 1758)
Atlantic cod	*Gadus morhua* Linnaeus, 1758
Rockling	*Gaidropsarus vulgaris* (Cloquet, 1824)
Ballan wrasse	*Labrus bergylta* Ascanius, 1767
Common dab	*Limanda limanda* (Linnaeus, 1758)
Haddock	*Melanogrammus aeglefinus* (Linnaeus, 1758)
Whiting	*Merlangius merlangus* (Linnaeus, 1758)
Hake	*Merluccius merluccius* (Linnaeus, 1758)
Lemon sole	*Microstomus kitt* (Walbaum, 1792)
Striped red mullet	*Mullus surmuletus* Linnaeus, 1758
Butterfish	*Pholis gunnellus* (Linnaeus, 1758)
Pollack	*Pollachius pollachius* (Linnaeus, 1758)
Coalfish	*Pollachius virens* (Linnaeus, 1758)
Small spotted catshark	*Scyliorhinus canicula* (Linnaeus, 1758)
Longspined scorpion	*Taurulus bubalis* (Euphrasen, 1786)
Poor cod	*Trisopterus minutus* (Linnaeus, 1758)
Topknot	*Zeugopterus punctatus* (Bloch, 1787)

*In addition to these species, 2 by-catch species (plate fish *Bothus lunatus* (Linnaeus, 1758), blenny fish, Blenniidae) were reported by fishermen in crustacean pots (Questionnaire study).

Appendix 6.2. Incidental species (mean body size < 45 mm or damaged sessile animals) list.

Common name	Scientific name
Cnidaria	**Cnidaria**
*Dead man's finger	*Alcyonium digitatum* Linnaeus, 1758
*Snakelocks anemone	*Anemonia viridis* (Forskål, 1775)
Polychaeta	**Polychaeta**
Polychaeta	Polychaeta spp.
Crustacea	**Crustacea**
Hermit crab	*Anapagurus laevis* (Bell, 1846)
Nut crab	*Ebalia* spp.
Strawberry crab	*Eurynome aspera* (Pennant, 1777)
Toad crab	*Hyas coarctatus* Leach, 1816
Spider crab	*Inachus* spp.
Spider crab	*Macropodia* spp.
Common hermit crab	*Pagurus bernhardus* (Linnaeus, 1758)
Hermit crab	*Pagurus prideaux* Leach, 1815
Gibb's sea spider	*Pisa* sp.
Long clawed porcelian crab	*Pisidia longicornis* (Linnaeus, 1767)
Porcelian crab	*Porcellana platycheles* (Pennant, 1777)
Mollusca	**Mollusca**
Needle whelk	*Bittium reticulatum* (da Costa, 1778)
Painted top shell	*Calliostoma zizyphinum* (Linnaeus, 1758)
Great top shell	*Gibbula magus* (Linnaeus, 1758)
Limpet	*Patella* sp.
Common tower shell	*Turritella communis* Risso, 1826
Arctic cowrie	*Trivia arctica* (Pulteney, 1799)
Bryozoa	**Bryozoa**
*Sea chervil	*Alcyonidium diaphanum* (Hudson, 1778)
Echinodermata	**Echinodermata**
Common brittle star	*Ophiothrix fragilis* (Abildgaard, in O.F. Müller, 1789)
Brittle star	*Ophiura albida* Forbes, 1839
Serpent star	*Ophiura ophiura* (Linnaeus, 1758)
Green sea urchin	*Psammechinus miliaris* (P.L.S. Müller, 1771)

*Three species (*Alcyonium digitatum, Anemonia viridis* and *Alcyonidium diaphanum*) were found as damaged body parts.

** In addition to listed incidental species, many small crustacean individuals (amphipods, tanaids and isopods) were found on the deck. However, their catch rate/abundance and species names could not be determined.