DOCTOR OF PHILOSOPHY

# Towards sustainable fisheries management; addressing evidence-gaps in baited-pot fisheries in the Irish Sea

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# Towards sustainable fisheries management; addressing evidence-gaps in baited-pot fisheries in the Irish Sea

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

By

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November 2020

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This thesis represents the progress I have made in my academic and professional life, with initial research having begun in Wales shortly after completion of my MSc. in 2014, and the final chapters representing recent work on the Isle of Man, where I now call home. The journey from a ‘green’ postgraduate research assistant based in Aberystwyth to my current desk at the DEFA office in St John’s, Isle of Man, has been shared with some of the most genuinely brilliant colleagues, including fellow researchers and academic staff, civil servants, and members of the fishing industry. Starting at the beginning, my utmost thanks go to Dr Jodie Haig and Professor Michel Kaiser in particular, who not only offered me my first ‘proper’ contract of employment, but also invested much of their own time and energy in my personal academic and professional growth. I certainly wouldn’t be in this position if it were not for their encouragement, mentorship, and inspiration. In addition, I would like to extend my gratitude to the rest of the Welsh EFF project staff, who made my brief stay in Wales incredibly fun, interesting and rewarding.

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## Abstract

Static-gear fisheries using baited pots are an increasingly valuable component of the fishing industry in the Irish Sea. Target species include Common whelk (*Buccinum undatum*), Edible crab (*Cancer pagurus*), European lobster (*Homarus gammarus*), and Common prawn (*Palaemon serratus*). Together, the harvest of these four species from the Irish Sea area (ICES division VIIa) by British vessels totalled 7,938 t in 2019 and were valued at £14.67 million at the point of first sale. However, there is an absence of evidence-based management applied to the fisheries as a consequence of data-poor status in key areas including biological and ecological understanding of life-histories, fisheries-dependent information on catch and effort, and scientific assessment methodologies for stock assessments. This thesis aims to address specific knowledge-gaps important for the sustainable management of baited pot fisheries in the Irish Sea.

Despite its relatively small size, the common prawn fishery is an economically important seasonal fishery in areas such as Cardigan Bay, Wales. The stock is prosecuted by a regulated open access fishery with no biologically referenced harvest control rules. In response to fluctuations in landings the fishing industry have adopted a size-selective harvesting regime of 10 mm carapace length (CL). This thesis presents a baseline of evidence for this fishery, and pays particular attention to the biological implications of size-selective harvesting and reproductive biology. Peak spawning occurred during the spring, whilst functional maturity of females was estimated at a CL of 9.9 mm. The species is sexually dimorphic, with females attaining a greater size than males. Size-selective harvesting results in a sex bias in landings as even large mature males often fail to recruit into the fishery.

Whilst whelk fishing activity covers large geographical areas of the Irish Sea, whelk populations are known to be vulnerable to localised overexploitation, and despite the prominence of common whelk fisheries in the Irish Sea, they remain relatively unrestricted. This thesis evaluates fundamental biological parameters within an environmental context, focussing in particular on reproductive biology and growth. Analyses highlight that, at the time of sampling, the majority of populations were not adequately protected by technical measures with size-at-maturity estimates being greater than the applicable minimum conservation reference size. Using previously validated ageing techniques, size-at-age relationships are presented for Irish Sea populations. $L_\infty$ showed a significant negative linear relationship with sea temperature. Other parameters, including maximum growth rates and the age at which growth rate begins to decrease, showed clear trends with sea-bottom temperature but linear modelling failed to detect significant relationships.

Despite the growing call to utilise fishery-dependent data in lieu of scientific stock assessments for data-poor fisheries, the resolution of these data are often insufficient for accurate catch and effort analysis. By trialling an Enhanced Electronic Reporting System (EERS) in the ‘mixed’ edible crab and European lobster fisheries in the Irish Sea, which integrates gear-in gear-out and mobile technologies, fisheries-dependent data has been shown to be a viable method of assessment. Using generalised additive models to investigate a dataset of environmental and fishing activity data, non-linear predictors of commercial landings-per-unit-effort (LPUE) data are estimated, which can be used to ‘standardise’ data.

These analyses and techniques are later discussed in terms of integrating standardised LPUE data into management of the Isle of Man edible crab fishery specifically, and baited-pot fisheries more generally.

Finally, population data are modelled to evaluate technical conservation measures in the European lobster fishery and common whelk fishery. Mark-recapture and size-structure data are combined to form an analysis and evaluation of the likely economic impacts to a change in minimum conservation reference size for European lobster in Isle of Man territorial waters. Size-selectivity of grading equipment trialled in the Isle of Man are assessed for common whelk fishery with reference to the earlier size-at-maturity estimates for the same population.

Separately, the data presented in this thesis address a range of knowledge-gaps in baited pot fisheries in the Irish Sea by focussing on specific data deficiencies. Together, they offer valuable improvements and insights into evidence-based fisheries science, conservation, and management in the region, and are useful references for management of baited-pot fisheries globally.

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# Chapter 1. General Introduction

## 1.1 Baited-pot fisheries in the Irish Sea: Introduction

Marine fish stocks are an important part of the world food system. Most existing analyses suggest overfishing is increasing, and there is widespread concern that fish stocks are decreasing throughout most of the world (Hilborn, et al., 2020). However, where stocks are managed according to a scientific evidence base and are scientifically assessed, stock abundances are increasing on average thereby delivering sustainable economic benefits to coastal communities, whilst safeguarding and conserving the marine environment (Hilborn, et al., 2020). Even within highly developed fisheries management areas (e.g. North-western Europe), many fisheries lack the fundamental data to address key knowledge gaps critical for evidence-based fisheries management, and therefore continue to operate without sustainable harvest strategies (CEFAS, 2013).

Static-gear fisheries employ capture technologies that do not move through the marine environment in order to capture target species; instead, the gear is set in the water to allow fish to swim into it, or target species are attracted to it by bait and consequently become caught by the gear (SEAFISH, 2011). Static-gear can include set nets, hooks and baited traps ('pots'), which are left for a period of time before being hauled, sorted and re-set. Unlike mobile-gear fisheries, static-gear fisheries do not necessarily require vessels to have high powered engines and winches in order to deploy, tow and retrieve fishing gear (e.g. trawls) and therefore include a diverse range of vessel designs and capacities, e.g. from estuarine coracles (~ 1 m) to mid-ocean longline freezer vessels (>50 m). The capacity of an individual commercial static-gear vessel to exert fishing effort can range significantly even within the same fishery and can be subject to different licensing, reporting and management regimes, even though they are operating within the same stock unit.

In the UK, static-gear baited-pot fisheries are generally considered to have lower environmental impact than mobile-gear fisheries owing to the perceived negligible benthic impact (Eno, et al., 2001) and live-release of non-target species by comparison to other methods (Jennings & Kaiser, 1998). This long-held view has led to a general absence of stock assessment and related scientific research, fisheries reporting requirements and evidence-based management for many baited-pot fisheries, and particularly those that are characterised by small inshore fishing operations. Nonetheless, UK fishing administrations now require these fisheries to operate within ecologically sustainable limits and demand 'fully documented' fleet activity. The data-requirements for these fisheries are only likely to increase as recent research suggests that their environmental impact may be more extensive than previously thought (Gall, et al., 2020; Hamilton & Baker, 2019). Developing robust evidence-based management regimes for these fisheries has become particularly important as they continue to grow in terms of effort, harvests and therefore economic significance within coastal economies.

Baited-pot fisheries within the Irish Sea (ICES Area VIIa) primarily target shellfish. Target species include, but are not limited to, European lobster (*Homarus gammarus*), edible crab (*Cancer pagurus*), Common whelk (*Buccinum undatum*) and Common prawn (*Palaemon serratus*). This thesis is a synthesis of research projects, several of which have been published in scientific journals (Chapters 2, 3, and 4) following peer-review, which address fundamental knowledge-gaps important for sustainable management of these fisheries. The work focusses primarily on species biology and the environmental drivers of spatial variation among populations within Manx and Welsh waters and presents the findings within the context of fisheries management. Alongside foundational biological and ecological parameterisation of species life-histories, this research also considers the impacts of changes in harvesting regimes as well as technological solutions for standardising and improving catch reporting among highly heterogeneous fleets. The implications of findings are presented within the context of fisheries management in the region.

## 1.2 Current practices

Fisheries in the Irish Sea that target shellfish using baited pots anchored to the seabed employ fishing methods with similar design principles and technologies as pre-industrial operations (Manx Heritage Foundation, 1991). However, whilst the fundamental practice of fishing with baited pots may not have changed over centuries, the capacity of the modern fishing fleet to exert fishing effort has increased significantly in both spatial and temporal terms in recent decades. Most significantly, developments in material durability (plastic-fibre twines), hydraulic hauling power, and vessel seagoing capabilities have allowed these fisheries to expand temporally (fishing throughout most of the year) and spatially (extending into fishing grounds further from ports) in recent decades (Marchal, et al., 2007). The design, size and setup of pots vary by target species and hauling capacity of the vessel, where larger vessels are more likely to employ larger, heavier pots. Examples of these pots are shown in Figure 1.1.

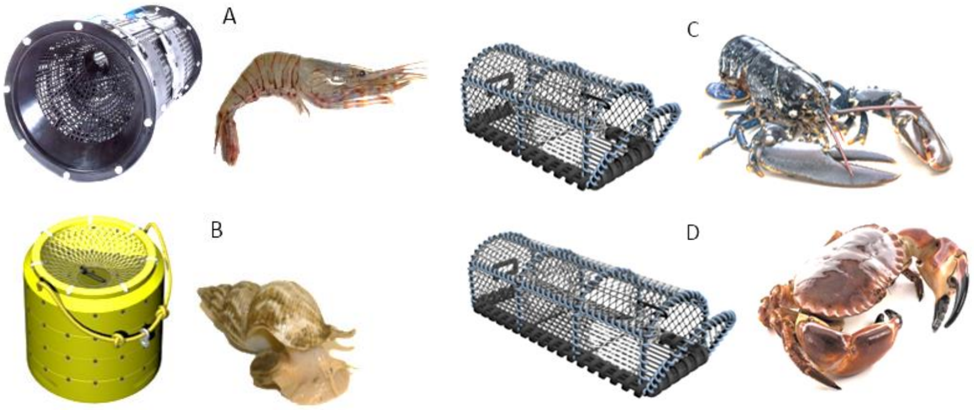

Figure 1.1 The pot design used to target shellfish species (shown side-by-side) typically used in the Irish Sea; A) a ‘roscoff’ style plastic pot used to target Common prawn (*Palaemon serratus*), B) an up-right drum shaped whelk pot with string-drawn net enclosure used to target Common whelk (*Buccinum undatum*), C) a D-shaped steel-framed lobster/crab pot (‘creel’) used to target European lobster (*Homarus gammarus*) and Edible crab (*Cancer pagurus*) and D) a similarly designed D-shaped steel-framed parlour pot (‘parlour’ meaning that the pot includes an additional area that retains greater quantities of catch) used to target primarily Edible crab (*Cancer pagurus*) with incidental catch of European lobster (*Homarus gammarus*).

Baited pots, including but not limited to the various designs highlighted above, can either be deployed (‘shot’) individually (‘singles’) or more typically in series attached to a single lead rope (‘string’ or ‘fleet’) (Figure 1.2). Baited pots set in strings are marked using a surface buoy with anchors fixed at both ends of the string in order to keep the string in location on the seabed. The average number of pots in a string varies according to vessel hauling capacity, deck area of the vessel, target species, location and skipper/crew preference. It is not uncommon for large vessels (> 15 m) to fish up to 100 pots in a string, and to haul up to 15 strings per day, when targeting whelk for example. By comparison, some of the smallest commercially licensed vessels in the Irish Sea may deploy only a small number of singles in shallow inshore reef systems (*pers obs.*).

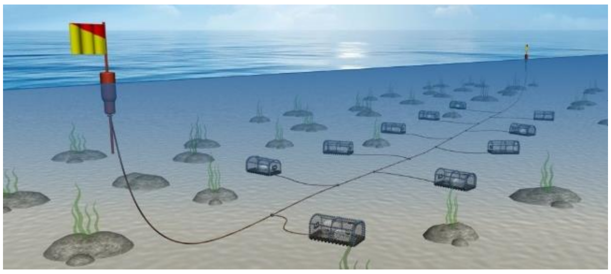

Figure 1.2. A computer generated image of a ‘string’ of lobster pots. Note that the anchor is not set on the lead rope in this image, but would be attached to the lead line on the outside of the two end-pots (source: seafish).

Fleets are hauled by firstly collecting the surface marker, which is usually a buoy or dhan design, using a hydraulic powered winch. The hauler sequentially brings the pots onto the deck of the boat, where the crew are able to clear the catch by storing the target species and discarding any bycatch, before then stacking the freshly re-baited pots on the vessel deck. Once the whole fleet is aboard and stacked, the skipper will manoeuvre the vessel to the next fishing location and re-deploy (‘shoot’) the fleet. This is usually achieved by manhandling the surface buoy, anchor and first pot through an opening in the stern or gunwale. The remaining pots in the string are towed off the deck and into the sea as the lead rope comes tight on the next pot in the string as the vessel powers ahead over the targeted fishing ground, until the anchor is finally deployed and the string is set on the seabed. This setup is standard among pot-vessels in the Irish Sea though some unique designs and operating procedures are evident, particularly among smaller vessels (*pers obs.*). For example a very small commercial lobster vessel in the northern Irish Sea employs a re-engineered electric golf buggy as a makeshift hauler and sets singles by man-handling each pot over the vessels low gunwale.

Figure 1.3. Top left) a small commercial pot fishing vessel (Auk CT25) in the Isle of Man; top right) an 8 m multi-hull potting vessel (Boy Shayne PL777) alongside FPV Barrule, with stacked whelk pots on the deck alongside bags of retained common whelk (*Buccinum undatum*); bottom-left) a large (12 m) mono-hull potting vessel (New Dawn PL1) entering Peel harbour, Isle of Man; bottom-right) three medium-sized multi-hull potting vessels (8-10 m; Dycosa DO22, Manx Cat PL2, Free Spirit II PL165) on Peel breakwater, Isle of Man. Photographs by Jon Wornham©, James Cubbon© and Bangor University.

## 1.3 Catch data reporting

Fisheries-dependent data, i.e. those data that are submitted by skippers pertaining to commercial fishing activity, generally varies depending on the:

- type of commercial activity (gear-specific, species-specific, etc.);
- size (length overall; LOA) of the vessel;
- jurisdiction within which the activity takes place, and
- specific area-based legislative requirements.

Fisheries dependent data in the Irish Sea can include, but is not limited to, the requirement to submit:

- basic commercial activity data (departure port, trip duration, etc.);
- spatial data (e.g. VMS, GPS, ICES Rectangle reference etc.);
- landings data (weight of retained species);
- effort data (specification and quantity of fishing gear deployed);
- bycatch data (e.g. EU Landings Obligation regulations), and
- additional scientific data (e.g. CCTV data, scientific observation logbook, etc.).

Catch-recording requirements are imposed inconsistently across vessels targeting stocks in the Irish Sea using baited traps. The inconsistency is primarily a result of varying requirements across vessel-length métiers, but also as a result of jurisdictional-specific regulations (there are seven fishing authority jurisdictions within the Irish Sea). This scenario is common throughout Europe despite efforts to establish overarching data collection principles within the EU Common Fisheries Policy (Article 25(2);Data requirements for fisheries management). However the Irish Sea can be seen as a particularly complex area owing to the:

- devolution of national and regional fisheries administrations within the UK
    - England; Inshore Fisheries Conservation Authorities (IFCAs) in the 0-6 NM and the Marine Management Organisation (MMO) 6 NM-EEZ limit (Marine and Coastal Access Act, 2009).
    - Scotland; Marine Scotland and Scottish Regional Inshore Fisheries Groups (RIFGs) (Scottish Adjacent Water Boundary Order, 1999; Marine (Scotland) Act, 2010).
    - The Welsh Zone, as defined in The Welsh Zone (Boundaries and Transfer of Functions Order, 2010)
    - The Northern Ireland Zone (The Adjacent Waters Boundaries (Northern Ireland) Order, 2002)
- Isle of Man (self-governing British Crown Dependency)

  - Territorial sea regulatory powers (see The Territorial Sea Act 1987 (Isle of Man) Order, 1991; Fisheries Management Agreement, 2012; Isle of Man Fisheries Act 2012)

- EU Member States (Republic of Ireland)
  - With responsibility to enact and enforce EU regulations and directives (EU Communities Act, 1972; EU Control Regulation, 2009) and with the power to introduce secondary legislation for the purpose of dealing with the organisation of fisheries control and enforcement within the Irish EEZ (Sea-Fisheries and Maritime Jurisdiction Act, 2006).

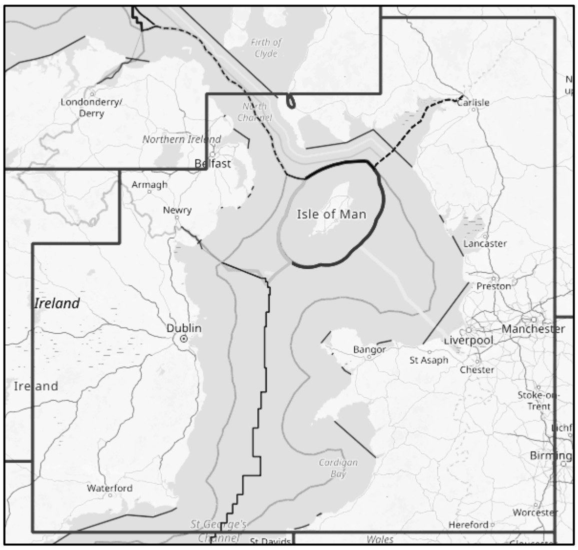

Figure 1.4. A map showing the Irish Sea (ICES Division 27.7.a "VIIa") with inter-and-intranational jurisdictional boundaries relevant to fisheries management. Data source: Marine Scotland Information

Nonetheless, since 2012, data reporting has become relatively improved and standardised among the various jurisdictions in the Irish Sea and data are held in a central UK database IFISH2 ('Integrated Fisheries System Holding data warehouse), which complies with the EU Data Collection Framework (DCF). This data reporting is composed of EU sales notes from British fishing vessels, and includes the basic following information for commercial activity irrespective of vessel metier:

- date of landing;
- landing port;
- gear-type;
- species type;
- landed weight;
- landed value;
- ICES Rectangle, and

- vessel details (registered nationality, size, engine-power, registration details, etc.)

The sales notes do not include data on fishing effort (defined most appropriately as the number of pot-lifts per trip) and string-specific information (e.g. soak-time, pot-type, pot-volume, latitude/longitude location, etc.) essential for understanding the dynamics of baited pot fisheries. Although these information are not typically required, several jurisdictions do involve some level of enhanced paper logbook reporting for smaller (<10 m) vessels (including the Isle of Man "Monthly Shellfish Activity Logbook", Marine Scotland "Fish1 form"). Unfortunately, these enhanced datasets are not centrally maintained nor accessible across jurisdictions without specific data-sharing arrangements.

Although the iFISH2 database cannot be used in isolation for stock-assessments of baited pot fisheries in the Irish Sea, nor used to explain general trends in catch, they can be used to profile these fisheries across a temporal and spatial scale.

## 1.4 Brief species summary: Ecology, biology and fisheries management

### 1.4.1 Common prawn (*Palaemon serratus,* Pennant, 1777)

Taxonomically, this species of prawn belong to the Class Malacostraca, the Order Decapoda, Infraorder Caridea, Family: Palaemonidae and Genus: Palaemon. The species is the largest of the native shrimp and prawn species around the British Isles and is distinguishable from other Palaemonidae by the number of rostral teeth along the upper and lower edge of the rostrum (Reeve, 1968).

Common prawn are widely distributed throughout the inshore waters of Europe (Kelly, et al., 2008), stretching from the Mediterranean to the temperate coastal waters of the British Isles in North-western Europe (Forster, 1951). Populations undertake seasonal migrations, moving from estuarine and rocky-shore habitats in summer to muddy habitats in deeper coastal waters during winter, correlating to seasonal spawning behaviours (Forster, 1951; González-Ortegón, et al., 2006). Common prawn have a relatively short life-span typically surviving no longer than three years (Fahy & Gleeson, 1996). The species is omnivorous and dioecious (Cole, 1958). Fertilisation is external and eggs are carried for a period of months before being released by the female into the water column (Cole, 1958).

The British fishery for common prawn is a spatially localised commercial fishery with the principal area of production being the inshore waters of the southern Irish Sea, primarily in the coastal waters of west Wales north through Cardigan Bay to the Llyn Peninsula (Percy, 2006). This stock is undefined and unassessed and there is no formal stock advice with respect to sustainable harvest limits or effort inputs. Harvest control rules, including effort limits, are therefore completely absent, including any spatial-temporal closures and size/sex-based limits that would aim to reduce the rate of mortality in spawning seasons/areas and among juvenile/egg-bearing individuals. The status of the fishery is unknown (Fahy & Gleeson, 1996) and there is concern that the species may be vulnerable to overfishing and 'boom-bust' dynamics (Percy, 2006; Kelly, et al., 2008).

### 1.4.2 Edible crab (*Cancer pagurus*)

Taxonomically, the edible crab (also referred to as 'brown crab') belongs to the Class: Malacostraca, the Order: Decapoda, Infraorder: Brachyura, Family: Cancridae and Genus: Cancer. Abundant populations are frequently observed in the North-east Atlantic on European coastal shelves around Britain and Ireland, with the distribution stretching as far south as the coast of North Africa and as far North as Norway on hard bedrock habitats, as well as mud and sand from shallow sublittoral areas to depths in excess of 100 m (Neal & Wilson, 2008).

Edible crab are nocturnal and are both predators and scavengers, feeding on a variety of live molluscs and crustaceans as well as carrion (Lawton, 1989; Skajaa, et al., 1998; Woll, 2003). Mating by copulation occurs during the spring and summer months, after a female has recently undergone ecdysis (Brown & Bennet, 1980). Egg-bearing ‘berried’ females migrate from the inshore, hard-substrate mating grounds into soft mud typically further offshore in order to incubate eggs (Nichols, et al., 1982). During this period, females exhibit very limited feeding activity (Howard, 1982) and consequentally are rarely captured within the baited pot-fisheries (Ondes, et al., 2019). Despite being difficult to accurately age due to growth by ecdysis (Sheridan, et al., 2015), it is accepted that the longevity of the species is typically up to 15 years, reaching a maximum size of 267 mm and 242 mm carapce width (CW) in males and females respectively (Tully, et al., 2006; Mill, et al., 2009).

In the Irish Sea, the minimum conservation reference size (MCRS) (minimum landings size) of edible crab is measured by CW and varies by jurisdiction, where MCRS is set at;

- 130 mm in the Isle of Man territorial waters, English northwestern Inshore Fisheries & Conservation Authority (IFCA) and UK Marine Management Organisation (MMO) management areas;
- 140 mm in the Welsh zone, Northern Irish zone and the Repblic of Ireland EEZ, and
- 150 mm in Scottish waters.

With the exception of within the Isle of Man territorial waters where there is a limit on pot numbers (maximum of 500 per licence, and no more than 300 in the 0-3 NM zone) and fishing licenses, the application of the MCRS and prohibition of landing berried females are the sole conservation measures for edible crab stock(s). The MCRS is set at a size greater than the estimated size-at-maturity for the species in this region (Haig, et al., 2016), therefore affording an appropriate level of protection to the spawning stock. There are no harvest limits (total allowable catch, TAC) in place in any part of the Irish Sea.

Irish Sea crab stocks remain undefined and unassessed. For example CEFAS does not currently include the Irish Sea fishery unit (FU) within the portfolio of length-based assessments conducted for edible crab elsewhere, indluding the Celtic Sea (inclusive of southernmost Welsh waters), Western English Channel, Southern North Sea and Central North Sea (CEFAS, 2017). Similarly, Marine Scotland (Science) does not undertake an assessment of brown crab within Scottish waters in the Irish Sea, although the geographically adjacent unit (Clyde) was assessed as Above $F_{MSY}$ for the most recent assessment period (Mesquita, et al., 2017). Likewise, the Marine Institute (Republic of Ireland) does not assess edible crab within the Irish Sea, although there are some commercial data presented in a recently published report (Marine Institute, 2018). The Isle of Man edible crab fishery was studied as part of a PhD thesis (Bangor University 2012-2013; Ondes, 2015) and a basic summary of fisheries-dependent data is provided within Bangor University annual reports to the Isle of Man as part of the independent fisheries science contract (2015-2020).

### 1.4.3 European lobster (*Homarus gammarus*)

Taxonomically, the European lobster belongs to the Class: Malacostraca, the Order: Decapoda, Family: Nephropidae and Genus: Homarus. Abundant populations are frequently observed in the North-east Atlantic on European coastal shelves around Britain and Ireland, with the distribution stretching as far south as the coast of North Africa and the Azores and as far north as Arctic Norway on hard bedrock and reef habitats, from shallow sublittoral areas to depths usually no greater than 50 m (Holthuis, 1991).

Compared to edible crab, European lobster have small home ranges, although they must expand their home-range as they grow (through the same process; ecdysis) in order to find suitable shelter. Adults are long-lived and iteroparous after reaching sexual maturity, which is evident through a number of morphometric (e.g. allometric growth in secondary sexual characteristics such as the abdomen and crusher claw) and behavioural (e.g. presence of eggs on females) indices (Wahle, et al., 2013). Despite a common misconception, European lobster are polygynous and females locate optimal mating partners in the days leading up to ecdysis, which in the Irish Sea is typically in mid-to-late summer depending on temperature (*pers obs.*). After ecdysis, when the female is ‘soft-shelled’, the male deposits spermataphores internally into the seminal receptacle of the female, which is thought can be stored for several years (Talbot & Helluy, 1995). Fertilization is external and females carry eggs under their abdomen by cementing them to the pleopods for 9-11 months during egg development (Branford, 1998). Eggs are released into the water column the following spring, after which the eggs hatch and lobster larvae spend several weeks in the water column and undergo a series of larval-stage moults, before the young-of-year descend to the sea-bottom in search of suitably complex habitat to avoid predation (Wahle, et al., 2013). European lobster are omnivorous, feeding on a variety of live molluscs and crustaceans as well as carrion (Wahle, et al., 2013). Size at maturity of European lobster has been found to vary around the British Isles from 80 mm CL to 110 mm CL (Lizárraga-Cuebedo, et al., 2003), whilst in the Irish Sea region it is estimated to be around 93 mm CL (Tully et al., 2001).

In the Irish Sea, the MCRS of European lobster is measured by carapace length (CL), and MCRS is set at 87 mm CL in all areas except in the Welsh zone, where the MCRS was increased to 90 mm. A maximum landing size is also applied in the Republic of Ireland (127 mm CL) and Scottish waters (155 mm CL). Throughout the Irish Sea there is a prohibition on landing lobsters that have been ‘v-notched’, which is a voluntary exercise undertaken by some fisherman that (harmlessly) marks the uropod of egg-bearing females. In Isle of Man territorial waters and in English waters, it is illegal to land egg-bearing (‘berried’) lobsters and also remove egg clutches from berried females (a practice known as ‘scrubbing’).

With the exception of Isle of Man territorial waters, where the number of crab and lobster pots and licenses are capped (see above), lobster fisheries are managed exclusively with technical measures relating to the size and condition of catch. Similarly to edible crab, stock assessments are not undertaken by CEFAS, Marine Scotland or the Marine Institute for the Irish Sea. Irish Sea European lobster fisheries are therefore undefined and unassessed, with the exception of a basic summary of fisheries-dependent data that is provided within Bangor University annual reports to the Isle of Man as part of the independent fisheries science contract (2015-2020).

### 1.4.4 Common whelk (*Buccinum undatum*)

Taxonomically, the common whelk belongs to the Class: Gastropoda, the Order: Neogastropoda, Family: Buccinidae and Genus: Buccinum. Common whelk are found in subtidal waters of the North Atlantic to depths of 1200 m (Ager, 2008). They are widely distributed on the Atlantic shelf from within the arctic circle (76° N) as far south as Delaware Bay, USA (39° N) at the western-most extent (Van Guelpen, et al., 2005). Populations are most frequently observed in abundance in the northeast Atlantic, particularly in the waters of north-western Europe from the Celtic Sea and Irish Sea through to Skagerrak and Kattegat Bay, including northern populations observed in Norwegian, Faroese and Icelandic waters.

The common whelk is the largest edible marine gastropod in the North Atlantic, reaching a total shell length (TSL) of 150 mm in some areas (Hancock, 1967). It exhibits late sexual maturation and low fecundity (Martel, et al., 1986), rendering commercially targeted populations vulnerable to recruitment overfishing (Shrives, et al., 2015). The reproductive strategy, i.e. the absence of a larval stage by which widespread dispersal of individuals to other areas is possible, combined with evidence of limited range of movement even after having recruited into the adult population, means populations may be isolated even within small geographic areas.

In the Irish Sea, the management of common whelk fisheries varies by jurisdiction despite vessels engaging in fishing activity throughout broader geographical areas (nomadic) that cross multiple jurisdictions (*pers obs.*). There is therefore a greater issue of regulatory alignment and enforcement of area-specific technical conservation measures for this species since the source of catch cannot always be easily determined. The common whelk is subject to an MCRS of:

- 25 mm shell width (SW) in Republic of Ireland waters;
- 45 mm total-shell-length (TSL) in English MMO and IFCA areas, Scottish waters, the Northern Ireland zone;
- 65 mm TSL in the Welsh zone, and
- 75 mm TSL in Isle of Man territorial waters.

With the exception of Isle of Man territorial waters, where the number of whelk pots and licenses are capped, whelk fisheries are managed exclusively with technical measures relating to size. No stock assessments are undertaken for this species in the Irish Sea.

## 1.5 Baited-pot fisheries in the Irish Sea: recent trends

Common prawn, common whelk, European lobster and edible crab have supported historic commercial fisheries in the Irish Sea for hundreds of years (Manx Heritage Foundation, 1991). The historic market-demand for these species will undoubtedly have been a small fraction of current harvests, and with a relatively greater proportion of the harvest destined for local markets (Manx Heritage Foundation, 1991). Today, these fisheries supply a global market with frozen, fresh and live shellfish, with significant economic throughput over an extensive and diverse supply chain (*pers comms.*, Island Seafare). Local demand does still exist for all of these main shellfish species, though the vast majority of commercial harvests are now delivered to wholesale, retail and small-business customers in continental Europe, the far-East and China (*pers comms.*, Island Seafare).

The four most valuable species in 2019 within the Irish Sea targeted by British vessels (including both UK and Crown Dependency registered vessels) using baited pots were the common whelk (*Buccinum undatum*; 5,873 t; £6.9 million), European lobster (*Homarus gammarus*; 309 t; £3.9 million), edible crab (*Cancer pagurus*; 1,741 t; £3.5 million) and the common prawn (*Palaemon serratus*; 13.5 t, £0.3 million), representing a total first point-of-sale value of £14.6 million (Figure 4 & 5) (Data: IFISH2 database). The greatest harvests for each species, for the whole of the Irish Sea, was in 2017 for common whelk (7,710 t), 2015 for European lobster (314 t), 2018 for edible crab (1,986 t) and 2018 for common prawn 25 t) (Figure 1.5). Non-British vessels (e.g. Republic of Ireland) are not routinely captured in the iFISH database unless they record landings at a UK port, and were not available for analysis.

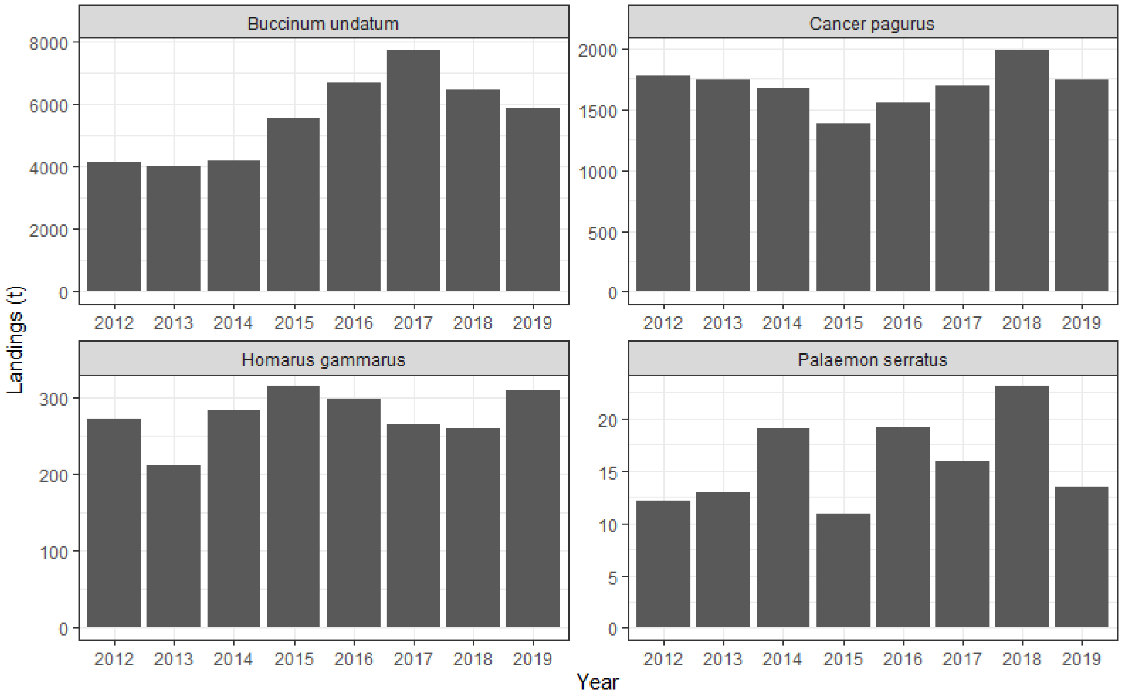

Figure 1.5. The annual landings (t) of common prawn (*Palaemon serratus*), common whelk (*Buccinum undatum*), edible crab (*Cancer pagurus*) and European lobster (*Homarus gammarus*) by British vessels in the Irish Sea (ICES Area VIIa) between 2012 and 2019. Data Source: iFISH2

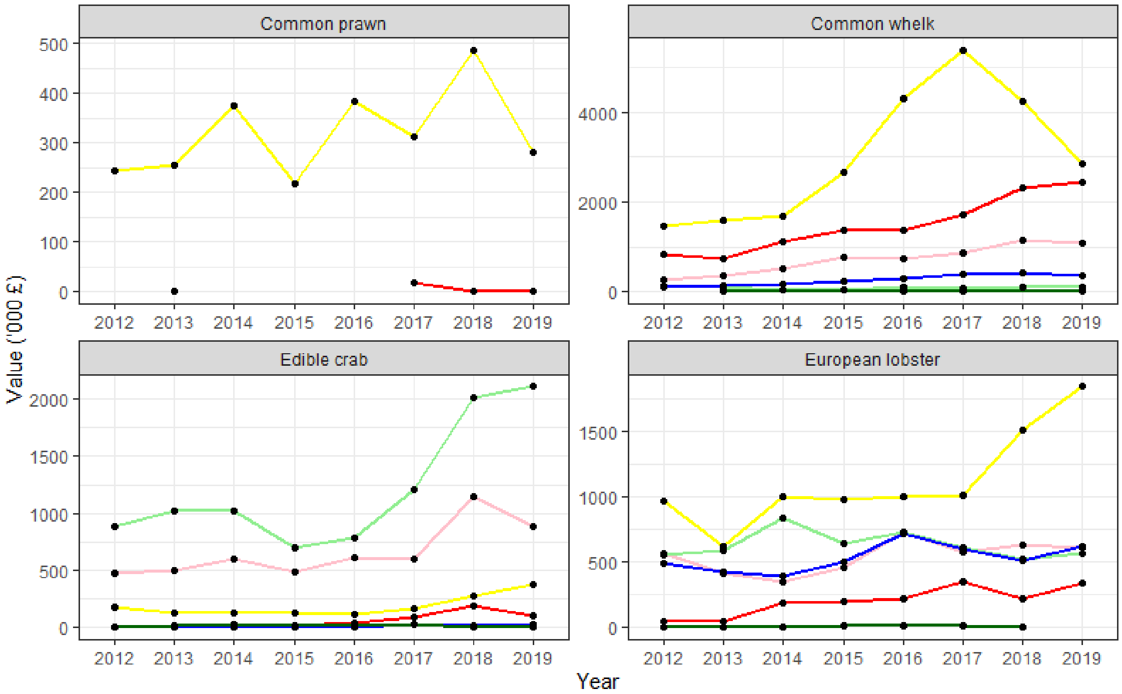

Figure 1.6. The annual value ('000 £) of common prawn (*Palaemon serratus*), common whelk (*Buccinum undatum*), edible crab (*Cancer pagurus*) and European lobster (*Homarus gammarus*) by Welsh (yellow), English (red), Scottish (blue), Northern Irish (light green), Irish Republic (green), and Manx (pink) vessels in the Irish Sea (ICES Area VIIa) between 2012 and 2019. Data Source: iFISH2

The relative economic importance of each fishery varies around the Irish Sea by geographic region. For example, common whelk is landed into ports throughout the Irish Sea from South-west Wales to northern England and Dumfries and Galloway in Scotland, including significant commercial landings in the Isle of Man. By contrast, common prawn is almost exclusively a Welsh fishery, with only small and occasional records of landings into west Cumbria, England. Commercial landings of edible crab are mostly in the northern Irish Sea, where the largest volume of catches are landed into Northern Ireland and the Isle of Man. However 50-100 tonnes are also usually landed into Wales annually. Finally, records of European lobster landings are present throughout the Irish Sea, as shown in Figure 1.6 and Figure 1.7.

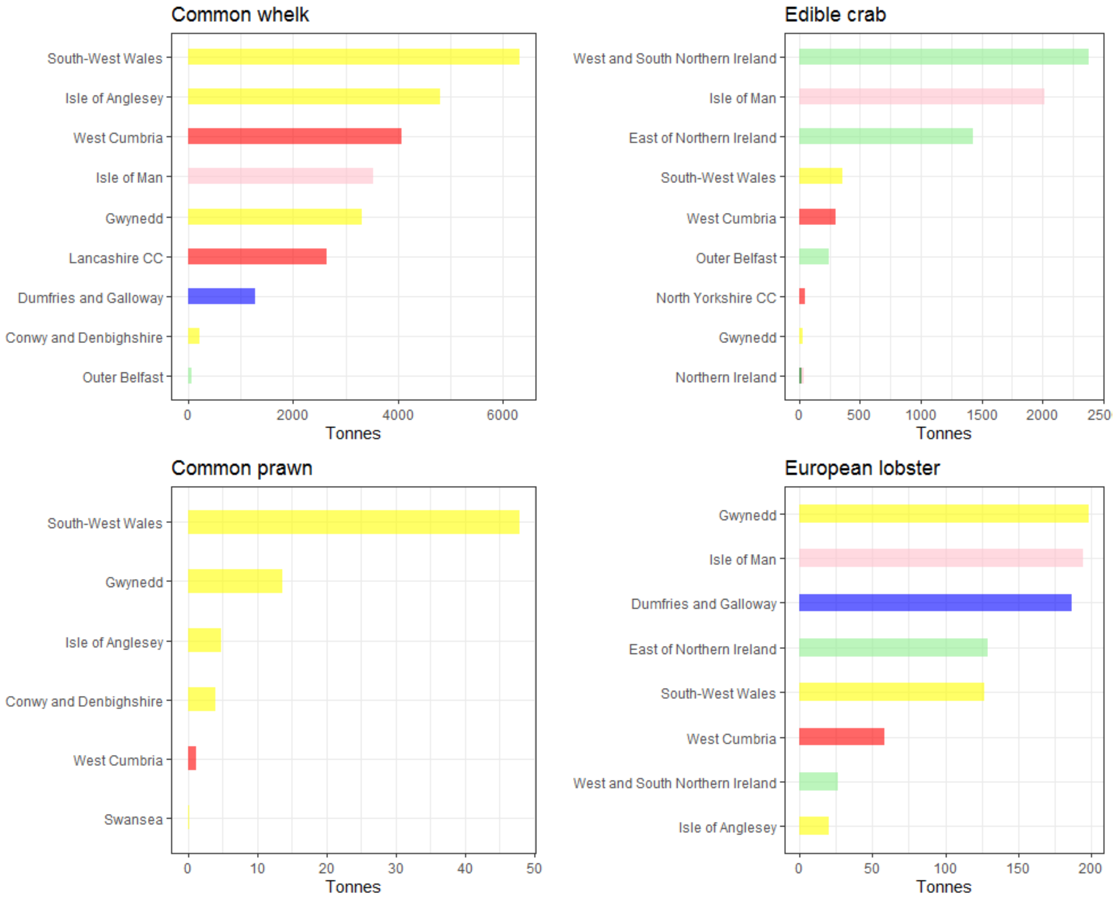

Figure 1.7. The landed weight of common whelk (*Buccinum undatum*), common prawn (*Palaemon serratus*), edible crab (*Cancer pagurus*) and European lobster (*Homarus gammarus*) in the Irish Sea, 2016-2019, by geographic region and country (Wales = yellow, England = red, Scotland = blue, Northern Ireland = light green, Republic of Ireland = green, Isle of Man = pink). Data Source: iFISH2

Between 2012 and 2019 92,952 vessel-days of effort were spent by British fishing vessels prosecuting the four shellfish species (common prawn, common whelk, European lobster and edible crab) (Figure 8). The total number of days, which is a coarse proxy for fishing effort, has been generally increasing since 2012 for all species with the exception of common prawn. The greatest amount of fishing effort among British registered vessels, defined here as a vessel-days, is spent fishing for European lobster.

Within the Irish Sea, common whelk has seen the greatest rate of increase in effort as the number of days spent at sea by British vessels has more than doubled since 2012 (Figure 1.8). Increases in effort targeting common whelk has been primarily in Wales, Northwest England and the Isle of Man although the number of days spent fishing for whelk in Wales has been in decline since the height of the fishery in 2017 (Figure 1.8). Of all the jurisdictions, the Isle of Man has seen the most consistent increase in fishing effort across all commercial species (other than common prawn, which is only fished in Wales) since 2012.

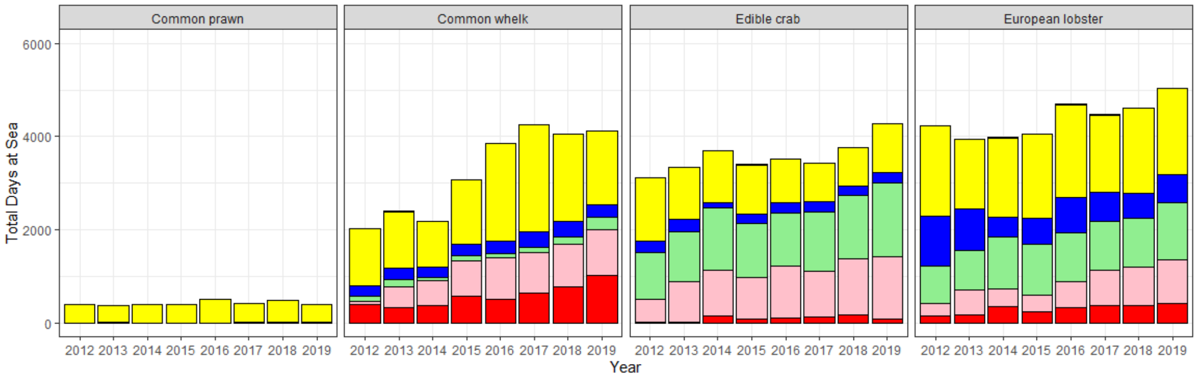

Figure 1.8. The number of days spent at sea (Fishing effort proxy) by British vessels fishing for common whelk (*Buccinum undatum*), European lobster (*Homarus gammarus*), edible crab (*Cancer pagurus*) or the common prawn (*Palaemon serratus*) by country in the Irish Sea (ICES Area VIIa) from 2012 to 2019 by country (Wales = yellow, Blue = Scotland, Red = England, Light green = Northern Ireland, Republic of Ireland = dark green, Isle of Man = pink). Date Source: iFISH2

The size-structure of the vessels engaged in the baited-pot fisheries in the Irish Sea (Figure 1.9) suggest that certain métiers characteristics are favourable for some species-specific fisheries compared to others, and that certain regions can support larger vessels than others. British vessels using baited pots in the Irish Sea are mostly very small (5 – 8 m) and small (8 – 10 m) sized vessels. There are a number of large vessels (over 15 m) that land into the UK and Isle of Man, as well as medium sized vessels (10-12 m) (Figure 1.10). The preference for small vessels under 10 m is likely a consequence of regulatory and licensing demands that are imposed on larger vessels, along with economic considerations such as capital cost, fuel-efficiency, crewing requirements and deck-space for storing daily catches, as well as logistical and operating constraints in regional port-facilities.

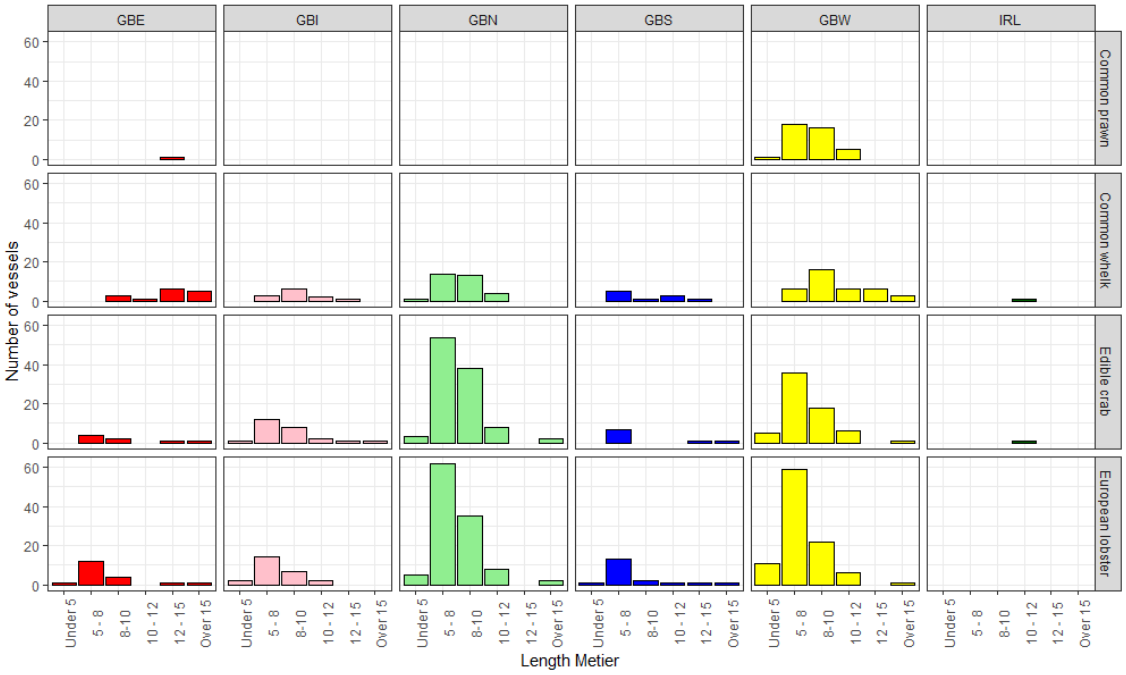

Figure 1.9. A frequency distribution showing the size metier structure (Length Overall groups) of the British fleet targeting shellfish species using static-gear during the period in 2019 in the Irish Sea (ICES Area VIIa) by country (England = Red, Isle of Man = pink, Northern Ireland = light green, Scotland = blue, Wales = yellow, Republic of Ireland = dark green) and target species (by row). Data Source: iFISH2

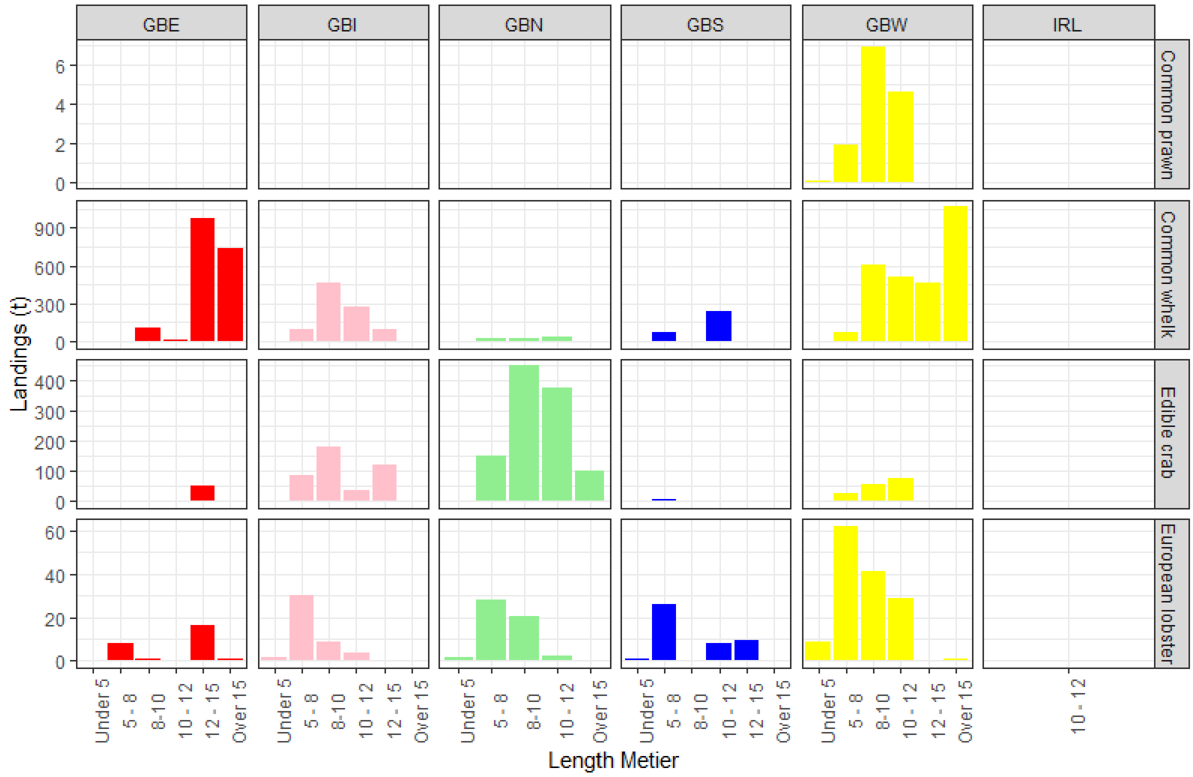

Figure 1.10. A bar chart showing landings (t) by vessel in each size metier (Length Overall groups) of the British fleet targeting shellfish species using static-gear during the period in 2019 in the Irish Sea (ICES Area VIIa) by country ('GBE' England = Red, 'GBI' Isle of Man = pink, 'GBN' Northern Ireland = light green, 'GBS' Scotland = blue, 'GBW' Wales = yellow, 'IRL' Republic of Ireland = dark green) and target species (by row). Data Source: iFISH2

Although the size-structure of Irish Sea fishing fleets show a greater number of smaller vessels, Figure 10 shows that landings within each fleet metier do not necessarily correlate with the number of active vessels for some species. The data highlights that larger vessels are responsible for a greater proportion of landings compared to their smaller counterparts, particularly considering species that are typically high-volume and low-value such as common whelk and edible crab (Figure 1.10). For example, common whelk landings into Wales during 2019 by vessels greater than 15 m LOA were greater than any other metier, despite the relatively small number of vessels in that specific metier.

Data from high-value and low-volume fisheries, such as European lobster and common prawn, show a greater correlation between vessel metier structure (Figure 1.10) and landings by metier (Figure 1.10). For example in the Isle of Man and Northern Ireland, the fleet structure of vessels landing European lobster shows that the most common metier is the 5-8 m and then the 8-10 m category (Figure 1.9). Landings data of European lobster into the Isle of Man and Northern Ireland during 2019 reflect this fleet structure, with approximately 30 t and 28 t landed by 5-8 m vessels and approximately 10 t and 20 t by the 8-10 m category in the Isle of Man and Northern Ireland respectively.

Larger vessels are able to deploy longer strings with a greater number of pots per string and therefore land greater amounts of catch during the day, as well as being able to retain a greater quantity of catch on the deck without creating stability issues for the vessel. This is particularly important in fisheries that target high-volume, low-value species such as edible crab and common whelk. Further, larger vessels are more capable of fishing in less favourable conditions compared to small vessels, and can therefore shoot and haul fishing gear over a greater spatial extent (e.g. in deeper water) as well as being able to operate in worsened sea-states. Larger vessels are therefore more likely to exert a greater proportion of fishing effort relative to the overall fleet composition. This is particularly true for vessels > 15 m LOA (Figure 1.11). Nonetheless, effort (as number of days at sea) broadly reflects the fleet composition in most countries and fisheries in 2019 (Figure 1.11). In the absence of more specific effort data throughout the fleet (e.g. number of pots hauled per trip), greater understanding into the proportion of fishing effort exerted by each metier within the Irish Sea baited pot fisheries is not possible.

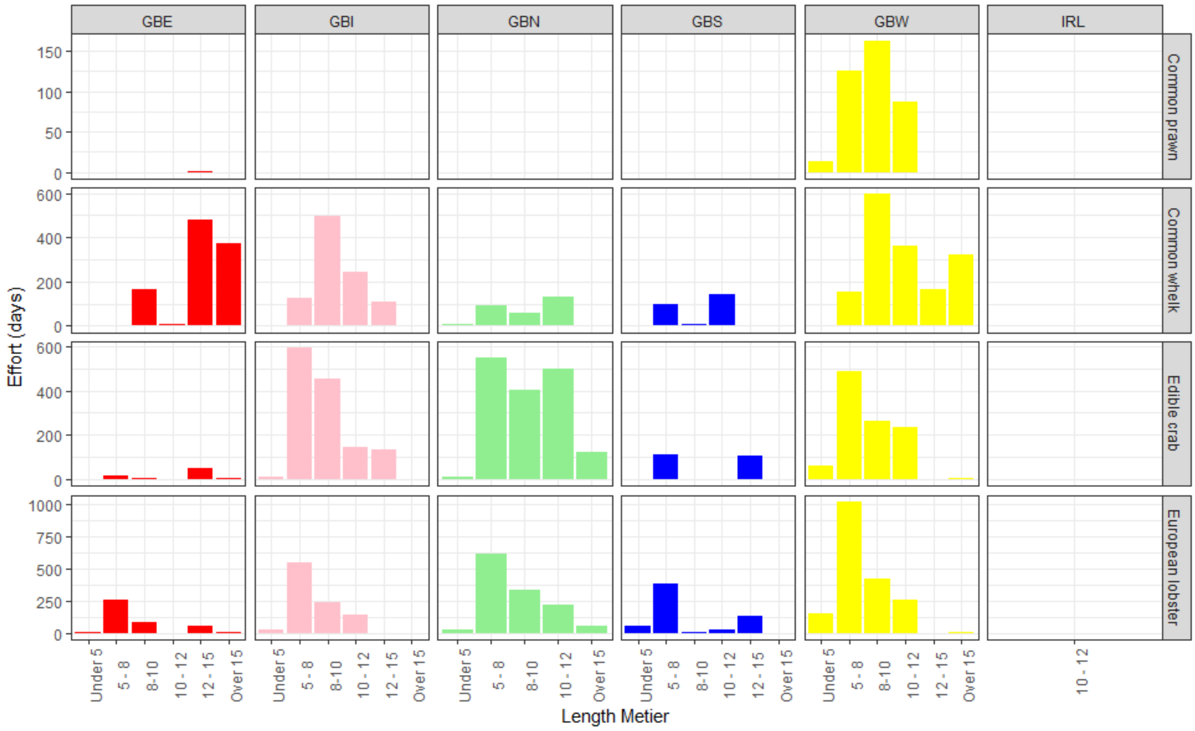

Figure 1.11. A bar chart showing effort (days) by vessels in each size metier (Length Overall groups) of the British fleet targeting shellfish species using static-gear during the period in 2019 in the Irish Sea (ICES Area VIIa) by country (England = Red, Isle of Man = pink, Northern Ireland = light green, Scotland = blue, Wales = yellow, Republic of Ireland = dark green) and target species (by row). Data Source: iFISH2

The quantity of shellfish landed each fishing trip also varies by area and length metier (Figure 1.12). Particularly among Welsh vessels, landings per trip are greater in larger size categories for all species. Elsewhere, for example in Northern Ireland, the relationship between vessel size and landings per trip is less clear. Furthermore, data from some smaller vessel metiers indicate greater productivity than larger vessels, for example the European lobster fishery in the Isle of Man and to a lesser extent Northern Ireland. European lobster fishery data are abnormal in this respect because European lobster are frequently kept in ‘stock pots’ for a period of time before landing, in order to achieve increased economic returns and greater shipping efficiency. Smaller vessels may therefore actually catch less per trip, but store catch over several days and submit a single logbook submission when the accumulation of retained catch are landed. European lobster data, in terms of landings per trip, are therefore unreliable.

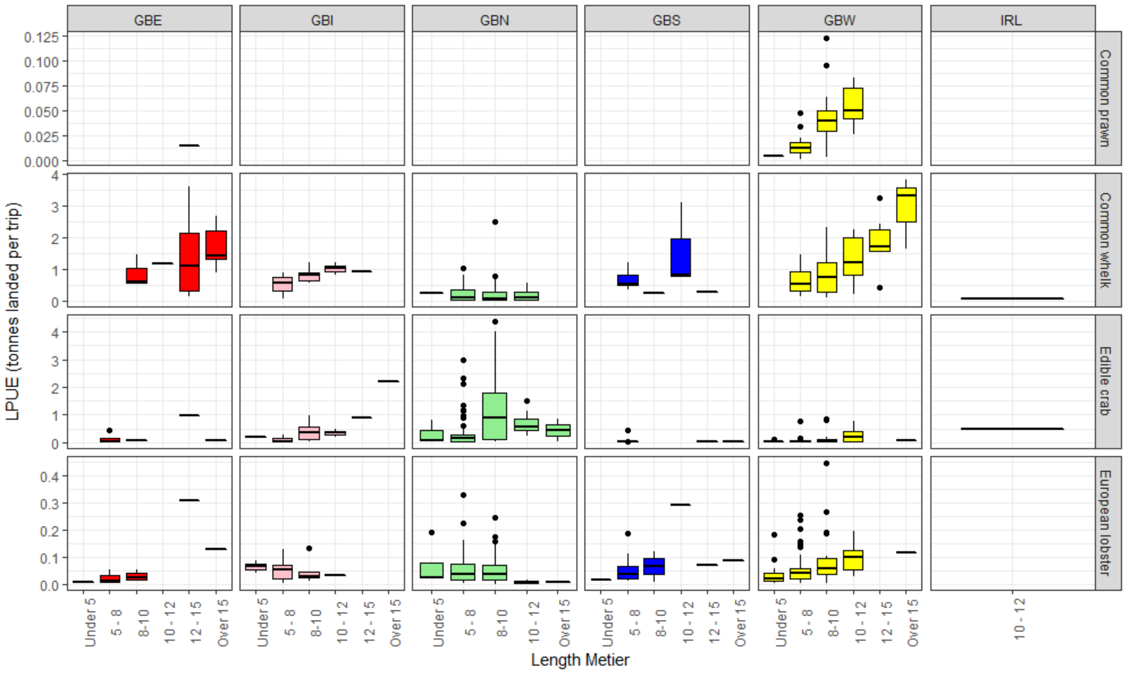

Figure 1.12. A boxplot showing landings-per-unit-effort (Landings per day) by size metier (Length Overall groups) of the British fleet targeting shellfish species using static-gear during the period in 2019 in the Irish Sea (ICES Area VIIa) by country (England = Red, Isle of Man = pink, Northern Ireland = light green, Scotland = blue, Wales = yellow, Republic of Ireland = dark green) and target species (by row). Data Source: iFISH2

## 1.6 Objective of the thesis and outline of the chapters

This thesis is a synthesis of studies that address specific research questions on particular issues in Irish Sea baited-pot fisheries, including: fundamental life-history parameters important for informing fisheries conservation measures, the drivers of regional and local variability in reproductive biology, how logbook reporting can be improved for scientific fisheries assessments, and the effects of changes in harvest-control-rules on population structure. The thesis delivers a series of data analyses and recommendations for fisheries management of the above baited-pot fisheries by addressing species-specific knowledge-gaps as well as broader issues relevant to data-poor fisheries more generally.

Chapter 2 describes the basic population structure of common prawn targeted in the Welsh (Cardigan Bay) fishery, making particular reference to reproductive biology, size-at-maturity and sex-specific morphology that are important considerations for size-selective harvesting controls. The analysis describes that current practices (size-selective fishing) leads to greater fishing pressure on females compared to males, and that the sex-ratio of catch shows a decline in relative abundance of females through the season. The study was unable to definitively conclude that size-selective harvesting is impairing the viability of the female population. Nonetheless, the findings serve as an important reference tool for fisheries management, particularly considering the highly variable trends in landings (Figure 5), which reflect 'boom-bust' scenarios that may be a consequence of impaired reproductive potential from high fishing mortality in female populations.

Chapter 3 describes the basic population structure and reproductive biology of common whelk in Welsh and Manx waters. In particular, data are used to describe region-wide variation in the reproductive cycle (as indicated by trends in gonadic development) and size-at-maturity, within the context of different

MCRSs being applied in Welsh and Isle of Man waters. Notably, and partly as a consequence of the analysis presented in this chapter, the MCRS was increased for this species in both Welsh and Isle of Man legislation. Finally, a mixed-modality analysis is performed on size data that showed clear cohorts within the distribution to estimate a size-at-age relationship.

Chapter 4 follows the previous chapter in addressing knowledge gaps specific to the Irish Sea common whelk fishery. The study adopts recently verified ageing techniques based on statolith analysis to estimate the size-at-age of whelk populations in a number of whelk fishing grounds ranging from the Point of Ayre (on the northern territorial limit of the Isle of Man, adjacent to Scottish waters) through the Welsh zone to Swansea Bay. The variation in age model coefficients are analysed in the context of sea-temperature alongside previously estimated size-at-maturity estimates from chapter 3. The findings suggest that abiotic factors, i.e. temperature, drive variation in whelk life history on a regional scale, which has implications for similar assessments for the species in beyond the study region.

Chapter 5 moves away from biological analysis of shellfish populations and instead focuses on logbook reporting systems, and how enhancing current systems with gear-in gear-out technology (i.e. data-collection technology that is activated by the deployment and retrieval of fishing equipment) can be used for fisheries management purposes. The study utilises data collected during a trial of enhanced electronic reporting systems (EERS) in the Isle of Man edible crab fishery in the 2018/19 season, which is associated with unprecedented effort and landings. The data, which was collected voluntarily by skippers in the Isle of Man, modelled fisheries-dependent LPUE by combining multiple variables such as location, depth, temperature and soak-time. The statistical model revealed that temperature, location and intra-specific interactions (i.e. bycatch of lobster) have a significant effect on Crab LPUE. The chapter also presents an argument that gear-in gear-out technology with string specific catch data can enable area-specific fisheries management in edible crab fisheries using enhanced fisheries-dependent data, whilst also discussing the limitations and barriers to management using current reporting systems (e.g. daily landing reports, VMS data, etc.). Although the data were collected from a single-species fishery in a specific location, the practical application of these technologies and methodologies have widespread global potential.

Chapter 6 uses European lobster mark-recapture data from the Isle of Man together with size data collected from commercial samples to investigate the effects of an increase in MCRS (from 87 mm CL to 90 mm CL) on the population structure of European lobster in the Isle of Man under *ceteris paribus* conditions. The length-based model considers a number of natural mortality rates and both a single-step increase and phased-increase approach to the MCRS increase. The results suggest that the initial decline in harvest opportunity immediately following an increase in MCRS is offset within 2-6 fishing seasons depending on the rate of natural mortality and whether the increase is single-step or phased. The results suggest that, in order to minimise economic impact on the fishing fleet that are reliant upon European lobster harvests sea fisheries policy in the Isle of Man should adopt a phased increase to 90 mm MCRS. This chapter was appended as an evidence-base to the Isle of Man Government's "Consultation on the Future Management of the Isle of Man Crab & Lobster Fisheries" in 2020.

Chapter 7 summarises a brief experiment that assesses the efficacy of a ‘riddle’ device in sorting catches of common whelk in the Isle of Man into undersize and above-MCRS, so that fishers can comply with newly regulated increases in MCRS (resulting from analysis presented in chapter 3). The sorting device works by allowing whelk to pass through a metal grid until they have reached a particular size, after which they are retained by the device and harvested. A selectivity curve was modelled for a standard riddle, which has a 35 mm grid spacing, using logistic regression with a binomial distribution. The model results are presented within the context of shell morphology data, which has been shown to vary regionally in other studies. The chapter concludes that bespoke devices may be required for vessels targeting common whelk depending on the area of activity, and that large vessels operating in multiple jurisdictions require an interchangeable device in order to comply with different MCRS regulations.

Finally, a general discussion of the key findings and contributions of this thesis to the current literature is presented in Chapter 8.

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# Chapter 2. Size-selective fishing of *Palaemon serratus* (Decapoda, Palaemonidae) in Wales, UK: implications of sexual dimorphism and reproductive biology for fisheries management and conservation.

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The candidate is lead author on the publication and undertook the field, and laboratory data-collection with assistance from G. Robson. The candidate performed all the data analyses presented in the chapter, as well as writing the methods and discussions sections. J. A. Haig managed the research project, designed the laboratory methods and verified data analyses and results. L. Le Vay and M. Kaiser conceived of the project and secured funding for the work. All authors provided critical feedback and helped shape the final manuscript.

## Abstract

The common prawn (*Palaemon serratus*) supports a small-scale but economically important seasonal static-gear fishery in Cardigan Bay, Wales (UK). Due to a lack of statutory obligation and scientific evidence, the fishery has operated to date without any harvest control rules that afford protection from overfishing. In response to fluctuations in landings and in pursuit of increased economic returns for their catch, some members of the fishing industry have adopted a size-selective harvesting regime, which we evaluate here using baseline data. Monthly samples were obtained from fishers operating out of five ports between October 2013 and May 2015 (n = 4,233). All prawn were sexed, weighed and measured, whilst the fecundity of females was estimated for a subsample of egg-bearing females. Peak spawning occurred during the spring and females were estimated to undergo a ‘puberty moult’ at a carapace length (CL) of 7.7 mm, whilst functional maturity was estimated at a CL of 9.9 mm. The sampled population exhibited sexual dimorphism, with females attaining a greater size than males. The current harvesting regime results in a sex bias in landings as even large mature males remained under the recruitment size to the fishery, unlike the large mature females. The temporal trend in sex-ratio indicates a continual decrease in the catchability of female prawn through the fishing season; however, whether this is caused by depletion via fishing mortality or migratory behaviour is yet to be resolved. Here, we provide a comprehensive baseline evaluation of population biology and discuss the implications of our findings for fisheries management.

## 2.1 Introduction

The fishery for the common prawn, *Palaemon serratus* (Pennant 1777; Neal 2008), is relatively small compared to other European "prawn" fisheries (*Nephrops norvegicus* and *Pandulus borealis*); however, in the UK it has significant regional economic importance. In Cardigan Bay (Wales), the fishery accounts for ~76% of total UK landings (estimate from 2013; MMO, 2015). Commercial exploitation of prawns in Cardigan Bay is exclusively an inshore static-gear pot fishery, with most vessels working within six nautical miles of the coast. The fishery begins to target prawn in early autumn and continues through to the following spring (Cardigan Bay Fishermen's Association (CBFA) *pers comm.*). The fishing season is dictated by the reproductive migrations of *P. serratus*, which are thought to move inshore to release larvae during the summer and then move offshore in winter. Similar seasonal migrations are reported in a range of palaemonid species, including for *P. serratus* in other regions (Guerao & Ribera, 2000; González-Ortegón *et al*., 2006). The seasonal migration of prawns inshore in the summer decreases static gear catches to levels that are no longer economically viable (CBFA *pers comm.*). Nonetheless, the Cardigan Bay prawn resource is integral in maintaining the economic viability of many fishing businesses as it provides income during a time of the year when the catchability of other target species, such as European lobster (*Homarus gammarus*), is low. The fishery is therefore an important element in a necessarily diverse static-gear sector.

Commercial demand for a larger-sized prawn has resulted in the introduction of voluntary size-grading of catch by fishers. Since 2008, many Cardigan Bay fishers have used a 10 mm bar-spacing riddle (CBFA *pers comm.*). Prawns that fall through the bars and into the sorting box are discarded overboard, whilst prawns retained by the riddle are stored onboard, usually within small viver systems.

As with many small-scale fisheries, the Welsh prawn fishery is considered data-poor, with little information pertaining to the fisheries biology of the species. Combined with limited management and the lack of a formal stock-assesment, there is considerable uncertainty about the future sustainability of the fishery. Indeed, fluctuations in inter-annual landings in the Irish fishery (Fahy & Gleeson, 1996; Kelly *et al*., 2009) suggest a variable biomass that may be vulnerable to periodic overfishing or recruitment failure in the absence of management. Understanding the interaction of fishing activites with the species biology is necessary to inform future evidence-based management of the fishery and more generally, understanding the reproductive biology of a fished species is critical information when considering 'supply-side' ecology of benthic populations with economic value (Underwood & Fairweather, 1989; Anger, 2006).

The common prawn is patchily distributed throughout European inshore waters (Kelly *et al*., 2009) and occurs between the Mediterranean Sea in the south and the temperate coastal waters of the United Kingdom and Ireland in the north (Forster, 1951). Although the longevity of the species has been speculated to be up to five years (Cole, 1958; Forster, 1959), *P. serratus* are more likely to have a relatively short life span, with individuals persisting for between two to three years (Forster, 1951; Fahy & Gleeson, 1996). Similar to other palaemonids, *P. serratus* is sexually dimorphic, with adult females attaining significantly larger sizes (Forster, 1951; Berglund, 1981). Sexual dimorphism may influence mortality rates between the sexes, from both size-selective commercial exploitation and natural mortality through predation (Berglund & Rosenqvist 1986). For female palaemonids, a larger body size also allows for increased fecundity (Guerao *et al*., 1994). Compared to other similar species, *P. serratus* broods contain larger eggs with high nutritional values (Morais *et al*., 2002), which are thought to reflect environmental conditions and increase successful recruitment through the larval phase (Parker & Begon, 1986). The planktonic larval phase is characterised by temperature dependent periods of incremental growth and metamorphis (Reeve, 1969a; Kelly *et al*., 2012), while salinity has been shown to influence mortality rates during the early life stages (Kelly *et al*., 2012).

The aim of this research was to fill the knowledge gaps for this data-poor fishery by presenting baseline catch and population biology characteristics (length frequency, sex ratio, size at maturity) during the adult stage of the species life-history and to highlight several potential implications of a mandatory technical conservation measure of riddling catches at 10 mm.

## 2.2 Materials and Methods

In August 2013, six commercial fishermen operating from five different ports in Cardigan Bay, Wales (Figure 2.1), were each given three standard prawn traps (referred to hereafter as "science pots"). The cylindrical pots were fitted with 8 mm mesh on all sides with 35 mm circular entrance at both ends. Once a month, when possible, each fisher recorded the date and GPS location of a haul and the entire contents of each science pot were kept separate and stored frozen. Samples were retained for scientific analysis during two fishing seasons (2013-2014 and 2014-2015), ending in May 2015.

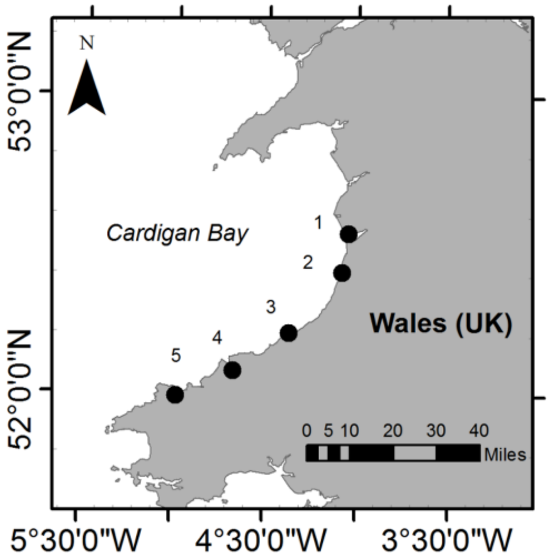

Figure 2.1. The homeports for the six active *Palaemon serratus* fishers in Cardigan Bay, Wales; who contributed monthly samples (when possible) during the prawn fishing seasons from 2013, 2014 and 2015. Ports are numbered north to south and are as follows: 1, Aberdovey (2 fishers); 2, Aberystwyth; 3, New Quay; 4, Cardigan; 5, Fishguard

Scientific pot samples were assessed in the laboratory using a dissecting microscope. All animals caught in the science pots were identified, weighed and measured. Palaemon species were identified according to the illustrated key published by González-Ortegón & Cuesta (2006). Sex was recorded; male prawns were identified by the presence of an appendix masculina on the second pleopod pair. All morphometric measurements were recorded to the nearest 0.1 mm and included the carapace length

(CL; the distance between the posterior of the eye-orbit to the posterior of the cephalothorax carapace segment), carapace width (CW; the widest point of the cephalothorax carapace) and pleura width (PLW; the widest section of the second abdominal pleura). The reproductive state (ovigerous or not) was also noted for female prawns and the fecundity of ovigerous females were calculated from a subsample of 10% of the entire egg mass (wet weight). The fecundity was estimated using the following formula (1); where ϒ indicates the subsample calculated as a proportion of the total eggs mass (T), which was then used to calculate fecundity (F).

$$\Upsilon_{(\mathrm{approx.}=0.1)} = \frac{\mathrm{Weight}_{\mathrm{subsample}}}{\mathrm{T}_{\mathrm{weight}}}$$

$$\mathrm{F} = \frac{\mathrm{Count}_{\mathrm{subsample}}}{\Upsilon} \qquad \textbf{(1)}$$

All statistical analyses were run in "R" (R Core Team, 2014). Prior to statistical modelling data were tested for normality using the Kolmogorov-Smirnov test and inspected visually using a Q-Q plot. Heteroskedasticity was tested using Levene's test and a Cook's distance plot was used to check for outliers. A Hartigan's dip test was used on length distribution data for non-unimodality. The likelihood of the sample having a 1:1 sex-ratio was tested using a G-test. Since we were not able determine size-at-age for the sampled population, age cohorts are inferred from the observed length distribution. A mixed population approach was used to determine statistical differences between sexes and cohorts within a mixed bi-modal dataset. Using the R packages "MIXTOOLS v1.0.3" (Young *et al*., 2015) and "MIXDIST v0.5-4" (Macdonald & Du, 2011), the mean and standard deviation of the two modes in aggregated male and female length distribution data is presented alongside a goodness-of-fit Chi-square test. We use the results to evaluate the length distributions of immature and mature populations as well as sexual dimorphism within a single mixed-population cohort.

The size of functional maturity was estimated by relating growth parameters (CL) and ovigerous status (binary variable, where 0 = no eggs and 1 = gravid) of females using a logistic regression model (Roa *et al*., 1999) reformulated by Walker (2005) to give:

$$P_i = \left\{ 1 + e^{-\ln(19)\left(\frac{\mathrm{CL}_i - \mathrm{CL}_{50}}{\mathrm{CL}_{95} - \mathrm{CL}_{50}}\right)} \right\}^{-1} \qquad \textbf{(2)}$$

where $P_i$ is the proportion of the female population gravid at a given CL. Model parameters were estimated using generalized linear model with logit link function and a binomial error structure. Confidence intervals were added by bootstrapping the generalized linear model (1000 runs). The base R code was constructed by Harry (2013) and is available online.

To describe morphometric maturity and determine at what CL positive allometry occurs, an iterative search procedure was used whereby PLW is modelled against CL for male and female populations separately using piecewise linear regression. The analysis examines the linear morphological relationship (CL:PLW) and searches for significant deviations between male and female growth patterns, indicating sex-specific morphological changes in preparation for sexual reproduction described as a “puberty moult” (Hartnoll, 2001). The method searches each potential “breakpoint” or “inflection” (*c*) within a predetermined range until the model has found the point at which the total residual mean standard error is minimised (Crawley, 2007). The model simulation then produces a value (CL) at which the linear models above and below the breakpoint *c* show the statistically strongest inflection. The model applied to both male and female datasets is described mathematically using the equation 3.

$$y_i = \begin{Bmatrix} \beta_0 + \beta_1 CW_i\,, & CW_i < c \\ \beta_2 + \beta_3 CW_i\,, & CW_i \geq c \end{Bmatrix} \qquad \textbf{(3)}$$

where $y_i$ is the CL of individual *i*, *c* is a breakpoint (inflection) between linear relationships applying above and below the value of carapace length equal to *c*, and the *β* parameters are the intercepts and slopes of the two linear relationships.

In order to relate the morphological estimate of population characteristics, fisheries catches (CL) results are converted to CW using the following equations (4) produced by linear regression ($p < 0.05$):

$$\mathrm{CW_{Male}} = 0.563\mathrm{CL_{Male}} + 0.643$$

$$\mathrm{CW_{Female}} = 0.6389\ \mathrm{CL_{Female}} - 0.297 \qquad \textbf{(4)}$$

Individuals with a CW < 10 mm are assumed to be discarded through the use of a 10 mm spaced riddle.

## 2.3 Results

Severe weather conditions during the 2013 and 2014 fishing seasons limited the fishing opportunities and the number of individual prawns that could be sampled within that season (n = 765). In total, fishers returned 82 pot-samples and 4,233 *P. serratus* underwent laboratory analysis (table 2.1).

Table 2.1. Total number of individual prawns (and number of pot samples returned) by CBFA members during the 2013-2015 *Palaemon serratus* research period in Cardigan Bay. (-) Indicates an absence of information on how many science pots were hauled for the given sample. Ports are displayed from north to south and are named as follows: 1, Aberdovey; 2, Aberystwyth; 3, New Quay; 4, Cardigan; 5, Fishguard.

| | **2013** | | | **2014** | | | | | | | | **2015** | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **10** | **11** | **12** | **2** | **3** | **4** | **5** | **9** | **10** | **11** | **12** | **1** | **2** | **3** | **4** | **5** |
| **1** | | | | | 123<br>(-) | 123<br>(-) | | | 95<br>(2) | 91<br>(2) | | | | 89<br>(3) | | |
| **2** | 10<br>(-) | 60<br>(-) | 125<br>(-) | | 116<br>(-) | | 43<br>(-) | 4<br>(3) | 32<br>(3) | 68<br>(3) | 169<br>(4) | 170<br>(6) | 119<br>(5) | 159<br>(3) | 753<br>(6) | |
| **3** | | 35<br>(-) | | | 48<br>(-) | 19<br>(-) | | 105<br>(3) | 195<br>(3) | 148<br>(3) | | 90<br>(3) | 179<br>(3) | 64<br>(3) | 282<br>(3) | 192<br>(3) |
| **4** | | | | | | | | | | 30<br>(3) | | 62<br>(1) | 39<br>(3) | 150<br>(2) | | |
| **5** | | | | 53<br>(-) | | | | | | 132<br>(-) | | 51<br>(-) | | | | |

Sexual dimorphism was evident in the length distributions of all samples. Moreover, prawn populations showed bimodal distributions when data was aggregated by fishing season and location (Hartigan's dip-test; $D_{Male} = 0.95$, $D_{Female} = 0.04$, p-value < 0.001). The majority of male prawns and the smaller sized cohort of female prawns caught in the small mesh science pots were of a size that would be discarded using the 10 mm riddle employed by Cardigan Bay fishers (Figure 2.2).

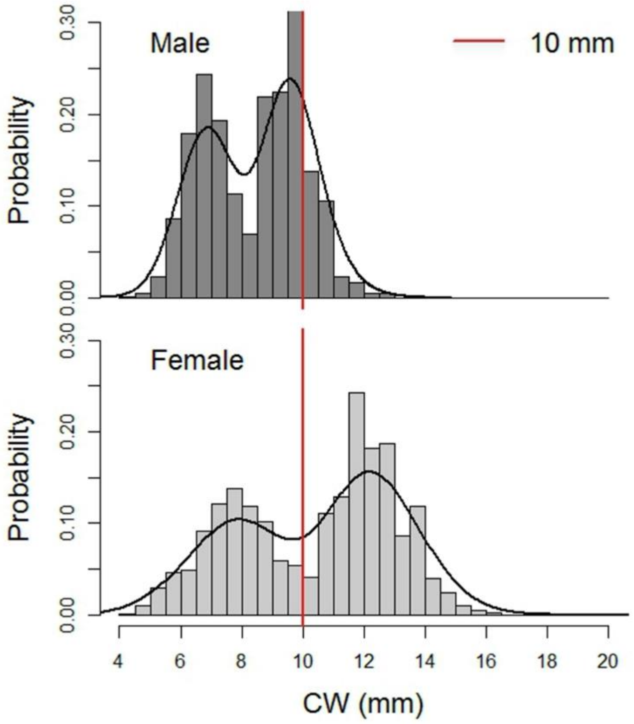

Figure 2.2. A length frequency histogram with a probability density function for male (above) and female (below) *Palaemon serratus* caught in science pots during the 2013-2015 *Palaemon serratus* research period in Cardigan Bay. The solid vertical red line represents the voluntary sorting size (10 mm CW) used by many fishers in Cardigan Bay

Carapace width varied significantly between sexes and two cohorts were identified using a mixed population cohort analysis ($1^+$ and $2^+$; summary statistics and ANOVA results in Table 2a). Table 2b compares dimorphism highlighted by Forster (1951) and the present study. A higher proportion of the males (78.3 %) caught were smaller than 10 mm CW compared to the females (39.7 %) in catches.

Table 2.2. A Descriptive statistics for mixed-population cohort analysis of 1+ and 2+ cohorts of P. serratus caught during the 2014/2015 fishing season in Cardigan Bay, showing CW as the morphometric measure (mm). B The average CL (mm) of male and female 1+ and 2+ cohorts of *Palaemon serratus* reported by Forster (1951) and this study. *Length data reported in Forster (1951) were presented in terms of total length (TL) and equated to CL using the formula described in Emmerson et al. (2015).

**A**

| | **Male (CW)** | | **Female (CW)** | |
|---|---|---|---|---|
| | **1+** | **2+** | **1+** | **2+** |
| **mean** | 6.78 | 9.64 | 7.69 | 12.32 |
| **median** | 6.71 | 9.55 | 7.42 | 12.04 |
| **s.d ($\sigma_{\bar{x}}$)** | 0.68 | 0.68 | 1.19 | 1.22 |
| **s.e ($\bar{x}$)** | 0.02 | 0.03 | 0.04 | 0.05 |
| **anova** | D.f | 12 | D.f | 9 |
| | $\chi^2$ | 147.34 | $\chi^2$ | 185.95 |
| | p-value | 0.001 | p-value | 0.001 |

**B**

| | **Male (CL)** | | **Female (CL)** | |
|---|---|---|---|---|
| **Study** | **1+** | **2+** | **1+** | **2+** |
| Forster | 8.8 | 10.9 | 15.0 | 18.3 |
| Present | 9.2 | 11.6 | 15.6 | 19.3 |

The maximum size observed in the sampled population showed females grew to a size considerably greater than males, whilst the length distribution of catches show that the average male prawn within the $2^{+}$ cohort does not reach a size at which it recruits into the Cardigan Bay prawn fishery.

The sex-ratio of catches varied significantly from the expected 1:1 ratio, with both male and female directed skews being observed throughout the sample period (Figure 2.3a)

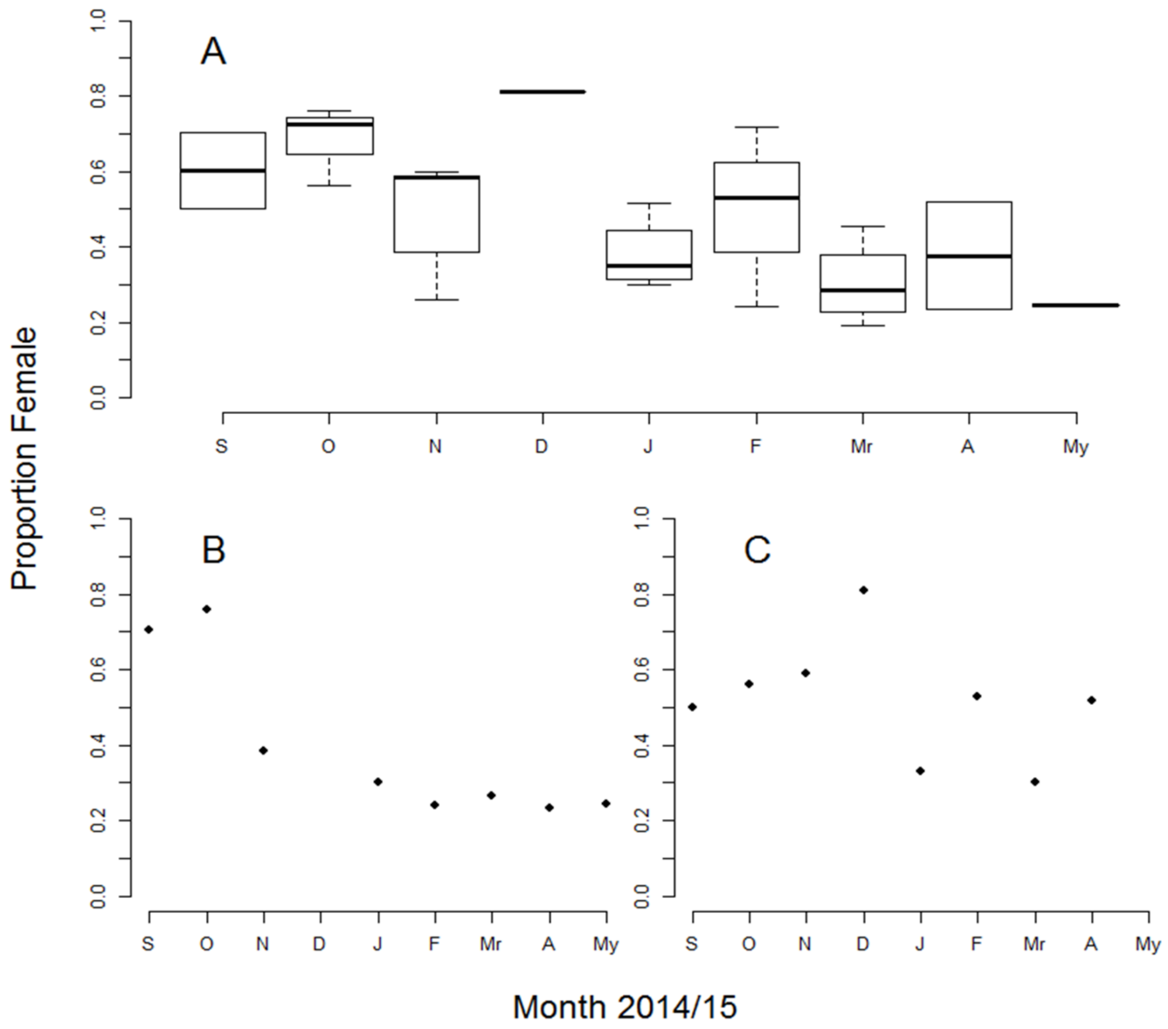

Figure 2.3. a) The sex-ratio of prawn (Palemon serratus) caught in science pots from during the 2014 / 2015 in Cardigan Bay and, b) the sex ratio of catches in localised datasets from New Quay and c) Aberystwyth.

For all locations sex-ratios were female skewed in autumn and winter samples, with a higher proportion of males caught in spring. Where an extended time-series was available from a single location, data exhibited strong temporal trends in the sex-ratio and declining abundance of females as the fishing season progressed in New Quay (3b); however, the data trend was less clear in the samples from Aberystwyth (Fig 3c).

Using an iterative search procedure, an inflection point was detected in the linear relationship between CL and PLW in the female dataset. The data suggests that for pleura morphometrics, males display an isometric growth pattern and females an allometric growth pattern. For females, the CL:PLW inflection point was detected at 12.5 mm CL (Figure 2.4).

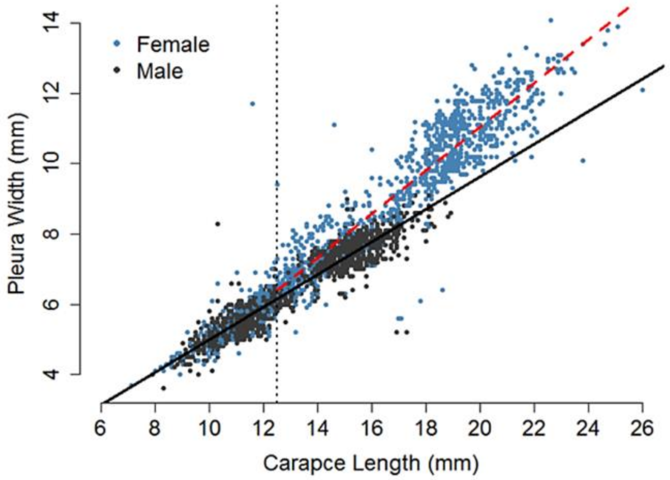

Figure 2.4. Inflection point indicating allometric growth based on morphometric variance between iterative tests on linear models of PLW and CL for the prawn *Palaemon serratus*. The dotted vertical line is the value with the lowest mean standard error (12.5 mm CL). Solid black line shows the linear male relationship. Hashed line shows the allometric female relationship after inflection event

Maturity is expressed as $L_{50}$, which is the size (CL) at which 50% of the females were observed to be gravid (carrying eggs). The maximum likelihood estimate of $L_{50}$ estimated by the generalised linear model with a binomial distribution was 15.9 mm CL (upper and lower confidence intervals = 16.4 mm and 15.4 mm CL respectively; Figure 2.5).

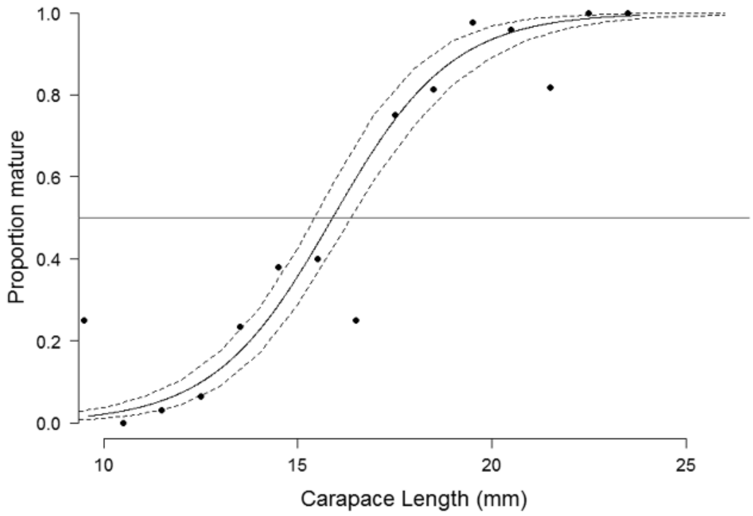

Figure 2.5. Functional maturity model fit for female prawn (*Palaemon serratus*) from Cardigan Bay (Wales) with 95% CIs as indicated by the presence or absence of eggs. The horizontal line represents L50 (15.9 mm CL) for the females sampled within period of peak spawning (April; n = 544)

Of the 616 gravid prawn that were captured by scientific pots, 273 (44%) were analysed for fecundity using the equation described (1). Prawn ranged in size from 14.2 mm to 25 mm (CL) and produced fecundity estimates of between 221 and 5,121 eggs per animal (Figure 2.6).

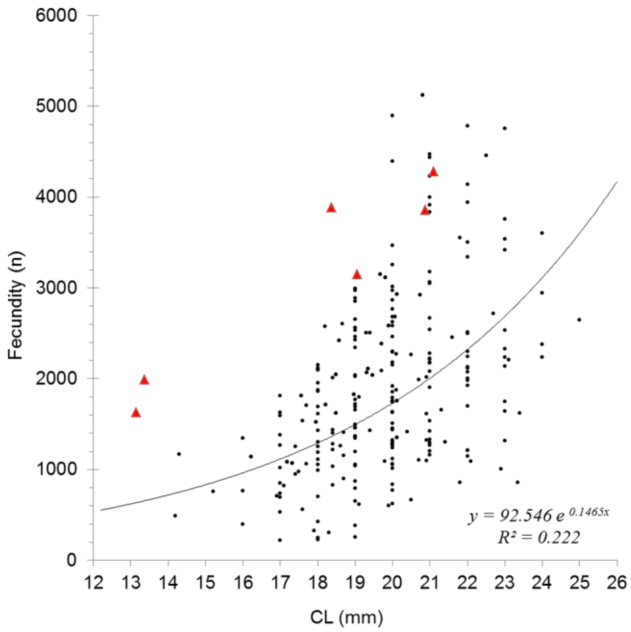

Figure 2.6. Fecundity of gravid prawn (*Palaemon serratus*) from Cardigan Bay (Wales) with size (CL) (n = 273). The solid line shows the power relationship between the correlating variables CL and Fecundity (p < 0.001; R2 = 0.222). The red triangle points show the fecundity data available from Forster (1951).

A Spearman's correlation was run to assess the relationship between CL and fecundity. There was a strong positive correlation, which was statistically significant ($r_S = 0.48$, $p < 0.001$) and is explained by the power relationship below (Figure 2.6; equation 5). The fecundity data exhibits a high degree of variability with CL explaining just 22.2% of the variation in fecundity. Data points shown as triangles represent available fecundity data from Forster (1951).

$$\text{Fecundity} = 92.546\ e^{0.1465\ CL} \quad \textbf{(5)}$$

## 2.4 Discussion

Our results confirm that *P. serratus* in Cardigan Bay are sexually dimorphic, with females occupying a broader length-distribution than males in the sampled populations. These results mirror the sexual dimorphism that has been reported elsewhere for *Palaemon serratus* (Guerao & Ribera, 2000) and many other *Palaemon* spp, with typically slower growth rates and smaller sizes in males. (*e.g.* Berglund, 1981; Ito *et al*., 1991; Bilgin *et al*., 2009; Al Maslamani *et al*., 2013).

The evolutionary cause for dimorphism in this species is likely to have resulted from selection based on the differing reproductive roles of the sexes (Shine, 1989). The current size-selective exploitation and resulting pressure on mature females could potentially result in evolutionary responses that change growth and reproductive patterns at a genetic level (e.g Conover & Munch, 2002; Walsh *et al*., 2006; Swain *et al*., 2007). Given the short life span of *P. serratus*, fishery-induced responses such as decreasing size-at-maturity and size-at age may occur over a timescale of years or decades (Reznick *et al*., 1997; Thompson, 1998; Koskinen *et al*., 2002; Stockwell *et al*., 2003), a phenomenon that has been demonstrated in a number of other exploited populations (e.g Grift *et al*., 2003; Olsen *et al*., 2004;

Barot *et al*., 2004). Indeed, the selection pressure towards large females and potential decrease in growth rates may have a negative effect on the value of the species in the long term, which runs contrary to the larger prawns desired by the market. Hence it is important to continue monitoring these life history characteristics, in order to determine any long term changes, particularly in females. It would also be valuable to compare populations with varying degrees of commercial exploitation.

At present, the fishery is not subject to any statutory harvest-control-rules or technical-measures that aim to encourage sustainable exploitation of prawn populations in Welsh waters in addition to the requirement for commercial fishers to hold a shellfish license. The voluntary riddling of catch using either a 10 mm riddle or > 10 mm pot mesh by some fishers ensures both a better market price and may return as many as 40% of females to sea including sexually immature individuals. Since the grading of prawns is an entirely voluntary practice, it is not possible to determine the relative proportion of common prawn landings in the UK that have been graded at sea, on the quayside or not at all. Whilst the mortality rate amongst prawns discarded at sea is still to be determined, personal observations indicate a very high level of mortality when prawns are graded on the quayside. The absence of information on discard mortality rates calls into question the real value of the riddling practice, particularly since the mortality rate is likely to be high. If the rate of mortality amongst discarded prawn is at a significant level, the sex-specific consequences of riddling may not be as severe as the data suggests. Nonetheless, there is a need to ensure that riddling is done at sea over fishing grounds and habitat from which the prawn were removed. Some fishermen argue that a larger mesh size on the fishing gear is a more appropriate conservation measure (*pers comms.*). We suggest that a gear comparison trial be conducted to determine the gear design that maintains catchability whilst promoting the escape of undersized prawn. Importantly the interaction between riddling and size-selectivity (i.e that a riddle will retain prawn only of a size ≥ 10 mm) is an assumption in this study and not empirically validated. Future research needs to collect data on retention rates of a known size distribution of animals being graded in order to evaluate the real the real size and sex specific implications of the technical measure.

In 2008, when voluntary measures were adopted by some Cardigan Bay fishers, it was hoped that the discarding of small prawn at sea would provide additional ecological and economic value by improving market prices and releasing immature prawns to improve yield-per-recruit and spawner-per-recruit respectively (CBFA *pers. comm.*). Our results show that by applying a size-selective harvesting regime, the Cardigan Bay prawn fishery subjects the female population to a much higher level of removal relative to the male population. Indeed, the immediate consequence of the quasi-minimum-landing-size would have been the discarding of approximately 78% of male prawns caught in pots, compared to a female discard rate of approximately 40% on average throughout the fishing season. The bi-modal distribution of size-frequency data was present in all spatial and temporal combinations, representing a strong indication that two cohorts of prawns are present during fishing the season. With the assumption that commercial activities select prawn at a size 10 mm CW under the voluntary MLS, data shows females are recruiting into the fishery in their second year at a mean size of 12.32 mm CW (SE ± 1.22).

However, fewer 2+ males are recruited into the fishery, as the average male in their second year is 9.64 mm CW (SE ± 0.84).

Our study shows similar patterns in length-cohort distribution to previous studies. Forster (1951) reported female population attaining a greater modal size than males within the 2+ cohort ($\mathrm{TL}_{\mathrm{Mo}}^{♀} \approx 92.5$ mm; $\mathrm{TL}_{\mathrm{Mo}}^{♂} \approx 77.5$ mm). The above values are comparable to those reported in this study; however, the historical data indicates a smaller average size of prawn within the 1+ group than we observed in this study (see table 2b), although the difference is unlikely to be significant. The difference in 1+ size is likely to be as a consequence of differing sampling methods employed by the two studies; Forster (1951) using fishery independent trawl surveys in contrast to the present study, which used fishery-dependent 'science pots', which were fished alongside commercial gear and therefore targeted the larger prawns.

A consequence to size-selective fishing and higher rates of removal of female prawn may be evident in the temporal trend of sex-ratios (Figure 3a), representing sex-overfishing on a regional scale. However, Fig 3b and 3c shows that decreasing catchability of female prawn is location specific, with samples from Aberystwyth showing a near 1:1 sex ratio late into the fishing season in comparison to fishing grounds to the south, although the proportion of females in spring is still lower than during winter. The decreasing abundance of females in catches marks the end of the prawn season as it is perceived by fishers as a weakening fishery that yields less marketable catch. Seasonal variation in sex-ratios have been observed in a range of palaemonid species (see Kim, 2005; Al-Maslamani *et al*., 2013) and has been attributed to differential migration patterns, seasonal habitat preferences and possibly mortality between males and females (Berglund, 1981). Female *P. serratus* are known to migrate between habitats to release larvae in Wales (Haig et al. *unpublished data*) and hence it is unsurprising that we observed temporal and spatial changes in sex-ratio as the fishing season progressed in Cardigan Bay as this may reflect localised differences in timing of migration or habitat availability.

On a regional scale, fishing behaviour follows an inter-annual pattern whereby fishers in the south experience the onset of the fishing season, with fishing opportunities gradually opening in a northward direction along the Cardigan Bay coast (*pers*. *obs.* and CBFA *pers comms*.). Similarly, fishing opportunities decline earlier in the south relative to the north, with fishermen from Aberystwyth and Aberdovey continuing to fish for months after fishing has ceased to be commercially viable in Fishguard and New Quay (*pers. obs*. and CBFA *pers. comm*.). Fishermen therefore hold the view that females migrate in a northerly direction, sustaining different rates of catch in different areas through the season. The scientific evidence presented here neither validates nor disproves this view on the migratory behaviour of prawn in the region. Further fisheries independent research (ideally using mark recapture methods) is required to determine if the observed patterns in female catch indicate sex-overfishing, decreasing catchability as a result of seasonal migration by females, or a cumulative response to both of these.

The potential for sex-overfishing identified by this study may have consequences on recruitment levels in the future, although the life-history of palaemonids (highly fecund and typically multiple broods per season) may safeguard it against depletion events. The data show female skewed catches in the early period of both fishing seasons (Emmerson *et al*., 2014), which indicates the population has a degree of resilience in sustaining size-selective fishing at present effort levels, the research presented here cannot draw a conclusion with regards to sex-overfishing in the absence of both long-term datasets and evidence pertaining to adult migration patterns.

Crustacean fisheries are most commonly managed in the UK using a minimum landing size (MLS), appropriated by maturity characteristics (Bannister, 2008). In order to determine a valid MLS in decapod crustaceans, maturity indicators such as morphological sexual maturity and functional maturity can be applied (Waddy and Aiken, 2005; Pardo *et al*., 2009). Size at maturity has been determined from allometric growth parameters (*e.g.* Hartnoll, 1974; Little & Watson III, 2005; Claverie & Smith, 2009) and specifically the CL:PLW relationship in Palaemonidae species (Cartaxana, 2003). In this study, the pleura has been shown to undergo allometric growth in female *P. serratus*, which expand the brood chamber in preparation for egg carriage at a size CW = 7.7 mm. At this point, females undergo an expansion in the PLW relative to males as they continue to grow. It is highly likely that this dynamic allometry amongst females represents a physical change of the abdomen in preparation for egg bearing and thus a sign of sexual maturity. Only 1.5% (n = 9) of ovigerous females were observed at a size below our estimate of morphological size at maturity, implying a high degree of confidence in the results of the iterative search procedure used. A total of 18.6 % of females (n = 361) captured by scientific pots throughout this study had a CW < 7.7 mm and were assumed to be sexually immature. With a CW < 10 mm, immature female prawn that have yet to develop their brood chamber and are released by Cardigan Bay fishers onto the fishing ground from where they were captured.

The size at morphological sexual maturity supports the results from this study's estimate of functional maturity ($L_{50}$), with the results implying that female prawn undergo a puberty moult at an estimated size CW = 7.7 mm, whilst 50% of females are able to contribute to the reproductive capacity of the population by the size CW = 9.9 mm (15.9 mm CL). In this way, the voluntary measure of releasing prawn below CW = 10 mm by CBFA fishers has been shown to be a potentially valuable conservation measure. The $CL_{50}$ reported here is greater than that reported in similar studies elsewhere for the species (Ireland; $CL_{50}$ = 12.5mm; Kelly, 2009), though similar to previous estimates for the Welsh population ($CL_{50}$ = 16.5; Huxley, 2011).

*P. serratus* were found to carry between 221 and 5,121 eggs at any one time (mean average = 1,916). This is similar to estimates published by Forster (1951), who found large prawn (TL = 105 mm) carry up to 4,282 eggs and within a similar range of other Palaemonidae species (Corey & Reid, 1991). The fecundity (number of eggs carried) of female prawns was positively correlated with body size (CL); however, there was a high degree of variability between individuals and CL only explained ~23% of the variation. Studies of similar species (*P. elegans*, *P. adspersus* and *P. xiphias*) report $R^2$ values > 0.95 (Guerao *et al*., 1994; Cartaxa, 2003; Bilgin & Samsun, 2006). Different methodologies for estimating fecundity may be the reason behind the variable $R^2$ values reported here and in the published literature. In particular, previous fecundity estimates were derived from the number of eggs at stage 1 (e.g Guerao *et al*., 1994) in order to account for egg loss during incubation, which can be the result of mechanical stress or parasites (Glamuzina *et al*., 2014) and has been reported to be as high as 38% in this species (Reeve, 1969 *in* Zimmermann *et al*., 2015). Egg counts by developmental stage were unavailable in this study, which is the likely explanation for the high variability in the fecundity estimate. Nonetheless, the results are within the range reported for the species, as shown in figure 6, and provide an important baseline from which to further understand the reproductive capacity of the Welsh *P. serratus* population by providing an estimate between the numbers of eggs laid on pleopods during spawning and the total that eventually hatched.

Fecundity can be influenced by temporal-spatial variations of environmental factors such as depth (e.g *P. naval*; Thessalou-Legakiand, 1992), mean bottom temperature (e.g *P. borealis*; Parsons & Tucker, 1986) and habitat (e.g *E. modestus* and *P. gravieri*; Oh & Park, 2000). We recommend future studies pay particular attention to the problem of egg loss during brooding on pleopods by staging eggs using the criteria outlined in Guerao and Ribera (1995). Preservation of samples would permit a more accurate estimate of real fecundity, which should incorporate egg stage, size-dependent egg losses and egg-quality into the fecundity estimate. The limited scope and resources dedicated to the present study has constrained the data available for our fecundity estimate; however, it provides a useful baseline from which to continue monitoring.

The aim of this research was to provide a series of region-specific indicators that can be used by fisheries managers in the Cardigan Bay prawn fishery to guide biologically appropriated management measures. The voluntary measures employed by some fishing industry members in Cardigan Bay are effective at protecting 50 % of the female brood stock in their catch, providing the discard mortality rate is low. The process of grading prawn on the deck of a commercial fishing boat can be resource intensive and fishers have engineered bespoke riddle systems or replaced gear for larger mesh traps that may increase the efficiency of the gear in selecting larger prawn. While the results presented here demonstrate the potential ecological benefits of using either a larger mesh size, or a riddle in the prawn fishery, many commercial operations do neither (CBFA *pers. comm.*). Given the potential economic and ecological value of increasing the size of prawn reaching the market and the reluctance of some industry members to alter their fishing strategy, a comprehensive analysis of technical options should be explored. This might include the effectiveness of escape panels and minimum mesh-sizes (Fothergill, 2006), which would allow animals to escape before being exposed to increased stress and mortality rates associated with handling.

The limited evidence presented here suggests that there has not yet been an observable effect of overfishing on size-at-maturity of females in Cardigan Bay. However, declining CPUE in other exploited populations of the same species on the coast of Ireland suggest that overfishing can occur (Fahy & Gleeson, 1996) and hence long term monitoring of any changes should be included as part of ongoing fisheries management. At present, there are no statutory requirements to collect size at maturity data on *P. serratus* despite it being recognised as an important parameter for fisheries management. Ideally, these investigations would be replicated at an appropriate temporal scale; and given the short-life span of *P. serratus*, we recommend biennial replication. Given the potential for sex-overfishing within a size-selective harvesting regime in the Welsh prawn fishery, the extent of which is yet to be fully understood, affording a scientifically-validated level of protection to juvenile females via a MLS would be a valuable safeguard against recruitment failures in the future.

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# Chapter 3. The complexities and challenges of conserving common whelk (*Buccinum undatum*, L.) fishery resources: Spatio-temporal study of variable population demographics within an environmental context.

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The candidate is lead author on the publication and undertook the field, and laboratory data-collection in the Isle of Man. The Isle of Man data were combined with data from Wales, which was collected by J.A. Haig. The candidate performed all the data analyses presented in the chapter, as well as writing the methods and discussions sections. J. A. Haig designed the laboratory methods and verified data analyses and results. I.S.M Bloor and M. Kaiser conceived of the project and secured funding for the work in the Isle of Man. All authors provided critical feedback and helped shape the final manuscript.

## Abstract:

The commercial fishery for common whelk (*Buccinum undatum* L.) has expanded significantly in the Irish Sea since 1990 and continues to grow, particularly in Welsh waters and the Isle of Man territorial sea, with landings throughout the region increasing by 227% between 2011 and 2016. Whilst whelk populations are known to be vulnerable to localised overexploitation due to inherent life-history parameters, fisheries remain relatively unrestricted by conservation measures in comparison to other fisheries operating in the area. With the exception of the northernmost fishing ground between the Isle of Man and Scotland (Point of Ayre), the size-at-maturity (L50) estimate for populations sampled during peak-aGSI (the months in which adjusted gonadosomatic index is highest) indicates that whelk are being fished before the time at first spawning throughout the study area. A correlation was detected between the size (total shell length) and depth, with smaller whelks found in deeper waters where there generally is greater fishing effort, although effort data is not available at a resolution to investigate this relationship quantitatively. No clear link between benthic infauna biomass and the average size (total shell length) or reproductive capacity (aGSI) of whelk sampled throughout ICES Area VIIa was found, indicating that the ecological energetics of whelk populations are more likely to be a function of scavenging opportunities than predation on benthic communities. A mixed cohort analysis utilized length-based data to infer a size-at-age relationship in the absence of direct age observations (e.g. statolith rings), with whelk recruiting into the Isle of Man fishery five years after hatching. The evidence presented in this study suggests that, prior to recommending a MLS that will adequately protect the spawning stock biomass, L50 values should be adjusted for pre-spawning growth between the ideal time of assessment (when aGSI values are at a peak) and the spawning season (when aGSI values decrease).

## 3.1 Introduction

The common whelk (*Buccinum undatum*, Linnaeus, 1758) is a neo-gastropod mollusc that is found in the subtidal waters of the North Atlantic to depths of 1200 m (Ager, 2008). It is widely distributed on the Atlantic continental shelf; from within the arctic circle (76° N) as far south as New Jersey, USA at the western-most extent (38° N) (Van Guelpen et al., 2005; Borsetti et al., 2018). Populations are most frequently observed in abundance in the northeast Atlantic, particularly in the waters of north-western Europe, from the Celtic and Irish Sea through to the Skagerrak and Kattegat Bay, including northern populations observed in Norwegian, Faroese and Icelandic waters (Ocean Biogeographic Information System, 2017).

Whelk are opportunistic scavengers that feed mainly on carrion (Nasution & Roberts, 2004) and detect feeding opportunities with a very acute chemo-sensory system (Himmelman, 1988). This allows whelks to be commercially exploited by fishers, who typically use specifically designed baited traps. Inshore whelk populations have been exploited by a mixed artisanal fishery in Europe since the early 20th century (Dakin, 1912). Annual landings in England and Wales equated to 4500 t in 1911 (Dakin, 1912) and European waters remain the principal area of fishing effort (FAO, 2017). The fishery has undergone significant economic and geographical expansion in response to emerging Asian markets, with global landings increasing from 7,000 t $yr^{-1}$ to over 35,000 t $yr^{-1}$ between 1990 and 2014 (FAO, 2017). The effects of fishing mortality (*F*) on the phenotypic traits of *B. undatum* may be significant, especially considering the expansion in commercial exploitation (Kuparinen & Merilä, 2007). Whelk are now amongst the most economically important shellfisheries in the UK (Haig et al., 2015) with total UK landings (21,606 t) equating to a value of £21.7 million in 2016 (MMO, 2017). Regionally, the Irish Sea (ICES Area VIIa) has seen an estimated 227% increase in the total landed weight of whelk between 2011 and 2016 and is the source of approximately 10% of global landings for this species. The most substantial increases in recorded landings in the region are from within the Isle of Man territorial sea (ICES rectangle 37E5) and Welsh waters (ICES rectangles 33E5, 34E5, 35E5) (IFISH2, 2017; Figure 3.1).

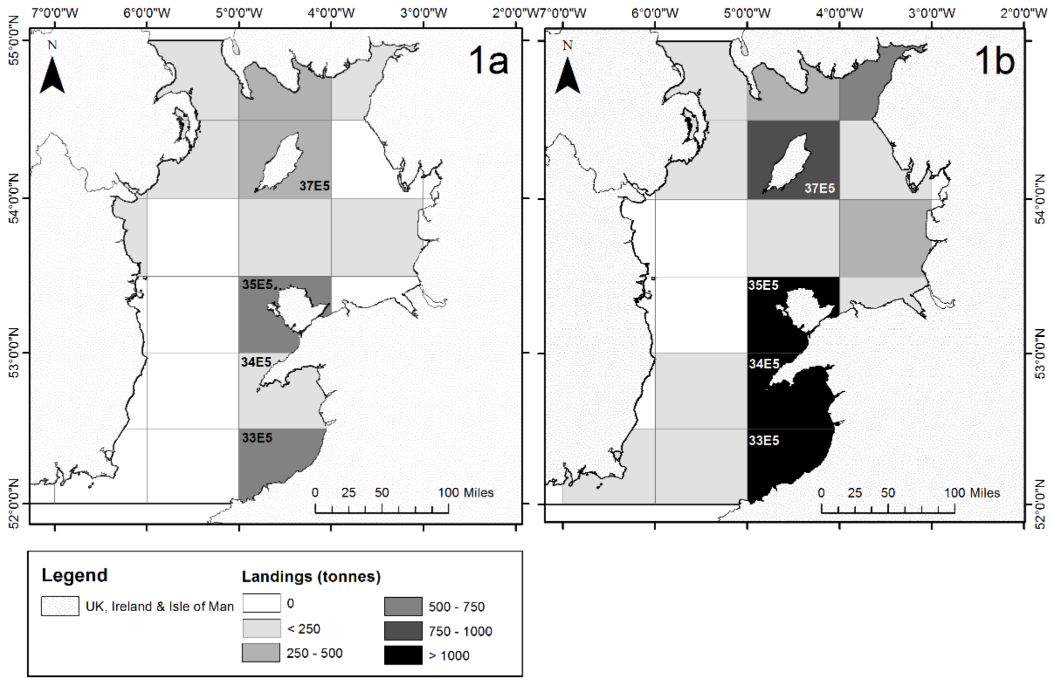

Figure 3.1. The spatial distribution of whelk (*Buccinum undatum*) landings in ICES Area VIIa by British vessels in 2011 (A) and 2016 (B) by ICES Rectangle. Source: IFISH2 database.

Within ICES Area VIIa, management regimes are not consistent. Similar to many other jurisdictions in the UK, whelk fisheries within Welsh waters are managed solely by a minimum landing size (MLS = 45 mm Total shell length; TSL) established by the European Union (EU), which has been shown to be set below the size at functional maturity in several studies (Shelmerdine et al., 2015; Haig et al., 2015). However, Isle of Man fisheries are subject to a MLS of 70 mm TSL, informed by Kideys et al. (1993) and the fishery now includes a restricted number of species-specific licenses, each of which has effort (pot number) restrictions.

The phenotypic plasticity displayed by other marine gastropod populations can be closely related to mortality and growth rates (Stearns & Koella, 1986), which vary spatially and temporally with fishing pressure and environmental conditions (Torrogolsa & Gimenez, 2010; Fahy et al., 1995). Whelks do not reach sexual maturity for several years, have limited dispersal potential (Martel et al., 1986a) and display little adult movement (Pálsson et al., 2014; Weetman et al., 2006). Therefore, populations are inherently vulnerable to high *F* and are particularly susceptible to recruitment overfishing (Shrives et al., 2015) and severe localised depletion (Nicholson & Evans, 1997). Environmental parameters have been shown to influence the biological characteristics of populations, with size-at-maturity being negatively correlated to bottom-temperature but positively correlated with depth (McIntyre et al., 2015; Haig et al., 2015). This is unsurprising given that the common whelk is a boreal species, although no clear latitudinal relationship has been observed (McIntyre et al., 2015) and local factors such as food availability and fishing presure are likely to have an influence in maturation and growth (Martel et al., 1986b).

There is presently little scientific evidence to suggest that the current MLS of 45 mm used as the baseline throughout the EU is an adequate fisheries threshold for sustainable exploitation. Shelmerdine et al. (2007) suggests that management measures should be considered on a regional basis after demonstrating significant differences in the biology of whelk populations sampled in Shetland and the south-coast of England. Haig et al., (2015) shows that the size at maturity ($L_{50}$) can vary considerably between populations over distances as small as 10 km (although application of management measures at this spatial scale are acknowledged to be impractical). Complications arrise when trying to compare research on size-at-maturity, as there is not currently a standard scientific methodology to determine this metric (Haig et al., 2015).

This study combines published data (Haig et al., 2015) from Welsh waters with data collected in the Isle of Man territorial sea. The aim was to compare spatial variation in size-at-maturity and also to determine reproductive response to spatial, temporal and environmental parameters.

## 3.2 Materials and methods

### 3.2.1 Field Materials (Fisheries Dependent Data)

Nine fishers, registered in Wales (3), England (1) and the Isle of Man (5), each fished two identical whelk pots once a month within the ICES area VIIa (Irish Sea) (Figure 3.2). The fishers retained the entire pot contents, including undersized bycatch and non-target species. The pots supplied to fishers were 36 litre Fish-tec™ 'WHELKER' pots, described by fishers as being 'stand-up' pots due to their orientation (Haig et al., 2015). The pots are made of thick plastic and are weighted with lead. The drainage holes in the base of the pot measure 30 mm in diameter and the entrance to the pot is covered with a purse-pull mesh netting.

Fishers completed data-forms with details on the location (latitude and longitude), date, soak-time and bait used. Isle of Man (Manx) samples were collected for a period of 12 months beginning in January 2016, with samples also collected in a pilot study in the Isle of Man during 2015. The Manx samples were compared to Welsh data collected over a 14-month period beginning in April 2013 (Haig et al., 2015). The general locations of the samples are displayed by area code to maintain commercial confidentiality (see Figure 2). The pots were fished separately and attached to commercial fishing 'strings', which varied in length but typically anchor between 20 and 50 pots to the seabed along ropes 400–700 m in length. The pots were baited with a combination of dogfish (*Scyliorhinus canicula*) and edible crab carcass (*Cancer pagurus*) and were 'soaked' for 24–48 hours.

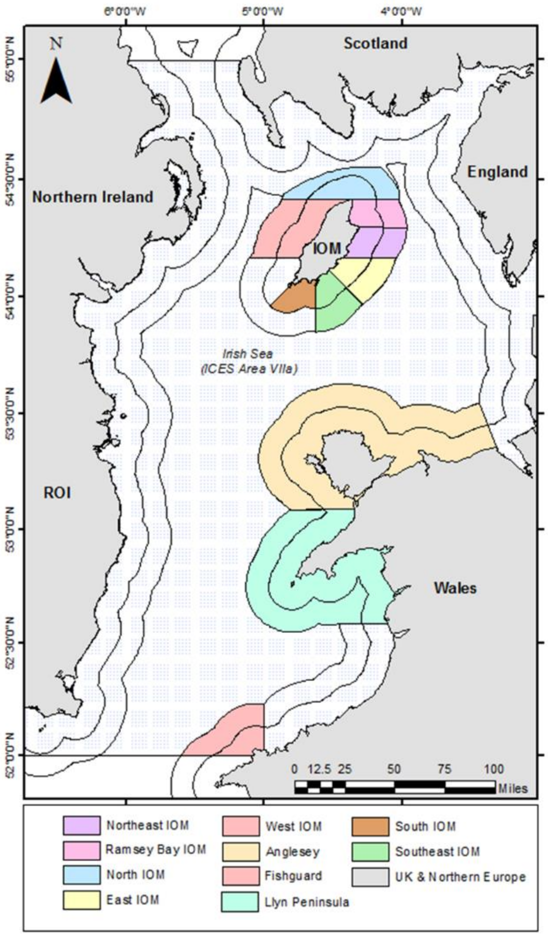

Figure 3.2. A map of the Irish Sea showing the areas where whelk (*Buccinum undatum*) were fished during the study in ICES Area VIIa. IOM = Isle of Man, ROI = Republic of Ireland.

### 3.2.2 Laboratory Analysis

Pot samples were frozen after landing and later defrosted before laboratory dissections. The latitude and longitude were recorded and the sample was assigned to an area. All individuals were sexed (presence / absence of a penis), weighed (total wet weight; 0.001g) and measured (total shell length (TSL); 0.1 mm).

A randomly selected subsamples of 30 individuals were taken from each pot-sample and further analysed. The penis length (PL) was measured from the point of attachment to the body to the tip accounting for natural curvature. Maximum and minimum shell width was recorded as shown in Haig et al. (2015). Additionally, the subsamples were dissected and the animal was removed from the shell. The wet weight of the flesh was recorded (0.01 g). The posterior lobe of the digestive gland, which is partially covered by the gonad on the dorsal surface, was visually inspected and the degree of differentiation (% gonad; 0, 0.25, 0.5, 0.75, 1) between the two organs was used to assign one of five maturity stages shown in table 3.1 (Haig et al., 2015; Hollyman, 2017a)

Table 3.1. The maturity-stage classifications of whelk (*Buccinum undatum*) as determined from visual inspection of the reproductive organs.

| | **Stage** | **Description** | **Mature** |
|---|---|---|---|
| **1** | Immature | Gonad non-differentiated from digestive whorl. Penis < 25 mm. Vas Deferens not visible. | 0 |
| **2** | Developing | Gonad beginning to differentiate on anterior edge of whorl but is thin. Penis likely < 25 mm. VD may be visible. | 1 |
| **3** | Mature (ripe) | Ovary is fully differentiated from digestive whorl and full (3/4 of whorl volume). Penis > 25 mm and VD visible. | 1 |
| **4** | Mature (spent) | Ovary is fully differentiated from digestive whorl but flaccid (occupying ¼ of whorl volume). Penis fully developed and VD visible. | 1 |
| **5** | Mature (recovering) | Ovary is fully differentiated from digestive whorl, typically occupying > 1.2 whorl volume. Penis fully developed and VD visible. | 1 |

The digestive gland and gonad, which are encapsulated by the same membrane forming the integument, were dissected away at the area where the anterior edge of the digestive gland meets the renal gland and weighed. The gonadosomatic index (GSI) was calculated by expressing the weight of the removed whorl mass (gonad and digestive gland) as a percentage of the wet flesh weight:

$$GSI\ (\%) = \frac{Gonad + Digestive\ Gland}{Total\ wet\ flesh\ weight}$$

Additionally, an adjusted gonadosomatic index (aGSI) was calculated by multiplying the above GSI value by the estimated proportion of the whorl occupied by the gonad gland (% gonad) in an attempt to focus analysis on reproductive patterns (as in Hollyman, 2017), where:

$$aGSI = GSI\ \times \%_{GONAD}$$

### 3.2.3 Statistical Analysis

All analysis was carried out in the statistical software programme R v 3.3.1 (R Core Team, 2014). Prior to statistical modelling, shell measurement and weight data were tested for normality (Kolmogorov-Smirnov test) and inspected visually using a Q-Q plot. Heteroscedasticity was tested using the Levene's test and Cook's distance plot was used to check for outliers. Transformations were applied to data where appropriate to achieve a normal distribution.

Significant deviation from the expected 1:1 ratio of sex ratio was tested using Chi-square test. Visual assessment of the gonadal maturity stage (*G*) (table 1) was used to determine a binary factor of functional maturity (immature or mature; see Table 1). Similarly, a binary factor indicating maturity in male data was also calculated using a penis-length index ($PL_i$), whereby if the ratio of penis length:total shell length is ≥ 0.5, the individual was considered behaviourally mature ($PL_{50}$) ( (Koie, 1969; Fahy et al., 2005).

Size-at-maturity estimates, the size at which 50% of the population is mature according to either *G* or $PL_{i,}$, were made using the logistic regression model (Roa et al., 1999) reformulated by (Walker, 2005) to give:

$$P_i = \left\{1 + e^{-\ln(19)\frac{TSL_i - TSL_{50}}{TSL_{95} - TSL_{50}}}\right\}^{-1}$$

where $P_i$ is the proportion of the population that is mature at a given size, $TSL_{50}$ and $TSL_{95}$ refer to the lengths at which 50% and 95% of the population are mature respectively. Model parameters were estimated using generalized linear model with logit link function and a binomial error structure. Confidence intervals were assessed by bootstrapping the model (1000 runs). The base R code for plotting the maturity ogives was constructed by Harry (2013) and has been adopted by Haig et al. (2015) and Hollyman (2017). The maturity estimates for both $TSL_{50}$ and $PL_{50}$ are considered for temporal and spatial variation.

To investigate whether TSL was the only factor that had a significant effect on $L_{50}$ estimates, data were analysed using generalised additive models (GAMs) in R. Modelling was conducted with the package 'mgcv' (Wood, 2017). Models were fitted using a binomial error distribution and a logit link function. Modelling attempted to employ a backward selection, reducing the complexity (number of parametric terms) by comparing AIC values (a model with an AIC value two points lower than a comparable model was preferred).

The $PL_{50}$ estimates for a male population, by way of further validation, is considered against an iterative search procedure on the relationship between TSL and PL, whereby PL is modelled against TSL using piecewise regression. The model examines the linear morphological relationship (PL:TSL) and searches for significant deviation from the linear model, indicating maturation (an increase in $PL_i$). The method searches each potential inflection (c) within a predetermined range until it has found the point at which the total residual mean standard error is minimised (Crawley, 2007). The model is described by the following equation:

$$y_i = \left\{\frac{\beta_0 + \beta_1 CW_i < c}{\beta_2 + \beta_3 CW_i \geq c}\right\}$$

where $y_i$ is the TSL of individual *i*, *c* is a breakpoint (inflection) between linear relationships applying above and below the value of TSL equal to *c*, and the parameter *β* parameters are the intercepts and slopes of the two linear relationships.

Temporal spatial variation in aGSI were displayed visually using the ‘ggplot2’ package in R and investigated using univariate techniques analyses of variance and covariance. Post-hoc analysis consisted of Tukey HSD tests with visual display of temporal-spatial trends using boxplots. Similarly, frequency histograms are used to display size-frequency data, which were used to make inferences on general population structure. Variation in population structure (TSL distribution) over time and space was investigated using the non-parametric Mann-Whitney U test or, if exploration revealed data to be normally distributed, *t*-test was employed for comparisons.

Depth data was assigned to each pot-sample using a high-resolution bathymetry layer (1 $m^2$) downloaded from EMODnet (EMODnet Bathymetry Consortium, 2017) . Since the possibility that whelk feed on small infaunal animals cannot be excluded (Himmelman & Hamel, 1993), TSL and aGSI data were plotted against estimates of benthic infaunal biomass (g $m^{-2}$ of wet mass; g WM $m^{-2}$), modelled by (Whiteley, 2013, p. 103), to observe any effect of benthic ecology on population structures and reproductive biology.

Due to the time and resource constraints on the present study, age-analysis of the statoliths (as described in Hollyman, 2017 and Hollyman et al., 2017) were not possible; however, the biological material for this analysis has been retained and will be investigated in the future. Therefore, when frequency histograms showed multi-modal distributions, length-frequency analysis within the mixed distribution was investigated as a proxy for size-at-age analysis. Using the R packages ‘MIXTOOLS v1.0.3’ (Young et al., 2017) and ‘MIXDIST v0.5’ (Macdonald & Du, 2012), the estimated mean and standard deviation of the cohorts were calculated and exported to MS Excel. Within Excel, the data was modelled using the LINEST function to estimate the coefficient values of the quadratic relationship along with the $R^2$ value.

## 3.3 Results

A total of 9,234 whelks were collected by fishers for the present study in ICES area VIIa with an average sex ratio of 1.14:1 females to male, which was significantly different from the expected 1:1 ratio ($\chi^2 = 24.077$, $p < 0.001$). The sex ratio varied temporally (Figure 3.3).

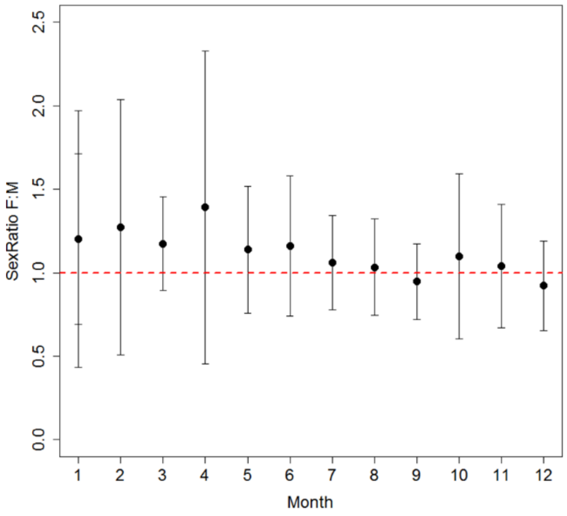

Figure 3.3. The average sex-ratio (F:M) of whelk (*Buccinum undatum*) samples collected throughout the study period ± standard deviation. The red dotted line represents the expected ratio of 1:1.

The sample size varied both temporally and spatially due to the fisheries dependent nature of the study (see table 2), thereby restricting the number of statistical comparisons available. A total of 3,290 individuals were selected as subsamples and underwent dissection. Gonadal assessment ($\%_{\text{GONAD}}$) was successfully recorded for 2,451.

Table 3.2 The total number of whelks (*Buccinum undatum*) sampled via fisheries-dependent methods (caught with scientific pots on commercial strings) in each month for all locations throughout the study period (2013-2016). Italicised numbers represent data from Haig et al. (2015).

| | **Winter** | | **Spring** | | | **Summer** | | | **Autumn** | | | **Winter** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Area-code** | **J** | **F** | **M** | **A** | **M** | **J** | **J** | **A** | **S** | **O** | **N** | **D** |
| **2013** | | | | | | | | | | | | |
| Anglesey | - | - | - | - | *91* | - | *87* | - | *68* | *152* | *212* | - |
| Llyn | - | - | - | *257* | *365* | *182* | *168* | - | *53* | *128* | *38* | - |
| Fishguard | - | - | - | *66* | *140* | *158* | *183* | - | *75* | *64* | - | - |
| **2014** | | | | | | | | | | | | |
| Anglesey | - | *57* | - | - | *112* | - | - | - | - | - | - | - |
| Llyn | - | - | - | *69* | *332* | - | - | - | - | - | - | - |
| Fishguard | - | *88* | *27* | - | - | - | - | - | - | - | - | - |
| Ramsey | - | - | - | - | - | - | - | 15 | - | - | - | - |
| **2015** | | | | | | | | | | | | |
| South | - | - | - | 46 | 63 | 79 | - | 34 | - | - | - | - |
| Southeast | - | - | 42 | - | - | - | - | - | 79 | - | - | - |
| East | 22 | 50 | - | - | - | - | - | - | - | 45 | - | - |
| **2016** | | | | | | | | | | | | |
| Southeast | 60 | 142 | 233 | 319 | 93 | 26 | - | - | - | 113 | - | - |
| East | - | 68 | - | - | 77 | 16 | - | 66 | 200 | 193 | - | - |
| Northeast | - | - | - | - | - | 161 | 84 | - | 156 | 87 | - | - |
| Ramsey | - | - | - | 175 | 57 | - | - | - | - | - | - | - |
| North | - | 164 | 427 | 332 | 571 | 315 | - | - | 494 | - | 354 | - |
| West | - | 138 | 51 | 54 | 20 | 61 | - | - | - | - | - | - |

Linear regression on log transformed data revealed a significant relationship between total weight and total shell length ($R^2 = 0.952$, $p < 0.001$) described using the equation $W = aL^b$, where a = $2.6 \times 10^{-4}$ and b = 2.795. Further analysis showed that this relationship did not have a significant interaction with sex but there was a significant interaction with country (ANOVA; $F_{1,169.2}$=25.382; $p < 0.001$) (Figure 4a) with the average whelk sampled in Welsh waters attaining more weight per mm TSL.

Table 3.3. The estimated values of coefficients a and b for the Length~Weight relationship W=aLb for whelk (*Buccinum undatum*) by area. The length weight relationship is applied to the current MLS in the Isle of Man (70 mm TSL) to illustrate the variation.

| | Area | a | b | $MLS_{IOM}$ (g) |
|---|---|---|---|---|
| WALES | ANG | 8.616 | 2.900 | 40.7 |
| | LLYN | 7.152 | 2.562 | 41.9 |
| | FSHGRD | 8.365 | 2.831 | 39.0 |
| ISLE OF MAN | SOUTH | 8.775 | 2.909 | 35.9 |
| | SOUTH-E | 8.510 | 2.835 | 34.3 |
| | EAST | 8.120 | 2.750 | 35.3 |
| | NORTH-E | 9.457 | 3.056 | 34.1 |
| | RAM | 8.634 | 2.889 | 38.1 |
| | NORTH | 9.001 | 2.956 | 35.2 |
| | WEST | 8.762 | 2.919 | 38.2 |

The size distribution of whelk sampled within the Isle of Man territorial sea was significantly larger than that of Welsh waters (Mann-Whitney U Test; $p < 0.001$), with the mean average being 77.7 ± 15.9 mm TSL and 72.0 ± 18.1 mm respectively. TSL data for male and female whelk were not significantly different in Wales, but were in the Isle of Man (Mann-Whitney U Test; $p < 0.001$). Significant spatial variation was observed in the length distribution (TSL) of whelks throughout sampled areas in ICES Area VIIa (ANOVA; $F_{9,\ 8687} = 266.3$, $p < 0.001$; Figure 4d). Post-hoc Tukey HSD testing revealed significant differences ($p < 0.05$) in the TSL distribution did not occur between all areas, as indicated by the lettering in figure 3.4.

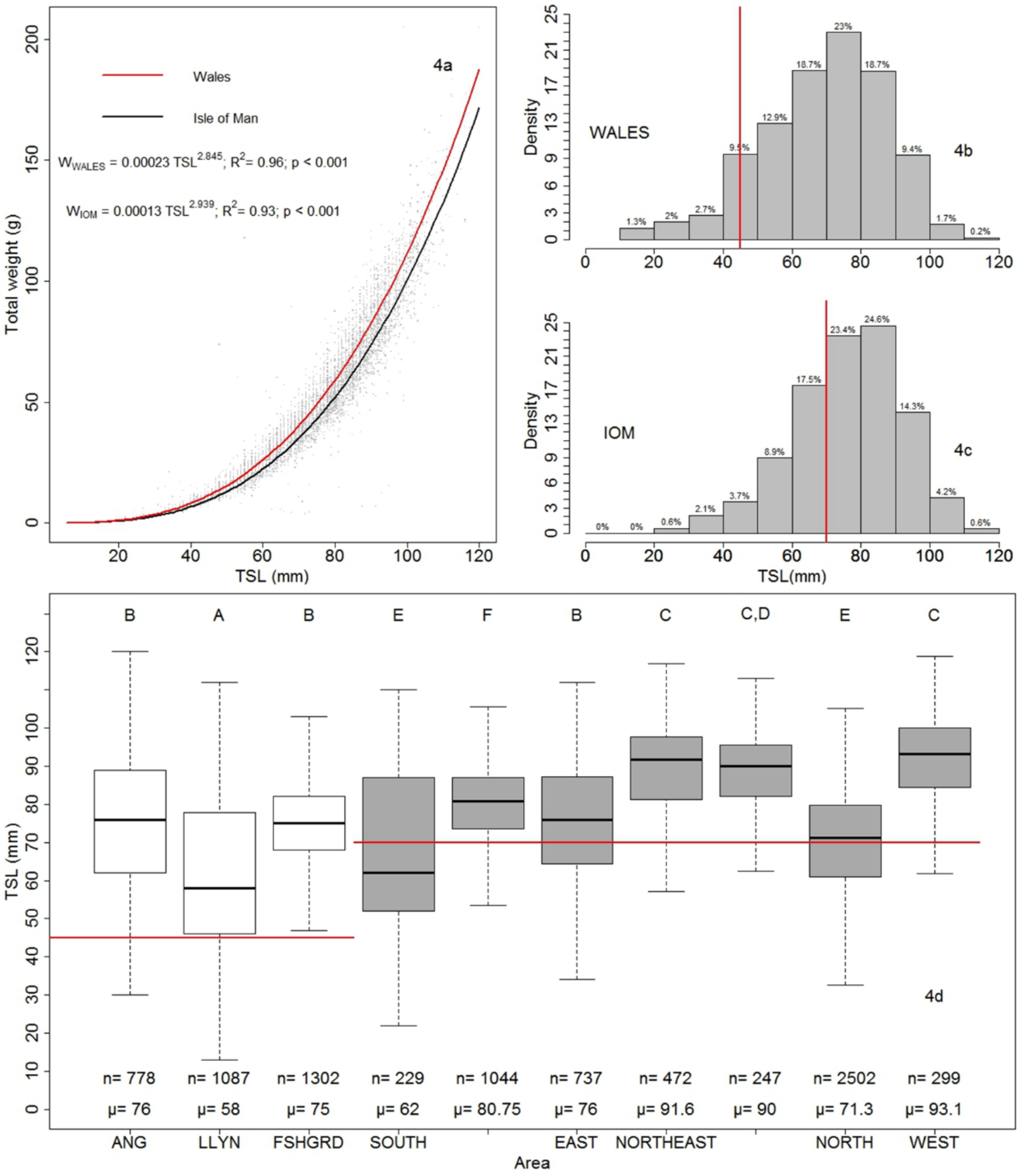

Figure 3.4. a) The total shell length (TSL; mm) by total wet weight (g) relationship for whelk, *Buccinum undatum*, in the Irish Sea (ICES Area VIIa). 4b & 4c) Length frequency histograms of the total shell length distribution for whelks from Wales (4a) and Isle of Man (4b) in temporally pooled data, with percentages above indicating the relative density of each 10 mm bin. The vertical (4b, 4c) and horizontal (4d) red lines represent the current minimum landing size in each fishery jurisdiction. Figure 4d shows the temporally aggregated TSL data for each survey area, displayed as boxplots. The letters above 4d indicate a significant difference ($p<0.05$), whereby matching letters indicate no significant difference. The white and grey boxplots represent Welsh and Isle of Man samples respectively.

Generalized linear models with a binomial distribution were applied to the aggregated dataset, which includes all sampling events throughout the study, to produce a maximum likelihood estimate of functional maturity ($TSL_{50}$) for the female (A), male (B) and combined sex (C; “Combined”) populations in the Irish Sea (Figure 5).

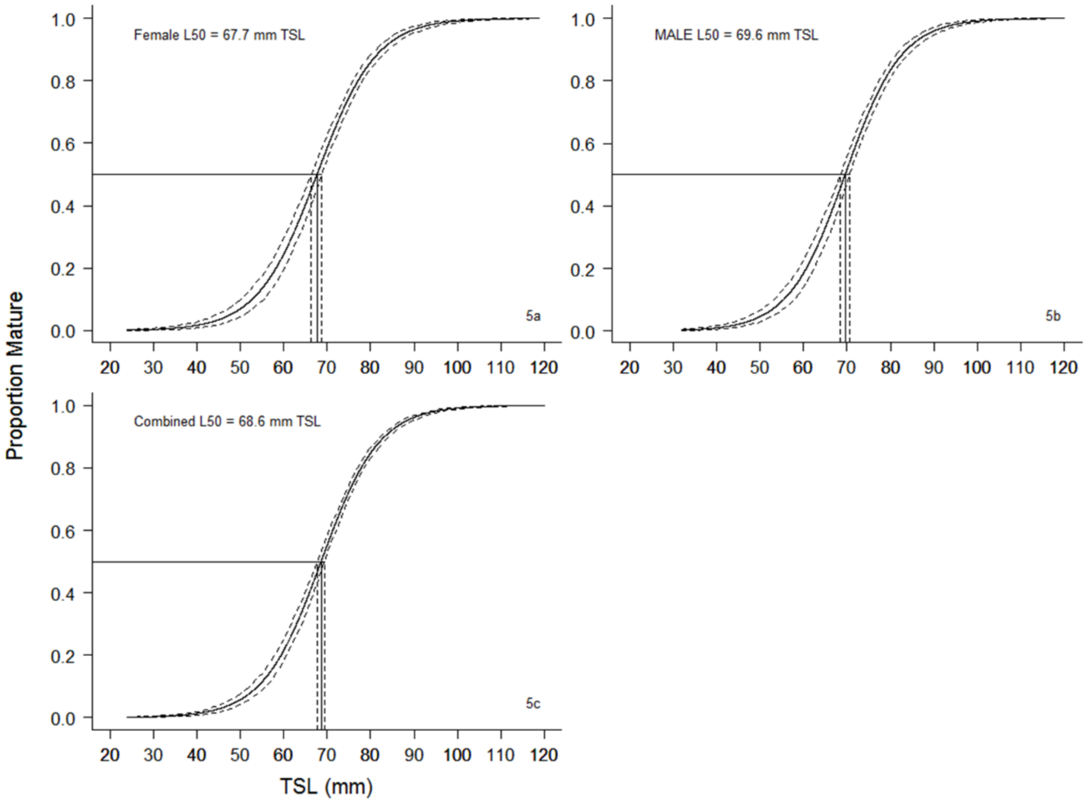

Figure 3.5. Maturity ogives showing the functional maturity estimates of whelk (*Buccinum undatum*) populations sampled in ICES Area VIIa during the study period. Three separate models were applied to female, male and combined sex data. The hashed lines represent the 95% confidence intervals of the model.

The narrow 95% intervals suggest a high level of confidence in the models applied to aggregated data, which showed TSL to be a highly significant explanatory variable for maturity ($p < 0.001$ in all three models). The smallest observed mature animal was observed at a size of 43 mm in Fishguard (West Wales).

Environmental or seasonal variables that might influence the proportion of mature whelk were considered further within general additive models, which were reduced in complexity according to a backward selection. The simplest model was able to explain 44.3% of the deviance (adjusted-$R^2$ = 0.497) in the data (AIC value =1894), described as;

$$Maturity \sim TSL + Area + Month + Sex + s(Depth)$$

**Model 1**

The modelled parametric coefficients are summarised in table 4. Note that “s” denotes an isotropic smoother applied to depth data (s(Depth); edf=1.193, $\chi^2 = 1.362$, $p = 0.491$).

Table 3.4. The estimated parameters, t-values, Std. Error and p-values for the preferred general additive model describing the relationship between maturity as a binary factor (0,1; immature, mature) and explanatory variables. (Significance codes: 0 '***', 0.001 '**', 0.01 '*', 0.05 '°', 0.1 '-').

| Parameters | Estimate | Std. Error | *t*-value | *p*-value |
|---|---|---|---|---|
| (Intercept) | -11.65 | 0.68 | -17.21 | < 0.001 |
| TSL | 0.17 | 0.01 | 24.43 | < 0.001 |
| Area-EAST | -1.01 | 0.33 | -3.04 | 0.002 |
| Area-FISHGUARD | -0.67 | 0.35 | -1.95 | 0.051 |
| Area-LLYN | -1.20 | 0.37 | -3.23 | 0.001 |
| Area-NORTH | -0.16 | 0.36 | -0.45 | 0.651 |
| Area-NORTHEAST | -1.29 | 0.39 | -3.24 | 0.001 |
| Area-RAMSEY | -0.79 | 0.52 | -1.52 | 0.129 |
| Area-SOUTH | -1.03 | 0.42 | -2.44 | 0.015 |
| Area-SOUTHEAST | -1.07 | 0.32 | -3.33 | < 0.001 |
| Area-WEST | -2.73 | 0.40 | -6.75 | <0.001 |
| FEB | 1.06 | 0.35 | 2.99 | 0.003 |
| MAR | 0.60 | 0.36 | 1.66 | 0.097 |
| APR | 1.10 | 0.35 | 3.12 | 0.002 |
| MAY | 1.67 | 0.36 | 4.57 | < 0.001 |
| JUN | 2.04 | 0.41 | 4.98 | < 0.001 |
| JUL | 1.14 | 0.42 | 2.70 | 0.007 |
| AUG | 0.80 | 0.44 | 1.81 | 0.070 |
| SEP | 0.92 | 0.37 | 2.51 | 0.012 |
| OCT | 0.58 | 0.36 | 1.63 | 0.103 |
| NOV | 0.38 | 0.43 | 0.87 | 0.385 |
| DEC | 2.18 | 0.94 | 2.31 | 0.021 |
| MALE | -0.34 | 0.12 | -2.87 | 0.004 |

The results from the GAM showed that the most significant terms to influence the binary response variable 'mature', were size, month, area and sex. In agreement with previous studies, size-at-maturity estimates are therefore modelled using the GLM approach separately for males and females on a finer temporal-spatial scale.

Considering that the month in which the sample is acquired has a significant effect on the response variable 'mature', a rationale is required for determining the time-period during which data should be modelled to estimate $L_{50}$. The objective is to minimise false classifications of an individual animals maturity stage (Table 3.1). Gonadal state is most visibly clear during a time period when ovaries and testes of mature animals are full, after having fully recovered from previous spawning. This period can be determined by analysis of the variation in gonadosomatic index.

Analysis of covariance found that the pattern in adjusted-GSI (aGSI) varied significantly amongst mature whelks, explained by sex ($F_{1,7081}$=452.8, $p < 0.001$), month ($F_{11,3525}$=20.5, $p < 0.001$) and area ($F_{9,2646}$=18.8, $p$=0.001), with significant interactions also between month and area ($F_{37,1946}$=3.36, $p <$ 0.001), month and sex ($F_{11,1148}$ =6.67, $p < 0.001$) as well as area and sex ($F_{9,400}$ =1.02, $p$ =0.002). The aGSI pattern for male and female populations samples, aggregated by month and country (Isle of Man and Wales) are visually displayed in Figure 3.6.

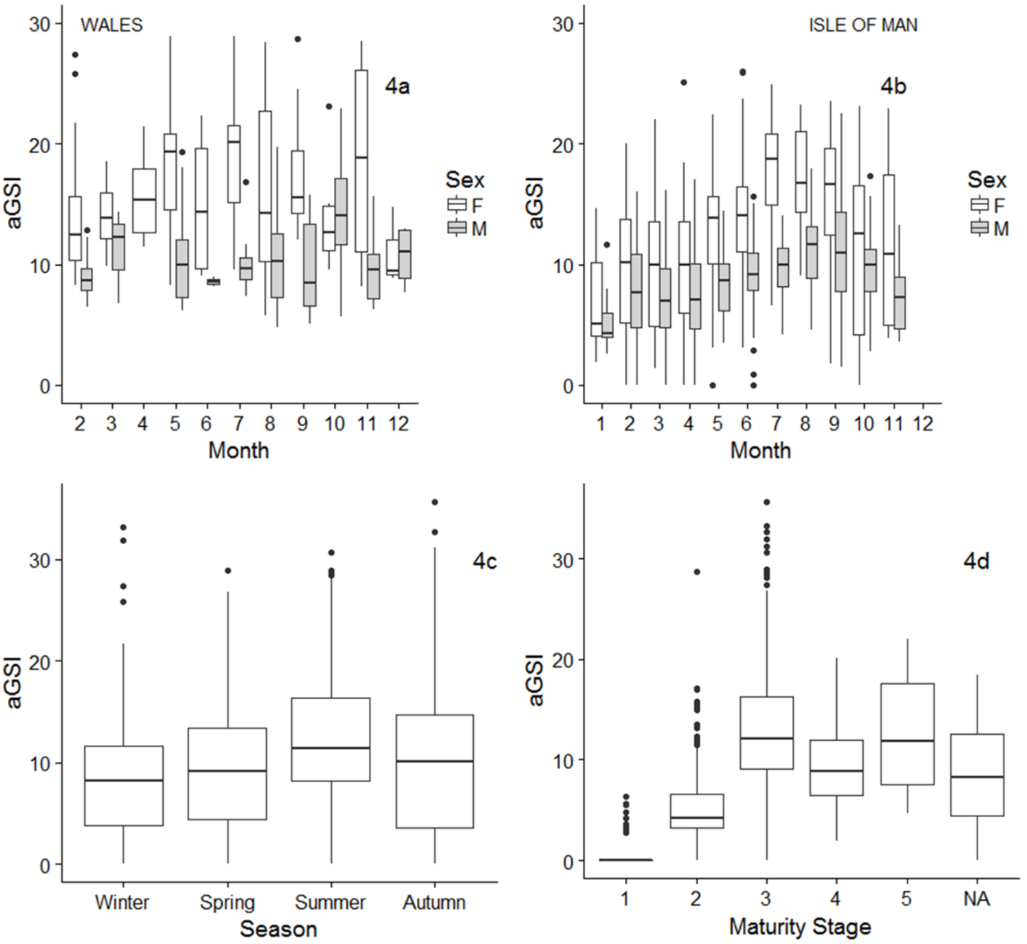

Figure 3.6. Boxplots showing the median average, IQ-range and 95% CIs of aGSI: A) mature male and female populations of whelk (*Buccinum undatum*) sampled in Welsh waters and B) the Isle of Man territorial sea by month. C) boxplot showing aGSI in each seasons (aggregated data) and D) aGSI of whelk assigned to each maturity stage (table 1). Dots indicate outliers.

Mature female whelk sampled within the Isle of Man territorial sea show a distinct reproductive cycle, with peak aGSI during July to September (Fig 6b). Welsh data within ICES VIIa reveals that whelk had a greater temporal range of peak aGSI, spanning from June until November (Figure 3.6a) with much greater variation.

Estimated aGSI varied significantly according to season (Fig 6c) (ANOVA; $F_{3,2996}$=23.91, $p < 0.001$), with significant differences occurring between all seasons aside from between winter (December – February) and spring (March – May) (Tukey *post hoc*, $p_{adj} < 0.001$) and peaking during summer (June - August). Similarly, aGSI varied significantly between maturity stages (6d) (ANOVA; $F_{4,40587}$=487.7, $p$ $< 0.001$), with significant differences occurring between all maturity stages (Tukey *post hoc*, $p_{adj} < 0.001$)

with the exception of between '5; recovering' and '3; ripe' (Tukey *post hoc*, $p_{\text{adj}} = 0.99$) and '5; recovering' and '4; spent' (Tukey *post hoc*, $p_{\text{adj}} = 0.32$), with 'ripe' whelk having the greatest average aGSI value.

Considering the analysis above, the most appropriate subset with which to conduct spatial comparisons of functional maturity $L_{50}$ is during summer and autumn (Fig 6a, 6b) prior to the spawning season, which is characterised by a low aGSI value. Again employing a GLM approach, $L_{50}$ is calculated for male and female whelk within each area, with data aggregated throughout the peak aGSI period. The results of the analysis, together with the sample size are presented in Table 3.5.

Table 3.5. Functional maturity (L50) estimates for male and female whelk (*Buccinum undatum*) by study area within the Irish Sea (ICES Area VIIa) during the summer and autumn months (June to October). Caution should be taken when considering samples with low sample size; *** = N too low to produce an estimate, * = N sufficient to produce an estimate, but with low confidence.

| | Area | Sex | $L_{50}$ (mm) | *N* |
|---|---|---|---|---|
| WALES | ANGLESEY | ♂ | 63.6 | *71* |
| | | ♀ | 65.6 | *78* |
| | LLYN | ♂ | 71.8 | *80* |
| | | ♀ | 71.3 | *86* |
| | FISHGUARD | ♂ | 62.5 | *102* |
| | | ♀ | 65.5 | *89* |
| ISLE OF MAN | SOUTH | ♂ | 71.1 * | *38* |
| | | ♀ | 63.9 * | *34* |
| | SOUTH-E | ♂ | 71.9 | *57* |
| | | ♀ | 73.1 | *68* |
| | EAST | ♂ | 74.9 | *100* |
| | | ♀ | 72.3 | *96* |
| | NORTH-E | ♂ | 75.0 | *145* |
| | | ♀ | 71.6 | *132* |
| | RAM | ♂ | NA*** | *5* |
| | | ♀ | NA*** | *5* |
| | NORTH | ♂ | 64.7 | *82* |
| | | ♀ | 67.3 | *79* |
| | WEST | ♂ | 65.5 * | *23* |
| | | ♀ | 75.1 * | *21* |

Penis length was also assessed in order to estimate size at maturity using temporally aggregated data. Logistic regression analysis estimated that the size at behavioural maturity for males ($PL_{50}$) for whelk in Welsh waters is at a size TSL = 78 mm; however, iterative searches observed an 'inflection' in the PL:TSL relationship at a size TSL = 68 mm. Similarly, for data aggregated from samples within the Isle of Man, $PL_{50}$ is estimated at a size 81mm, whereas an inflection in the PL:TSL relationship is observed in the same data at a size TSL = 77. In both sets of data, an allmoetric change in the penis is observed before $PL_{50}$ is observed.

Neither the reproductive output (aGSI; Fig7a), nor size (TSL distribution; Fig 7b), showed a clear trend with modelled benthic infaunal biomass. Nonetheless, statistical testing revealed a significant difference in the size distribution (TSL; ANOVA, $F_{6,6838} = 53.17$, $p < 0.001$) and reproductive output (aGSI; ANOVA, $F_{6,1552} = 575.2$, $p < 0.001$) of whelk in areas of varying benthic infaunal biomass. Post-hoc Tukey HSD tests, indicated by the letter-text in Fig 7, highlight that although differences are observed between group, there is no clear correlative pattern. Note that dissected whelk from areas with a benthic infaunal biomass > 300 g WM m$^{-2}$ did show an aGSI value approximately 100% greater than elsewhere; however, a low sample size (n = 19) limits the confidence in the statistical result (Figure 3.7a; D*). In contrast, depth (analysed here as a categorical variable), appears to have a negative relationship with both reproductive output (aGSI) and average size (TSL). Average ovary weight (ANOVA; $F_{5,1743} = 16.15$, $p < 0.001$) and average size (ANOVA; $F_{5,8346} = 64.86$, $p < 0.001$) varies significantly between depth categories. Post-hoc Tukey HSD tests show that significant differences are generally observed between groups with increasing depth (Figure 3.7c and 3.7d).

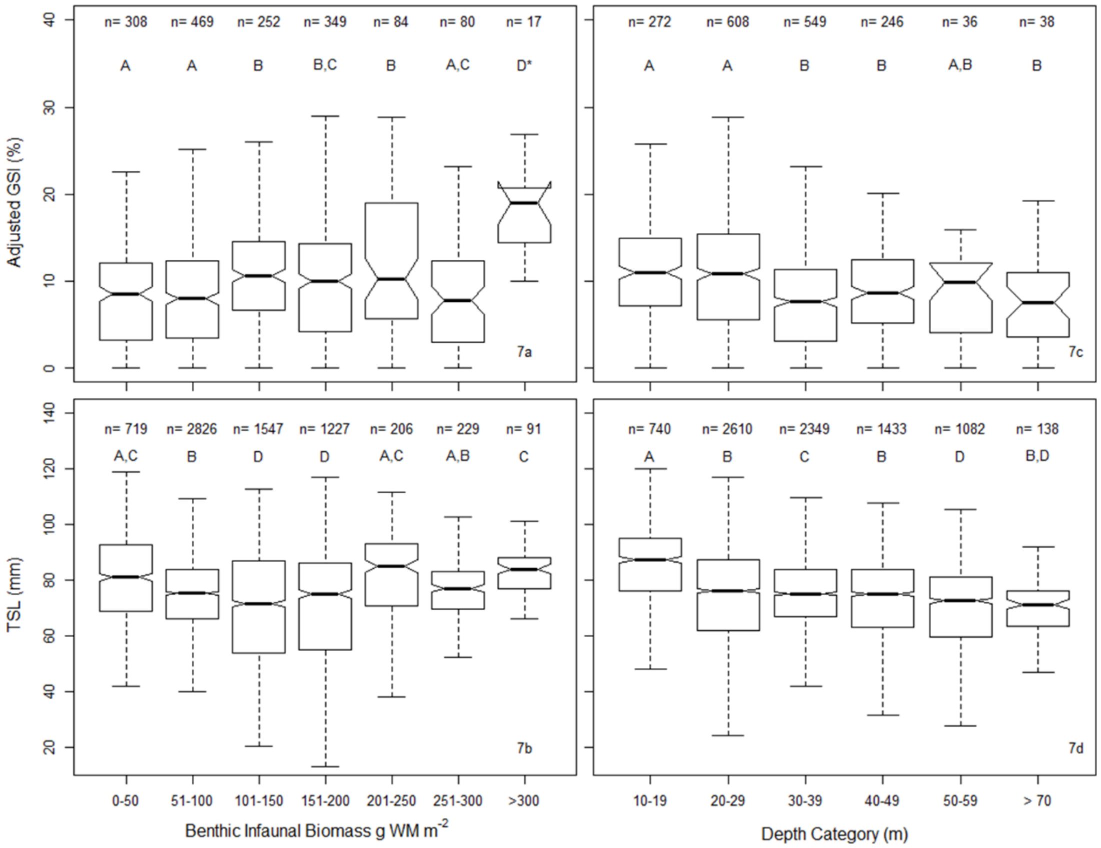

Figure 3.7. Reproductive output (aGSI %) and population structure (TSL; mm) displayed as boxplots plotted across two grouped environmental parameters; Benthic infaunal biomass (g WM m$^{-2}$) and depth (m). The letters indicate where post-hoc testing revealed significant differences in data, whereby matching letters indicate no statistically significant differences between data.

A sample, from within the NORTH survey area in March 2016 (n = 427), showed a multi-modal distribution (Hartigan's dip test for uni-modality; $D_{12.37} = 0.014$, $p$-value = 0.83 [alternative hypothesis accepted, i.e at least bimodal]) with between five and seven modal intervals (cohorts). Using a mixed-population cohort analysis, summary statistics (mean and standard deviation) estimates for individual cohorts may be indicative of the population size-at-age relationship (Figure. 3.8). The estimates suggest that whelk in this area initially grow approximately 15 mm yr$^{-1}$ with the rate of growth decreasing with age. In the fifth year of growth, whelk reach the MLS (70 mm TSL). Since the sample was collected in March, it is also assumed that individuals have undergone a full annual growth period since initial spawning (age 0).

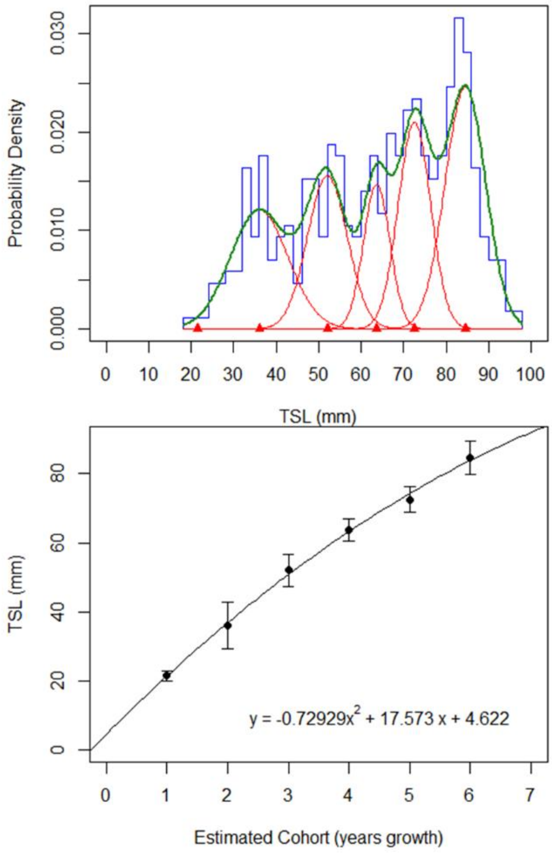

Figure 3.8. a) A probability density histogram showing the multi-modal TSL distribution of whelk within a single pot sample (NORTH-March 2016). The green lines show the probability function of the mixed data and the red lines show the modelled distribution of each estimated modal interval. The red arrows on the x-axis represent the mean value of the modal intervals; b) a scatter plot showing the estimated size-at-age relationship modelled using the results of the multi-modal analysis. The points represent the average value of each modal interval (red arrows in fig 8a) ± standard deviation. The quadratic term and $R^2$ value are shown.

## 3.4 Discussion

The whelk fishery in the Irish Sea (ICES Area VIIa) has recently undergone significant expansion both in terms of landings and effort (MMO, 2017), with landings increasing from 2,900 t yr$^{-1}$ to over 6,700 t yr$^{-1}$ (+227%) between 2011 and 2016, with a similar trend observed globally (FAO, 2017). Our results suggest that, with the exception of one site to the north of the Isle of Man, there is a risk of recruitment overfishing as the average whelk recruits into the fishery (at 45 mm in Wales and 70 mm TSL in the Isle of Man) before they have an opportunity to spawn. It is possible that fishing under the size at maturity may already have resulted in recruitment overfishing in principal fishing grounds in the Irish Sea. This may culminate in long-term stock depletion in a fishery that is increasingly valuable to coastal and island economies in the Irish Sea (DEFA, 2017).

Routine stock assessments are absent throughout the vast majority of the whelk fishery distribution, with the exception of the States of Jersey, which began annual data collection in 1996 using baited-pots (Morel & Bossy, 2004; Shrives et al., 2015) and the inshore waters of Québec, where commercial fishery performance indicators (catch per unit effort; CPUE) are assessed every three years (Brulotte, 2015). There are methodological challenges in using capture data from baited-pots to estimate absolute or relative population densities (Borsetti et al., 2018), considering the unknown effects of highly variable environmental parameters such as tidal strength, season, bait-type and soak-time as well as the inherent sex-specific or size-specific selectivity of whelk pots (McQuinn et al., 1988). An improved sampling method may be to use dredge-based surveys. In a similar study, Borsetti et al. (2018) used a dredge-based survey methodology, whilst acknowleding that gear-specific efficiency studies for dredges may facilitate absolute abundance assessments in the future. However, in the absence of accepted methods to conduct annual stock assessments, the sustainable prosecution of the whelk resources in the Irish Sea is difficult to manage. Fisheries managers in the region now seek to manage whelk fishing with robust evidence (DEFA, 2017; Welsh Government, 2017) and transition towards routine assessments of stock health. The results presented in this paper detail important population parameters, such as size-at-maturity, size-at-age and length~weight relationships ($W=aL^b$), which are essential components of biomass estimates in several stock-assessment techniques. Moreover, the variation within national waters (see table 3 and table 5) may also need to be considered if future stock assessments are attempted at a finer spatial scale, which has been the advice from other studies (Shelmerdine et al., 2007).

The sex-ratio was significantly different to the expected 1:1 ratio, indicating that the catch efficiency of static-gear is higher for females. This is particularly evident during late winter and spring, when females are recovering from egg-laying and are likely to be attracted to baited pots to feed after spawning in order to replenish energy reserves. Similar patterns were observed in data collected elsewhere in the region (Hollyman, 2017a, p. 40). The consistent removal of a higher proportion of females may result in sex overfishing under a sustained level of heavy fishing pressure, which has been shown for other species targeted by static-gear fisheries in the region (Emmerson et al., 2017). In order to protect spawning stock biomass, the sex-dependent selectivity of gear, as well as the underlying biological and environmental drivers, should be carefully considered in a management strategy that may include temporal fishery closures (Hollyman, 2017, p. 294). The results from models presented here highlight that size-at-maturity ($L_{50}$) and the reproductive cycle of whelks are vital elements of evidence for fisheries managers that wish to initiate appropriate management measures to protect spawning biomass, such as MLS and temporal closures to protect spawning.

The length frequency distribution shows significant spatial variation between country and between intra-national fishing grounds. This is also important to policy-makers that need to consider the spatially variable economic impact of a legislative change in MLS. Apart from a correlation between average whelk size and water depth, other important environmental and ecological drivers remain poorly understood for the species such as habitat type, sea bottom temperature and salinity. Benthic infauna biomass, the foundation of the benthic food-web, was hypothesised to influence the mean size of whelk, though no correlative relationship with TSL distribution was observed in the data. It remains possible that benthic infauna biomass correlates with whelk population density, though further investigation is needed to test this hypothesis. The indication that smaller whelk, with lower aGSI values (i.e. lower relative weight of ovaries to total body weight), were caught in deeper waters suggests that there could be habitat partitioning of life history stages driven by biological (food availability and reproductive needs) and environmental (sea-bottom temperature and substrate type) preferences.

Increased temporal monitoring of population structure should reveal how whelks respond to both environmental and anthropogenic factors, such as climate change as well as direct and indirect fishing mortality. The population structure of whelk in the inshore grounds to the east of Douglas exhibit a similar size range (TSL) to that reported by Kideys (1991), suggesting that the levels of fishing experienced in recent years may not have impacted length frequency. This is notwithstanding the increase in fishing effort in other sectors of the industry, which may have either positive or negative, direct or indirect impacts on whelk populations. Within the Isle of Man territorial sea, the principal whelk grounds are subject to heavy fishing pressure from scallop dredging (Shepperson et al., 2014). Bottom-towed, or trawling gear, is known to impact other commercially fished species; for example, egg-bearing female brown crabs are regularly caught as bycatch in the Isle of Man scallop gear (Ondes et al., 2016). Conversely, trawling indirectly influences common whelk populations by providing additional food resources in the form of damaged bivalves, echinoderms, and crustaceans following trawling disturbance (Ramsey et al., 1998). The scavenging opportunities created by benthic disturbance may be a significant energetic input for whelk populations considering the results presented in this study, that benthic infauna biomass shows no clear correlation to whelk population parameters. Understanding this interaction would be a positive step towards ecosystem-based management, a process which would require mapping of commercial effort in order to quantify the cumulative impacts of indirect and direct interactions between fisheries (Murray et al., 2008).

The analysis presented in this paper exhibits progress towards understanding the reproductive cycle of whelk populations in the Irish Sea and, importantly, provides clear rationale for routine assessment of maturity in this region and elsewhere. The methodology discussed, that maturity analysis should be conducted during peak-aGSI, is in agreement with other recent work (Hollyman, 2017, p. 287). McIntyre et al. (2015) attempted to minimize seasonal variability in their analysis of SOM in various English locations by collecting samples during January – May. However, under the assumption that whelk populations in the English Channel and North Sea also spawn in late winter, McIntyre et al. (2015) likely overestimated $L_{50}$ due to low aGSI values in the sampled whelk. Martel et al., (1986b) calculated GSI values with eviscerated weight (total meat weight minus the weight of the testis, digestive gland and seminal vesicle for males, and the total weight minus the weight of the ovary, digestive glans and pallial oviduct for females) used as the denominator, in contrast to this study which used total meat weight. Arguably, eviscerated weight would provide a more accurate GSI as the weight of reproductive organs vary temporally. However, as Welsh data did not include eviscerated weight and in order to conduct a regional comparison in the Irish Sea, the same methodology was adopted for Manx samples. This demonstrates the need for the adoption of a standard assessment protocol to enable comparisons between different studies, in different regions and in different countries. This will become increasingly important to understand the broader scale impacts of increasing fishing pressure as well as climate change and ocean warming. Sea surface temperature data strongly suggests that seasonal onset of maturity, as indicated by an increase in aGSI values within a population (indicating the development and ripening of gonadal organs) being linked to local temperature regimes. Historical sea-surface temperature (SST) data for the Irish Sea region highlights a potential correlative relationship, considering that SST peaks in the Isle of Man during July, August and September (exceeding 13 ºC), whereas peak SST from Welsh waters shows a more prolonged temporal period within which temperature data exceeding 13 ºC, observed from June until November (CEFAS, 2017). However, a greater temporal data-set of aGSI is necessary to understand whether temperature may have a causative effect on aGSI observations. Benthic temperatures would provide a more comprehensive picture, particularly if the water column is highly stratified. The temporal patterns observed show that ovaries are most full during July to September in the Isle of Man, which was also observed by Kideys (1991), and from June to November in Welsh samples.

Growth was assessed using mixed-modality analysis of length-based data. Identifying growth parameters using direct observations made in laboratory or by investigating statolith ring analysis was outside the scope of this study, although samples have been retained for analysis using the methods developed by Hollyman et al. (2017). Nonetheless, the size-at-age model presented here provides some preliminary detail on growth, which is an important consideration when interpreting $L_{50}$ values, as well as potentially modelling recovery rates of depleted populations and formulating advice for temporal datasets in size-at-maturity. It is recommended that size-at-maturity estimates are repeated over a period of time relevant to the life-history of a species (EU, 2010). In this case, the advice is to perform biennial assessments of size-at-maturity and model the change in the mean average $L_{50}$ of the current and previous assessment (i.e a moving four-year average, a time-period which approximates to age of the average whelk beginning to develop reproductive organs) (ICES, 2008). This method helps alleviate sampling variability, maturity-stage uncertainty and significant changes in fishing practices; however, it may also mask genuine changes in population parameters caused by environmental or anthropogenic factors (ICES, 2008). Acknowledging high spatio-temporal variability is especially pertinent for whelk, considering current fishing pressure on brood stock, restricted movement of populations and changing temperature regimes due to climate change.

When fitting a logistic curve to the maturity data, it does not always follow that output value ($L_{50}$) should be the recommended MLS. It is important to account for additional information when available, such seasonality and frequency of spawning events (including skipped spawning events as in gadoid species) as well as fecundity-at-size estimates and eggs-per-recruit models (ICES, 2008). In the case of whelk in the Irish Sea, the appropriate time for maturity assessment (i.e. peak-aGSI, when reproductive organs exhibit the clearest distinction between mature and immature) is between June and September. However, our results suggest that egg-laying occurs in late winter, during which time the assessed population is expected to have grown beyond the $L_{50}$ estimate. During that period in the Irish Sea, our data indicates that a whelk may have increased TSL by 5-7 mm. For example, the logistic model applied to the population sampled “North” of the Isle of Man in this study produced an $L_{50}$ estimate of 67 mm TSL. The size-at-age model (shown in figure 8b) estimates an individual is 4.5 years at that size. With an additional 6 months growth until spawning, at age 5, that individual is estimated to be at a size 74 mm TSL. It is therefore vital that growth is understood for this species on a regional basis, as $L_{50}$ values are likely to require a correction factor before being presented as evidence to inform MLS regulations.

## 3.5 Conclusion

This study provides the most comprehensive scientific evidence to date with which to manage and conserve the common whelk resources within ICES Area VIIa. Additionally, we propose a clear rationale for undertaking routine assessments biennially for size-at-maturity, which are biologically-referenced to the time at which aGSI is at a peak in the population and visual classification of gonads is most accurate. The evidence presented here suggests whelk are exposed to significant fishing mortality before they have the opportunity to lay eggs for the first time with the existing MLS regulations. Although no data is available to indicate that populations are recruitment overfished, current understanding of whelk biology suggests that a precautionary approach should be adopted in order to conserve resources in the light of this additional evidence.

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# Chapter 4. Effect of temperature on the growth of the commercially fished common whelk (*Buccinum undatum*, L.): A regional analysis within the Irish Sea.

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The candidate is lead author on the publication and undertook the field, and laboratory data-collection in the Isle of Man. The Isle of Man data were combined with data from Wales, which was collected by P.R. Hollyman. The candidate performed all the data analyses presented in the chapter, as well as writing the methods and discussions sections. P. R. Hollyman designed the laboratory methods and verified data analyses and results. I.S.M Bloor and S. R. Jenkins were research programme leaders on the Isle of Man project. All authors provided critical feedback and helped shape the final manuscript.

## Abstract

In response to increased demand in Asian markets, the commercial fishery for the common whelk (*Buccinum undatum*, L.) has expanded in north-eastern Europe. In the Irish Sea region (ICES Area 20 VIIa), increased effort and landings have raised concerns about long-term stability of the fishery amongst stakeholders. Fisheries in Welsh waters and the Isle of Man territorial sea are now subject to an increased minimum landing size according to the best available scientific data. This study addresses key knowledge gaps by investigating the size-at-age relationship of the species across the latitudinal extent of the fisheries management region. Our findings show that growth parameters, modelled using growth rings observed in the statolith, vary between populations and show a broadly latitudinal pattern. Thermal-time (expressed as sea bottom temperature degree-days) showed a significant negative linear relationship with the asymptotic size reach by whelk populations ($L_\infty$), where whelk grew to a larger maximum size in cooler waters. Other parameters, including maximum growth rates and the age at which growth rate begins to decrease, showed clear trends with sea-bottom temperature but linear modelling failed to detect significant relationships, where warmer waters increase the rate of growth in the early life stages of whelk but cooler waters allow growth to continue until later in life. Whilst there are substantial requirements to further validate and refine the relationship between growth and sea-bottom temperature, extrapolation of these data to other regions in Northeast Europe may provide a valuable tool in approximating important life-history characteristics in stock assessments, such as $L_\infty$, age-at-L50 and age-at-recruitment.

## 4.1 Introduction

The common whelk (*Buccinum undatum*, Linnaeus, 1758) is a neo-gastropod mollusc that is found in the subtidal waters of the North Atlantic to depths of 1400 m (Mercier & Hamel, 2008). The species is widely distributed on the Atlantic continental shelf and is frequently found in densities that support commercial fisheries in both Europe and America (Emmerson, et al., 2018; Borsetti, et al., 2018). A small scale fishery has existed in Europe for over a century, with recorded annual landings in England and Wales of 4500 t in 1911 (Dakin, 1912). European waters are the principal area of production (FAO, 2017) and the fishery has undergone significant economic and geographical expansion in response to emerging Asian markets, with global landings increasing from 7000 t yr-1 to over 35000 t yr-1 between 1990 and 2014 (FAO, 2017).

Whelk are the 6th most economically important shellfish species in the UK, with total UK landings (20,800 t) equating to a value of £22.7 million in 2017 (MMO, 2018). What was once a small-scale inshore fishery is now characterised by a fleet increasing in average length and fishing capacity. For UK vessels under 12 m in length, whelk has overtaken crab and lobster as the most important shellfish species by total landed weight in the 'pot and trap' sector (Lawrence, et al., 2017). For larger vessels (> 12 m) they now rank as the second most important by volume. The same data highlight that over the last decade, the economic significance of whelk has also increased. Among the five most valuable species from 2008 to 2017 in the '10-12 m pots & traps' sector, catch data shows the relative economic contribution of whelk increase by 10%, whereas, European lobster and edible crab value increased merely by 5% and Nephrops decreased by half (SEAFISH Economics, 2018). Regionally, the Irish Sea (ICES Area VIIa) has an estimated 447% increase in the total landed weight of whelk between 2000 and 2016 by British registered vessels, with the most significant increases being recorded in the Isle of Man territorial sea (ICES rectangle 37E5) and Welsh waters (ICES rectangles 33E5, 34E5, 35E5) (Emmerson, et al., 2018). In the Irish Sea, whelk are the third most valuable shellfish resource after Nephrops and scallops (Pecten maximus), worth £8.5 million in 2017 at first-sale value (16.5% of the total value of all species landed by UK vessels in ICES VIIa) (MMO, 2018). The value of whelks landed into Wales by UK vessels was greater than all other species combined in 2017 (MMO, 2018).

The sustainability of whelk fisheries has been questioned by both fisheries scientists and industry stakeholders (see Nicholson & Evans, 1997; McIntyre et al., 2015). It is clear, for example, that the widely adopted EU minimum landing size (MLS) (45 mm total shell length; TSL) fails to protect juvenile individuals (individuals below the size of functional maturity; L50) from harvest in many regions of the British Isles (Shelmerdine, et al., 2007; Haig, et al., 2015; Emmerson, et al., 2018). The uncertainty, knowledge gaps and localised variation in basic biological parameters such as maturity (Haig, et al., 2015; McIntyre, et al., 2015), fecundity (Valentinsson, 2002) and mortality (Laptikhovsky, et al., 2016), combined with low resolution data on fishing effort and catch has meant that a conceptual framework for stock assessments has not yet been developed. As a consequence, the fishery is considered 'data-poor' and there are no biologically referrenced catch or effort restrictions. Fisheries management responses to apparent whelk population declines have therefore been precautionary in approach when compared to management decisions for other commercially important species (Fahy et al., 2000; Fahy et al., 2005; Shrives et al., 2015).

An understanding of size-at-age and longevity of exploited marine species are fundamental in most stock assessment models. For effective fisheries management to take place, scientists must be able to understand changes of stock size and structure in response to dynamic anthropogenic (primarily fishing mortality) and environmental factors (Hilborn & Walters, 1992). Using a size-at-age relationship to estimate parameters such as age-at-recruitment and age-at-first-spawning are especially valuable for evaluating existing management measures that are typically defined using size based metrics, as in the case of whelk fisheries. Modelling the growth parameters of a marine species allows scientists, managers and industry to formulate informed harvesting strategies with a medium-to-long term perspective.

A reliable assessment of age and longevity in whelk populations is problematic for fisheries scientists (Hollyman, et al., 2017b), primarily due to the heterogeneity between populations even over small spatial scales (Shelmerdine, et al., 2007; Haig, et al., 2015). Age determination of this species and other marine gastropods has typically been estimated by counting the growth rings on the operculum, an organic 'shield' on the posterior edge of the animals foot (Santarelli & Gros, 1985). However, issues of precision, accuracy and reliability (see Kideys, 1996) has meant that the methodology is viewed as suboptimal, with < 20% of samples displaying clear readable rings (Hollyman, 2017a). Novel techniques examining the statolith, which are an accretory calcareous particle typically < 300 µm and integral to the animals central nervous system, have been developed to assess age and growth of gastropod molluscs (Barroso, et al., 2005; Chatzinikolaou & Richardson, 2007). This has led to a significantly improved degree of accuracy, precision and reliability in determining the age and growth parameters of whelk (Hollyman, et al., 2018). Observing annual periodicity of growth rings in the statoliths of whelk has also been validated using controlled laboratory tank-rearing experiments (Hollyman, et al., 2018a) and by direct chemical analysis of the calcium carbonate structures themselves (Hollyman, et al., 2017b).

Body temperature (Tb) affects the behaviour and physiology of ectotherms (Huey & Stevenson, 1979; Angilletta Jr., et al., 2002), including aspects such as locomotion (Bennett, 1980; Young, et al., 2006), sensory input (Werner, 1976), and rates of feeding and growth (Navaro & Iglesias, 1995). Hollyman (2017a) observed clear variation in growth rates and seasonality of growth in whelk across the British Isles. Across this latitudinal range, warmer sea bottom temperatures in the south stunted $L_\infty$ (the theoretical average maximum size of the sampled population) and whelk in cooler waters to the north were hypothesised to have a greater time-window within which shell growth could occur, maximising $L_\infty$ values. Variable growth rates were highlighted by Haig et al. (2015) as a potential key driver in localised variation in size-at-maturity (L50) and size-structure of whelk populations sampled in South Wales. Haig et al. (2015) also hypothesised that these observations were likely a consequence of local temperature regimes. Whelk experience a large range of sea temperatures across the geographical range of the species (0 – 22 °C; Smith, et al., 2013). Physiological processes are bound by critical thermal limits, beyond which the processes cease, defined as the critical minimum (CTmin) and critical maximum (CTmax) Tb that permit performance (Angilletta Jr., et al., 2002). The thermal performance curve of whelk is not known but typically may be asymmetric with maximum performance of individuals occurring at some intermediate temperatures (Angilletta Jr., et al., 2002), otherwise known as a thermal preferendum (Sharpe & DeMichele, 1977).

Degree-days (DD; i.e. the calculation of thermal-time as the cumulative temperature values of each day over a period of time) are an increasingly popular method for explaining variation in growth and development of marine organisms (Chezik, et al., 2014), despite only accounting for 5% of all temperature related growth studies between 1980 and 2006 (Neuheimer & Taggart, 2007). Neuheimer and Taggart (2007) found strong linear functions of the DD metric can explain > 92% of the variation in size-at-age data among forty-one data sets representing species from a variety of marine and freshwater environments as well as laboratory studies. Since the metabolic functioning of whelk, a boreal species, is expected to decrease linearly from a thermal preferendum, we model temperature as a function of DD (Sharpe & DeMichele, 1977; Angilletta Jr., et al., 2002).

This study presents a regional analysis of data from statolith samples collected in the Irish Sea, specifically from within Welsh waters and the Isle of Man territorial sea. Spatial comparisons of the size-at-age relationships are coupled with satellite-derived sea-bottom temperature data in an attempt to empirically explain the relationship between temperature and growth parameters for this geographical area.

## 4.2 Materials and methods

### 4.2.1 Biological samples

Whelk were collected by industry participants from exploited fishing grounds in both the Isle of Man territorial sea and Welsh waters (Figure 4.1) using industry-standard Fish-tec© pots (see Emmerson et al., 2018 for details). Samples were collected in the Isle of Man during autumn 2016, whilst samples in Wales were collected through 2016 to spring 2017. The whelks were not 'graded' according to MLS to ensure that the maximum range of size classes were available for analysis. They were stored in freezers at -20°C upon landing. Precise spatial details of the sampling locations are not presented in agreement with the participants' requests to protect commercially sensitive data. After thawing, the TSL of each whelk was measured to the nearest 0.1 mm using Vernier callipers.

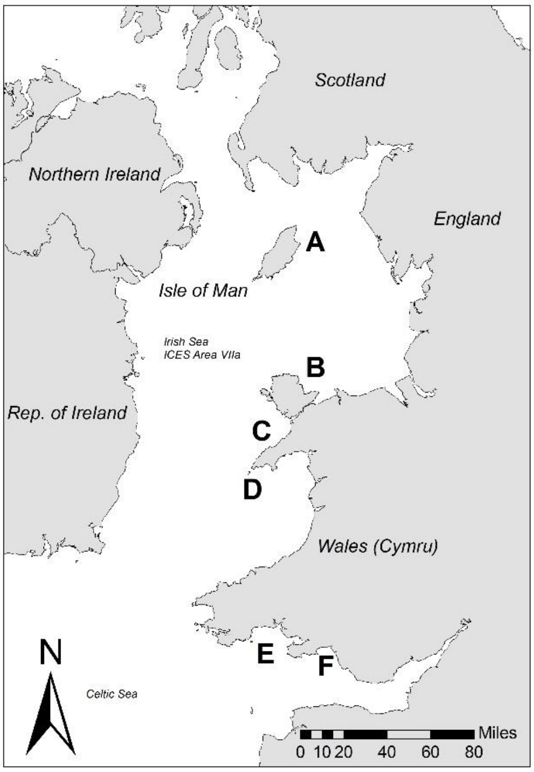

Figure 4.1. A map of the Irish Sea showing the general locations where whelk (*Buccinum undatum*) were sampled. A = Isle of Man, B = Amwlch, C = Nefyn, D = Bardsey Island, E = Carmarthen Bay and F = Swansea Bay.

### 4.2.2 Statolith analysis

One statolith from each specimen was extracted using the methodology described by Hollyman, et al. (2018a). The statoliths were mounted onto separate microscope slides using CrystalbondTM 509 thermoplastic resin and imaged under a Meiji Techno MT8100 microscope with a Lumenera Infinity 3 microscope camera at 20x magnification. Extracted statoliths were visually assessed according to the rankings described by Hollyman et al. (2018) (see figure 3 in Hollyman et al. (2018) for a visual comparison of the quality and clarity rankings of statolith rings; StR) and only specimens ranked 3 or 4 were used for subsequent analysis. Photomicrographs were analysed using ImageJ v1.48 (Ferreira & Rasband, 2012) to count and measure the width of each statolith ring (StR) starting with the hatching ring (Figure 4.2). After initial training by Phil Hollyman (PH), the agreement in age determination by StR between the two readers was 89.2%.

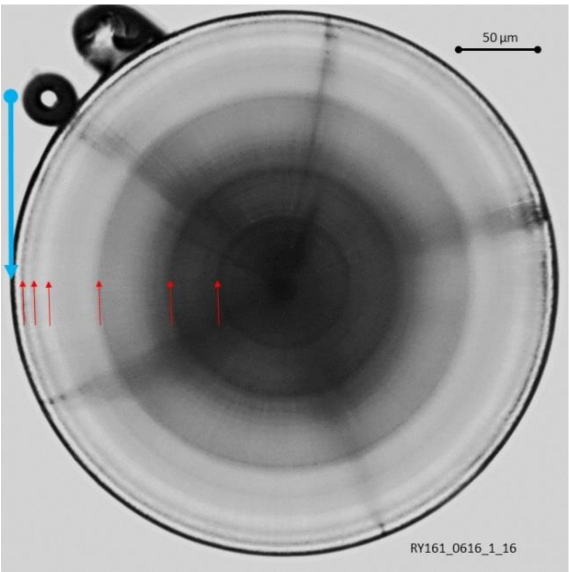

Figure 4.2. An example of a photomicrograph of a statolith (sampled in the Isle of Man territorial sea, June 2016). Red lines indicate the growth rings observed, with the centremost arrow showing the hatching ring. The blue arrow at the extremity of the statolith structure shows the edge of the statolith and is not counted as an annual growth ring.

### 4.2.3 Temperature data

Sea bottom temperature (SBT) data for each sampling location were extracted from the Global Ocean Physics Reanalysis Products “GLOBAL-REANALYSIS-PHY-001-030”, which was acquired through the Copernicus Marine Environmental Monitoring Service (CMEMS) (http://copernicus.eu).

The data provides global ocean eddy-resolving (1/12° horizontal resolution and 50 vertical levels) reanalysis covering the altimetry era 1993-2016. It is based largely on the current real-time global forecasting CMEMS system. Observations are assimilated by means of a reduced-order Kalman filter. Along track altimeter data (Sea Level Anomaly), satellite Sea Surface Temperature, Sea Ice Concentration and in situ temperature and salinity vertical profiles are jointly assimilated. The global ocean output files are displayed on a standard regular grid at 1/12° (approximatively 8 km), with the most relevant grid square to the sampling location being extracted from the overall time series.

The annual sum of degree-days (with a base temperature, T0, near to the minimum temperature in the coldest extremes of the species; B. undatum: 0 °C) can be used to explore the relationship between physiological processes and temperature. Degree-days are an expression of thermal-time (Chezik, et al., 2014) or thermal opportunity for growth (Chezik, et al., 2015), where the degree-day for a single day (DD; °C·days) is expressed as:

$$DD = \frac{(T_{Max} + T_{Min})}{2} - T_0$$

**(1)**

Data were filtered to include SBT for the period 2010-2016. The time series of daily mean SBT data for each location were then calculated as Annual Degree-Days (°C) (aDD) (equation 2). The number of measurements for each region were equal.

$$aDD = \frac{\sum DD}{time_{years}}$$

**(2)**

### 4.2.4 Modelling growth and L∞

TSL-at-age data of each specimen was calculated using a formula calculated by Hollyman (2017a, p. 183), which estimates y (size TSL; mm) to be a function of x (statolith width; µm) such that:

$$y = 43.439x^{0.4259}\ (R^2 = 0.96, n = 1719).$$

**(3)**

The measurements from each ring within each statolith sample were then modelled using equation 3 to create an account of growth for each individual whelk. These data were analysed by location and modelled using equation 4 to estimate the average size at each age (ring) within the sampled populations.

This pre-analytical calculation was necessary to fill data gaps brought about by difficulties in sampling small whelks under the 45 mm MLS, so that growth curves could be modelled with a greater goodness-of-fit to size-at-age data. Importantly, this technique avoided the unrealistic application of TSL ≤ 0 mm at age t0 (hatching), which would result in incorrect asymptotic estimates (Hollyman, et al., 2018).

Using R (R Core Team, 2017), the size and age data for each observation were modelled using a non-linear least squares regression model fitted with a gompertz growth curve (Tjørve & Tjørve, 2017), which captures the sigmoidal relationship of growth in *Buccinum undatum* and other marine gastropods more than other models (see (Hollyman, 2017a) , whereby:

$$TSL_t = L_\infty\ e^{-e^{-k_G(t-T_i)}}.$$

**(4)**

TSLt is the size of a whelk shell at time t, L∞ is the theoretical average maximum size of the sampled population, kG is the growth-rate coefficient (which affects the slope), and Ti represents time at inflection of growth (i.e. where the curve is orientated against the x-axis, or when growth begins to slow).

The estimated coefficient value of L∞, kG and Ti for each sampled population was then plotted against aDD for each location. Further, aDD was also modelled against maturity (L50) estimates taken from existing literature (Haig et al., 2015; Hollyman, unpublished data; Emmerson et al., 2018). The relationship between estimated coefficients and aDD were tested using linear regression to assess whether any significant linear relationship exists.

## 4.3 Results

A total of 1,796 individual statoliths were examined (2,973 ring observations) with a size range from 25.9 mm to 109.4 mm TSL across six locations (Figure 4.3). The oldest whelk sampled had 8 clear growth rings (excluding the hatching ring).

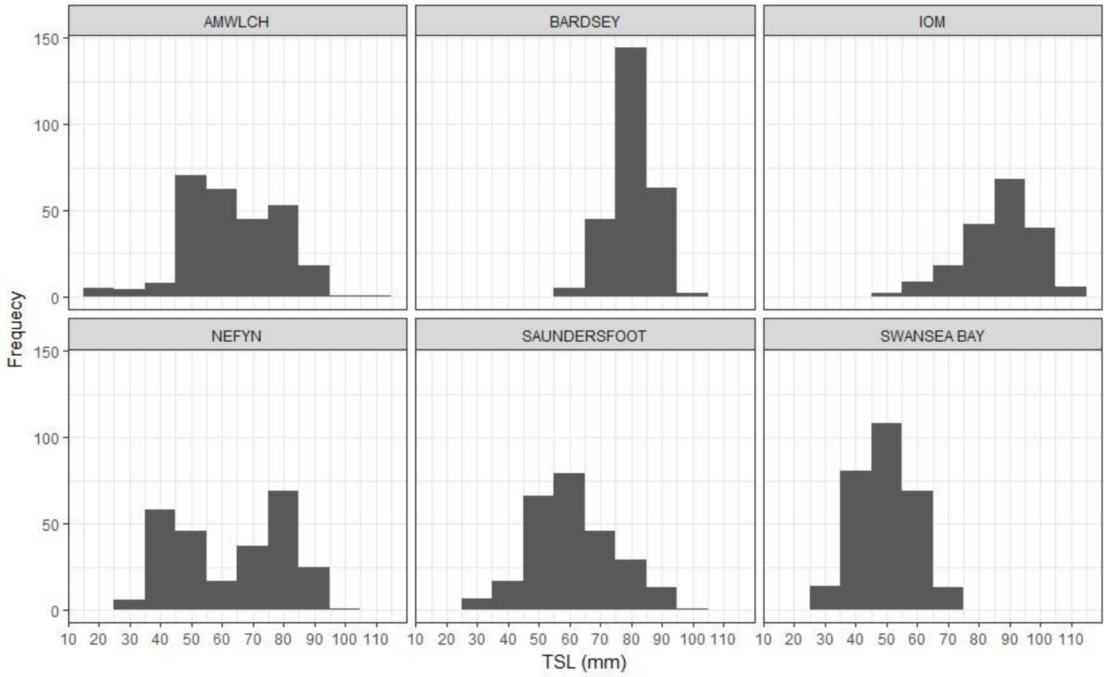

Figure 4.3. Size-frequency histograms of whelk (*Buccinum undatum*) sampled at Amwlch (n=287), Bardesy Island (n = 279), Isle of Man (IOM) (n = 185), Nefyn (n = 278), Saundersfoot (Carmarthen Bay) (n = 278) and Swansea Bay (n = 304).

The pattern of growth of whelks differed significantly by location (Figure 4.4, table 4.1). $L\infty$ ranged between 59.9 mm in Swansea and 116.8 mm in Isle of Man samples. The variation in $L\infty$ follows a broadly latitudinal trend, with the larger maximum size of whelk being observed in samples in the northern Irish Sea. In contrast, the growth rate kG decreased with increasing latitude, meaning that whelks in the south grew at a faster rate (max = 1.04, Carmarthen Bay) than in the north (min = 0.44, Isle of Man).

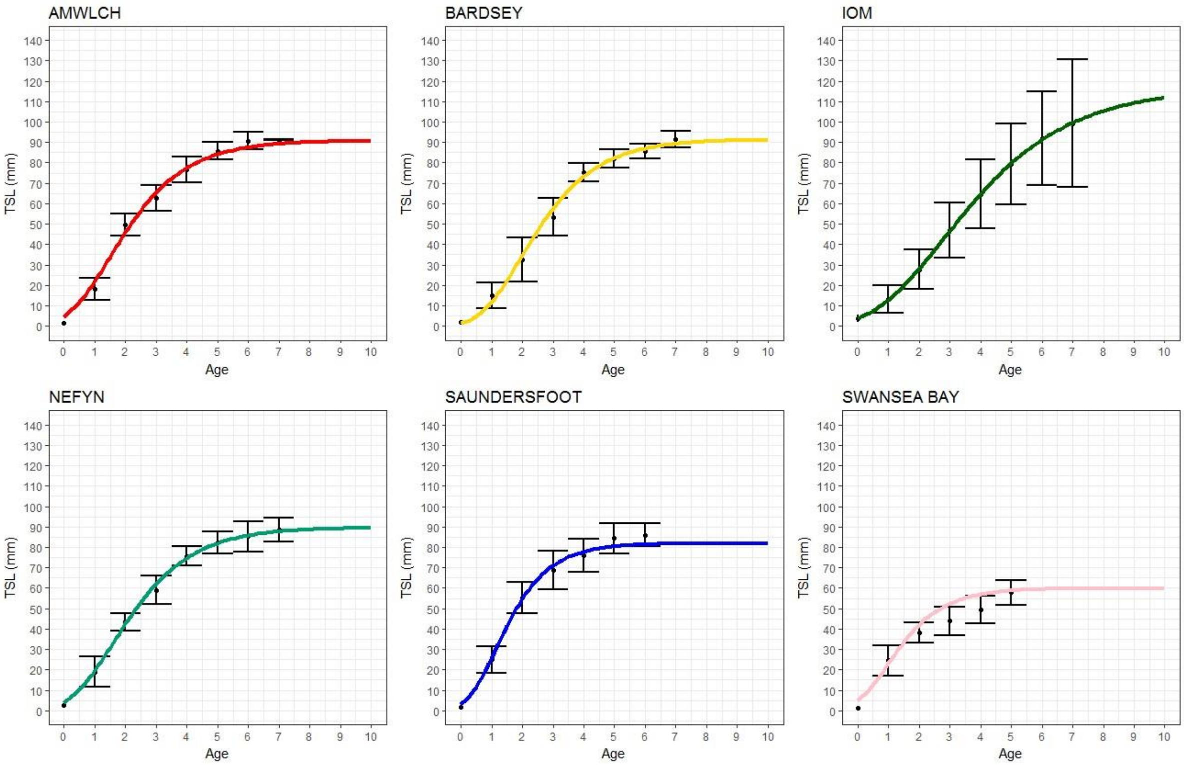

Figure 4.4. The modelled size-at-age relationship of *Buccinum undatum* by sample site in Welsh waters and the Isle of Man territorial sea. Points represent mean TSL at Age ± S.E.

Table 4.1. Summary of results from growth models for each location, including parameter estimates for model coefficients, where L∞ is estimated maximum shell size, kG is the growth-rate coefficient and Ti is the point of inflection in the model curve. Parameter statistical significance shown by p-value (*** = <0.001).

| Model | Param | Est | S.E | t-value | sig. |
|---|---|---|---|---|---|
| **Isle of Man** | $L_\infty$ | 116.8 | 4.77 | 24.5 | *** |
| | $k_G$ | 0.44 | 0.02 | 17.7 | *** |
| | $T_i$ | 2.81 | 0.11 | 24.5 | *** |
| **Anglesey** | $L_\infty$ | 90.9 | 1.45 | 1.162.6 | *** |
| | $k_G$ | 0.72 | 0.03 | 22.2 | *** |
| | $T_i$ | 1.47 | 0.03 | 44.2 | *** |
| **Nefyn** | $L_\infty$ | 89.6 | 1.19 | 74.9 | *** |
| | $k_G$ | 0.71 | 0.03 | 24.2 | *** |
| | $T_i$ | 1.59 | 0.03 | 55.9 | *** |
| **Bardsey** | $L_\infty$ | 91.5 | 0.99 | 92.0 | *** |
| | $k_G$ | 0.74 | 0.03 | 26.2 | *** |
| | $T_i$ | 1.96 | 0.04 | 54.6 | *** |
| **Carmarthen Bay** | $L_\infty$ | 81.9 | 1.49 | 54.9 | *** |
| | $k_G$ | 1.04 | 0.06 | 16.8 | *** |
| | $T_i$ | 1.14 | 0.04 | 30.3 | *** |
| **Swansea** | $L_\infty$ | 59.9 | 1.77 | 33.7 | *** |
| | $k_G$ | 0.98 | 0.06 | 11.1 | *** |
| | $T_i$ | 0.94 | 0.08 | 13.5 | *** |

The satellite data show clear seasonal variability in temperature at each location (figure 4.5). The lowest minimum temperature was in the Isle of Man (5.8 °C) and highest minimum temperature in Carmarthen Bay (6.9 °C). The lowest maximum temperature was also recorded in the Isle of Man (16.5 °C), whilst the highest maximum temperature was in Swansea Bay (18.4 °C) between 2010-2016 (Figure 4.5).

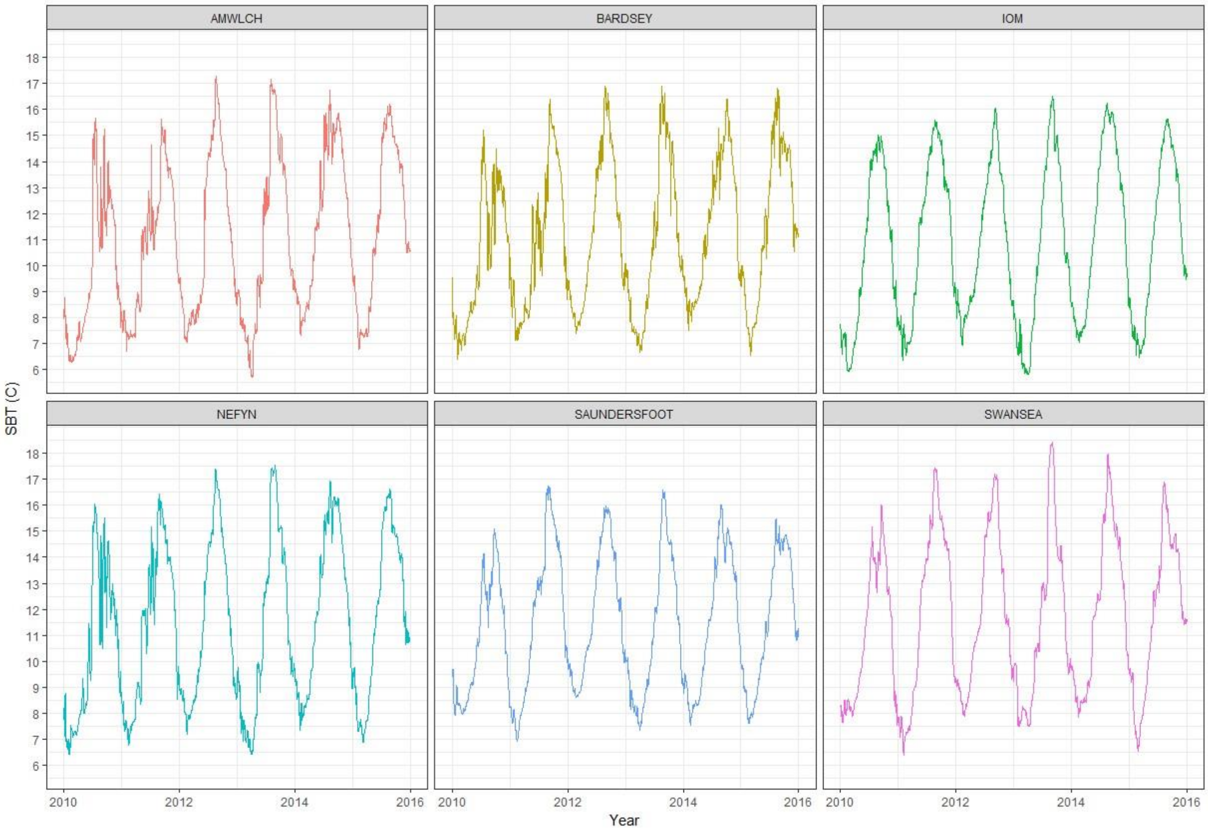

Figure 4.5. The daily sea-bottom-temperature (SBT º C) at each location sampled for whelk in the Irish Sea for the period 2010-2016.

The average aDD for each location varied between 4004 (Isle of Man, coolest) and 4267 (Swansea Bay, warmest). This equates to an average daily difference of 0.72 ºC between the warmest and coolest locations.

When the size-at-age parameters are plotted against the average aDD value for each location, there are clear negative trends in the data for all parameters with the exception of kG which is positive (Figure 4.6). Linear regression analysis shows a significant effect of aDD on L∞ (R2 = 0.72, p-value = 0.03) and is described by equation 5a. Linear regression was unable to model the effect of aDD on other growth variables to the same statistical certainty, where p = 0.07 for K_G and T_i and p = 0.11 for L_50. Extrapolating the significant linear model of L∞ over the aDD data available presents a graphical display of the estimated maximum TSL for whelk populations in the Irish Sea (Figure 4.7).

**5a**) $L_\infty = 696 - 0.15\, aDD$; $R^2 = 0.72$, p = 0.03 *

**5b**) $L_{50} = 317 - 0.06\, aDD$; $R^2 = 0.63$, p = 0.11

**5c**) $K_G = -5.7 + 0.002\, aDD$; $R^2 = 0.60$, p = 0.07

**5d**) $T_i = 21.7 - 0.001\, aDD$; $R^2 = 0.59$, p = 0.07

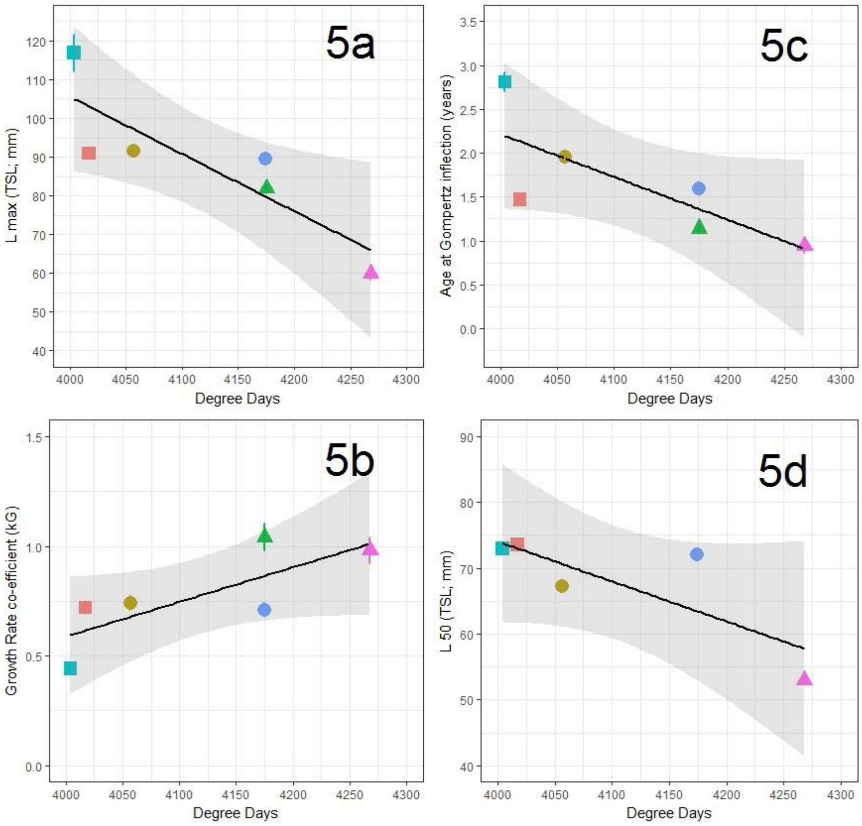

Figure 4.6. Scatterplots showing the relationship between estimated L∞, Growth rate (kG), Age at Gompertz inflection (Ti; years) and functional maturity (L50) of whelk (*Buccinum undatum*) and sea-bottom-temperature (SBT) expressed as annual average degree-days (aDD) in the Irish Sea. The black lines represent the linearly modelled relationships (equation 5a – 5d) while the grey area shows the standard error in the model. Error bars around the point show the standard error in the parameter estimations. N.B no maturity data is available for Carmarthen Bay samples.

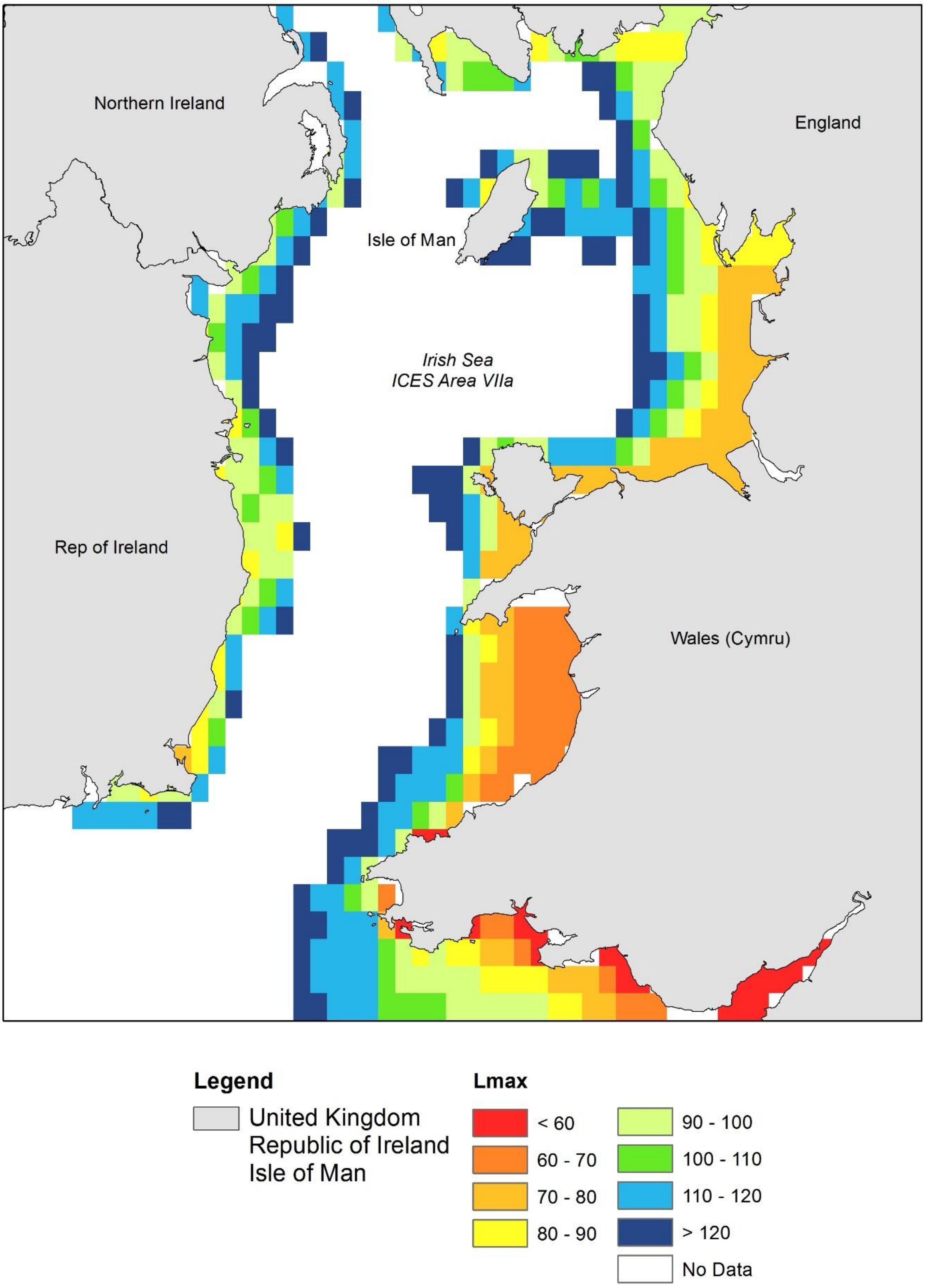

Figure 4.7. The estimated L∞ for whelk, *Buccinum undatum*, extrapolated throughout the data range of average annual sea bottom temperature (2010-2016) for ICES Area VIIa.

## 4.4 Discussion

Using growth rings observed in statoliths, the size-at-age relationship was modelled for whelk populations in the Isle of Man territorial sea and Welsh waters using specimens harvested by commercial fishers on exploited fishing grounds. The modelled growth parameters varied by location, with a clear latitudinal trend of increasing asymptotic size with latitude in the Irish Sea. The largest potential size (on average) of whelk populations varied from a maximum of 116.8 mm TSL (Isle of Man) in the north to 59.9 mm TSL (Swansea Bay) in the south, a pattern analogous with observations by Hollyman, et al. (2018) where samples were taken across a geographic range from Shetland to Jersey. This pattern is also observed in the size-distribution data for Irish Sea whelk presented in Emmerson et al. (2018). Whilst we observe large variation in size and growth of whelk over latitudinal scales, similar levels of variation have been observed in size-at-maturity and population structure at local levels, suggesting the growth of whelk may vary significantly over local scales (Haig et al., 2015). Studies examining the life history of this species have consistently alluded to or hypothesised that sea-bottom temperature is the fundamental environmental driver of variation (see Bell & Walker, 1998; McIntyre et al., 2015; Hollyman, et al, 2018). This study is the first to test the relationship between growth parameters and SBT using observed data from statoliths sampled throughout the latitudinal extent of a fisheries management area together with SBT derived from modelled satellite data.

A significant negative linear relationship between temperature, expressed as aDD, and $L\infty$ was found for the species on a regional scale in the Irish Sea (ICES Area VIIa), where the average maximum size of an individual within a population decreases with increasing average annual sea-bottom temperature. The Swansea Bay area experienced the greatest aDD of 4267 between 2010 and 2015 with populations showing $L\infty$ of 59.9 mm TSL. Cooler waters in North Wales around the Llyn peninsula (aDD = 4174) and Anglesey (aDD = 4017) meant whelk there reached a larger $L\infty$, 89.6 mm and 90.9 mm TSL respectively. The coolest waters were in the Northern Irish Sea around the Isle of Man (aDD = 4004) where whelk grow to the greatest maximum size observed in this study ($L\infty$ = 116.8 mm TSL). The variation in estimated size-at-age produced by the gompertz model (figure 4) was larger in the Isle of Man sample than in other samples. Intra-site analysis showed that this increased variation resulted from cross-sampling across several distinct whelk populations on the east coast of the Isle of Man, with ‘Northeast’ and ‘East’ sites exhibiting significantly different size structures (see Emmerson, et al., 2018). Low sample size for each site prevented separate analysis of statoliths, highlighting the need for spatially specific sampling at local scales, particularly where localised hydrographic and bathymetric variations affect ambient temperature. Significant differences in growth rate between the northeast area of the Isle of Man and the rest of the territorial sea have also been observed in king scallop populations (Dignan, et al., 2014).

Other Gompertz growth coefficients (KG and Ti), i.e. the maximum rate of growth and the point of growth rate inflection, showed marginally non-significant linear relationships with aDD ($p = 0.07$ for both coefficients). Increased sampling may change the outcome of these analyses, since visual interpretation of the data (figure 6) shows that there is a trend between aDD and both KG and Ti. The maximum rate of growth (KG) showed a strong positive correlative trend with aDD, where populations of whelk in Swansea Bay and Carmarthen Bay (South Wales) had the highest coefficient value, 0.98 and 1.04 respectively. These values indicate that the warmer sea bottom temperature, whilst limiting the maximum potential size of whelk, also accelerates the rate of growth of individual during early life-stages. The slowest growth-rate coefficient value was observed in cooler waters around the Isle of Man (KG = 0.44). The point at which this gompertz growth rate begins to decrease from the maximum (Ti) showed a negative correlative trend with aDD. Growth of whelks in warm waters such as Swansea Bay begins to decrease at age 0.94 years, whereas in the Isle of Man growth rate begins to decrease at 2.81 years.

Whelk populations found at higher latitudes in the northern hemisphere generally have a larger maximum body size than those living further south (Hollyman, 2017a), despite initial slower growth rates. This is a common pattern among many ectotherms, such as the scallop *Pecten maximus* (Chauvaud, et al., 2012). Chauvaud et al. (2012) observed that low annual growth rates in northern populations are not due to low daily growth rates, but rather a fewer number of days (thermal window) within which scallop growth could occur, which was also hypothesised in the case of whelk by Hollyman (2017a). Chauvaud et al. (2012) also showed that, “despite initial lower annual growth performance … differences in asymptotic size (L∞) as a function of latitude resulted from persistent annual growth performances in the north and sharp declines in the south”. Classical growth models have failed to capture this dynamic in long-lived ectotherms that have thermally constrained growing seasons (Chauvaud, et al., 2012), such as whelk. The growth observed in the data for whelk in the Irish Sea point to Bergmans rule, “a general trend of animal sizes to increase with latitude” (Blackburn, et al., 1999). Clearly, higher ambient temperature drives rapid growth in whelk in the early life-stages of the species with larger time-windows for growth, but they reach a smaller asymptotic maximum size earlier in life. These patterns are captured in the behaviour of the gompertz curve, which explained growth in Buccinum with a greater R2 and goodness-of-fit values than other analyses (Hollyman, et al., 2018). We also hypothesise that as well as being temperature drive, the time-window for growth decreases with age in whelks, which is consistent with the notion that as they mature there is a trade-off between growth and reproduction or defence, resulting in a decrease in the length of growing season with age (Stearns, 1992; Lankford, et al., 2001). Chauvaud et al. (2012) were able to demonstrate with scallops that the decrease in the length of growing seasons with age is more rapid at lower latitudes, a hypothesis that may also be reflected in the data presented here.

It is important that data and models explaining species life-history are incorporated into fisheries management where possible. Whelk fisheries in both the Isle of Man and Wales are considered “data poor” though they are managed primarily with an MLS informed by size-at-maturity studies (Haig et al., 2015; Emmerson et al., 2018). Viewing the analyses in this study in the context of other work on whelk in Welsh waters and the Isle of Man (see Haig et al., 2015; Hollyman, 2017a; Emmerson et al., 2018) suggests that, on average, populations reach functional maturity (L50) by age 4. It may therefore be possible to also estimate reproductive characteristics, upon which MLS is ideally referenced, using solely temperature data if the temperature~growth parameters are further investigated and the relationship is substantiated with additional data. Broadly speaking, management of whelk fisheries in the Northeast Atlantic should follow a latitudinal pattern of increasing MLS with latitude. The EU minimum conservation reference size (MCRS) of 45 mm TSL may well be sufficient to protect spawning stock according to L50 estimates in parts of the English Channel (McIntyre, et al., 2015), but it is insufficient in the Irish Sea where L50 has been shown to be up to 75 mm TSL (Emmerson, et al., 2018). As whelk fisheries continue to expand throughout the British Isles, it is essential that management is both evidence-based and regionalised.

Within the context of the Irish Sea region, a linear relationship sufficiently explains the variation in the SBT-L∞ relationship ($p = 0.03$) and provides good cause to suspect the relationship can be explain other growth coefficient factors (KG and Ti). However temperature in the Irish Sea varies over a relatively narrow range compared to the temperatures experienced by whelk over the full geographical extent of the species. Whelk are highly eurythmic and have been reported to survive in temperatures from below 0 °C to above 22 °C (Smith, et al., 2013). We hypothesize a non-linear relationship between temperature and L∞ of this species over its geographical distribution with asymptotic limits to the size of whelk in populations as average SBT approaches the lower and upper critical thermal limits (Figure 4.8). Indeed, anecdotal evidence supports this hypothesis, such that preliminary observations in the Orkney Islands (northern Scotland) show TSL∞ ≈ 140 mm at aDD = 3,465 (M. Coleman, unpublished data). A broad-range study to explore this relationship would also reveal whether populations of whelk exhibit ecotypical characteristics, where subpopulations may have undergone genotypic adaptions to specific environmental conditions that affect life-history traits such as growth. It is possible that, following successful validation of the DD~growth relationship in further studies by combining both laboratory and field-based methodologies, the growth rate of this species can be modelled throughout its distribution based solely on open source satellite-based temperature data. However, more work is required to validate the relationship in the first instance.

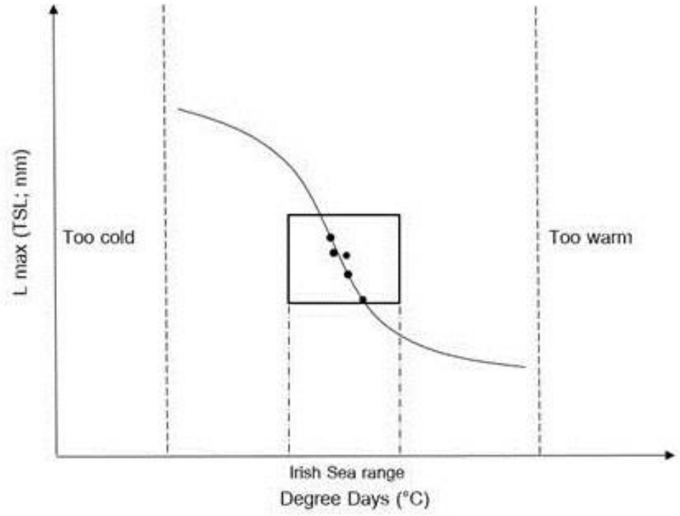

Figure 4.8. A hypothetical illustration of the relationship between degree days (°C) and L∞ for the common whelk (*Buccinum undatum*).

It is anticipated that refinement of the aDD variable according to critical thermal limits of the species, which are currently unknown, may result in the analytical models showing a statistical significance in the temperature ~ growth relationship for all parameters. This study analysed the growth parameters of whelk against a single aDD value (the average annual DD for the period 2010-2016), however further investigations looking into the parameters that define DD over time (the maximum rate of increase in DD (DDr), the point of inflection in DD (DDi) during the year) are warranted. That is to say, the mechanistic effect of temperature on whelk may be such that aDD, which calculates the average annual thermal input into the environment, has limited explanatory power. Instead, for example, it may be that it is the rate of thermal input within specific season that provides greater statistical power in explaining growth. In order to precisely analyse these hypotheses and to observe localised hydrographic anomalies, temperature data would have to be generated from direct observations using temperature loggers fixed to the seabed as opposed to the low resolution satellite data used in this study. Another method that may further validate the temperature ~ growth relationship would be laboratory-based studies, which control the temperature of the environment as a fixed variable in order to fully understand the specific thresholds that drive and limit the energetic input into shell growth, as well as the species specific thermal preferendum. In contrast to this study, which conducted a post-hoc analysis using available temperature data, controlling for temperature as part of the experimental design would add greater certainty to the relationship. The importance of understanding the environmental context of sampling locations (fishing grounds) has been highlighted previously (Hollyman, et al., 2018). Indeed, any specific thermal preferendum that exists to encourage energetic investment in shell growth for this species would necessitate an experimental design that controlled for specific thermal parameters as well as other confounding variables (e.g. food availability (Nasution & Roberts, 2004), predatory pressure and aquatic chemistry). Given the opportunistic post-hoc nature of this study, and that the analysis was performed on aggregated one-dimensional temperature data (aDD), it is encouraging that a clear and significant relationship is observed (Figure 4.7).

This study presents the first comparison of growth rates of sampled whelk populations throughout the latitudinal extent of a fisheries management region (ICES VIIa), using data modelled from statolith analysis. A linear trend was observed between SBT, expressed as aDD, and $L_\infty$ whereby warmer waters limited maximum shell size. When extrapolated throughout the entire geographical extent of ICES VIIa, the data broadly mirrors the reported parameters in other studies. Further verification of the temperature ~ growth relationship for this species is required, combining both broad geographical collaborations and controlled laboratory methodologies. Validating this relationship may lead to broad-scale extrapolations throughout the species distribution, which would provide an increadibly valuable and timely resource to fisheries managers who would otherwise depend on dedicated sampling studies to understand the life-history parameters of whelk stocks, which are currently recognised as being data-poor and potentially over exploited.

## 4.5 Acknowledgments

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# Chapter 5. Enhancing fishery-dependent information in data-poor fisheries; integrating gear-in-gear-out sensor technology and electronic reporting in the Irish Sea edible crab (*Cancer pagurus*, L.) static-gear fishery.

This work is being prepared for publication in a peer-reviewed journal.

## 5.1 Introduction

Demonstrating progress towards ecological sustainability and realising maximum economic benefits in wild-capture fisheries is now a priority for fisheries administrations (FAs) and fishing industry organisations throughout the world. In order to successfully achieve these goals, FAs rely on a suite of data to inform and support decision-making, ideally using stock-assessments which, through reference to biological reference points (BRPs), inform harvest control rules (HCRs) (Jensen & Marshall, 1982; Caddy, 2004; Shertzer, et al., 2008). The prerequisites for most stock assessments include several years of uninterrupted data supply from multiple sources, including; fishery-independent surveys (abundance and recruitment surveys, size-or-age structured demographic data), biological/ecological parameterisation (natural mortality (*M*), $L_{inf}$, $L_{mat}$, stock-recruitment models) and fishery-dependent inputs (landings, discards and effort data). However, globally >80% of fish stocks lack the adequate data coverage for stock assessment modelling (Costello, et al., 2012) and are therefore considered 'data-poor' .

Whilst formal stock assessments are the ultimate goal in developing sustainable fisheries, the development of 'indicators' that track trends in fisheries-dependent data are becoming more accepted in the provision of fisheries management advice (Trenkel, et al., 2007; Ye, et al., 2011; Tidd, 2013; Trenkel et al., 2013, Miethe et al., 2016). Miethe et al. (2016) highlight a number of possible fisheries-dependent indices that may be considered as proxies for traditional BRP's, including the use of catch-per-unit-effort (CPUE) and landings-per-unit-effort LPUE as indices of abundance, where the latter excludes any bycatch of non-target species or discards. However, there are a number of methodological concerns associated with the use of commercial CPUE as an indicator of relative abundance (Murray & Seed, 2010; Murray, et al., 2013; Skerrit et al., 2020) as well as underlying issues of data resolution, precision and accuracy (Miethe, et al., 2016). For example, even in situations where vessels do report basic catch and effort data that could be expressed as CPUE, the data are characterised by 'noise' that can result from complex biophysical interactions between fisheries, fish stocks and the marine environment, which can be driven by factors that vary on both spatial and temporal scales (McQuinn, et al., 1988; Caley, et al., 1996, Skerrit, et al., 2020; Sheehy & Bannister, 2002; Mullowney, 2016). The factors that create variability in commercial CPUE are often overlooked by the coarse resolution of fisheries-dependent data and 'static-environment' assumptions built into traditional assessment and management tools (Szuwalski & Hollowed, 2016). Here we address such concerns through testing of an enhanced electronic data reporting system (EERSs) in a static gear (pot) fishery for the edible crab *Cancer pagurus*.

Better integration of fisheries-dependent CPUE into assessments of data-poor fisheries require accurate and consistent geolocation (i.e. Latitude and Longitude) of fishing activity (Skerrit, et al., 2020). Whilst VMS data has been beneficial for producing evidence for some ecological indicators in the EU (EC, 2008), its usefulness is limited by low-frequency of reports, that are unable to take account of fine-scale spatial data clusters (Gerritsen, et al., 2012; Murray, et al., 2013) as well as excluding EU vessels

<12 m that make up 70% of registered vessels in the EU (STECF, 2016; Needle, et al., 2015; Russo, et al., 2016). While the technology is being increasingly used in smaller inshore fleets, whuch are typically mlore relevant for data poor fisheries, its value for assessment purposes may be limited considering that individual data points cannot be verified against activity nor exact catch data. High-precision spatial data requirements remain absent from the vast majority of data collection frameworks (for an exception see ICES, 2016), particularly in fisheries that are assumed to have little-to-no effect on the benthos (Eno, et al., 2001; Coleman, et al., 2013) such as baited-pot fisheries that target crustacean (e.g. *Homarus gammarus, Cancer pagurus, Palaemon spp, Nephrops norvegicus*) and mollusc (e.g. *Buccinum undatum*) stocks.

Pot fisheries in the UK have historically had a lower profile than well-documented fin-fisheries although many have undergone significant expansions in effort and landings. The main lobster and crab fisheries in the UK are considered to be either fully-exploited or over-exploited (Bannister, 2006; Bannister, 2009) although the management response to date has been limited (Skerrit, et al., 2020). Typically, pot fisheries report landings and effort data to ICES statistical rectangles, which are approximately 30 NM$^2$, and therefore cannot capture the variation between distinct local fishing grounds. The mandatory reporting systems for the majority of vessels are usually manual (relying on paper submissions), very onerous (e.g. MMO, 2018), prone to (unintentional) inaccurate reports and omit additional data important for modelling CPUE in these fisheries. Even where efforts have been made to improve reporting (e.g MMO, 2019), standard logbook records fail to capture fishing activity variables (e.g. pot-type, bait-species, soak-time, pot-density), observations of the physical environment (e.g. sea-bottom-temperature; SBT, tidal-coefficient, depth), ecological parameters (e.g. by-catch, discarding, population structure) nor precise fishing activity locations among potentially highly heterogeneous fishing grounds. Additional and potentially significant variables that drive CPUE (Bennett, 1974; Smith & Tremblay, 2003; Öndes, et al., 2017; Murray & Seed, 2010; Mesquita, et al., 2015) are only occasionally documented by on-board observer programmes and scientific studies (e.g. Coleman & Rodrigues, 2017; Öndes, et al., 2017; EMFF, 2020), which rely on recurrent funding to maintain enhanced datasets or otherwise risk being ‘snapshots’ of stock dynamics and of limited use in fishery assessments that require long-term time series of data. However, enhanced fisheries-dependent data may improve assessments that rely heavily on commercially derived CPUE as an indicator of abundance, particularly where target species have life-histories that are highly variable on a local scale (e.g. *Buccinum undatum*, see Haig, et al., 2015, Woods & Jonasson, 2017). Furthermore, using EERSs in fisheries assessments has been shown to improve accuracy of fisheries-dependent reporting and encourage a greater sense of ownership and custodial attitude towards datasets among fishers (Dörner, et al., 2015; Emery, et al., 2019). Nonetheless, it is important to consider the additional demands that data-collection can place on fishers during commercial activities and ensure that EERSs are well-designed.

In this research, our objectives were to (1) develop an integrated EERS for pot fisheries so that skippers could easily submit effort and catch reports to a central database on a daily basis; (2) increase the spatial-temporal resolution of catch and effort data compared to standard logbook reporting to an appropriate scale; (3) enhance the EERS with ancillary sensors that passively record potentially important variables; (4) model the data collected to assess drivers of variability in CPUE and (5) provide insight for the future development of ERSs for data-poor fisheries so that CPUE can be more confidently used as an index of abundance.

## 5.2 Materials and Methods

### 5.2.1 Fishery

The Isle of Man is situated in the northern Irish Sea (ICES statistical Area VIIa) with most of the territorial sea (TS) associated with the ICES statistical rectangle 37E5 (Figure 5.1). Static-gear fisheries operate within the TS and target several shellfish species including edible crab, European lobster, *Nephrops* and common whelk. Crab and lobster are targeted within a mixed fishery using a net-enclosed metal-bar based trap (‘pot’), though it is anecdotally understood that fishers adapt fishing practices in order to shift the probability of capture from one species to another (Skerrit, et al., 2020). We focus the analysis of this research exclusively on the investigating the edible crab component of the fishery.

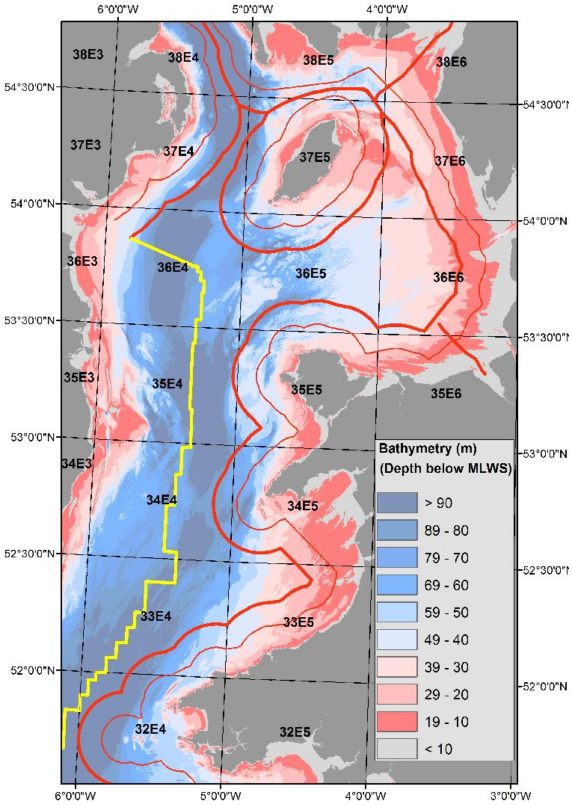

Figure 5.1. The Irish Sea showing British Fishing Administration territorial limits (12 NM and 6 NM) against a bathymetry layer. Yellow line represents the median-line between the British and Irish EEZ. Bold text shows ICES Statistical Rectangles.

Historically, static-gear fisheries were less economically valuable than the mobile-gear sector that target King scallop (*Pecten maximus*) and Queen scallop (*Aquipecten opercularis*) and have had a lower profile in terms of monitoring and management. Recently however, favourable export-market opportunities have led to significant investment in static-gear fisheries meaning they are more economically important than in the past (DEFA, 2018). This is particularly evident in the edible crab fishery, which has increased in real economic value from c.£0.3 million at the point-of-first-sale (2005) to c.£1.2 million in 2018 in the Isle of Man (DEFA, 2018). The edible crab fishery is populated by mainly

<10 m vessels, with several vessels 10-12 m and > 12 m, with each sector complying to different statutory data collection systems in accordance with IOM, UK and EU legislation (Table 5.1). The data provides the Department for Environment, Food and Agriculture (DEFA; FA for the Isle of Man TS) with the ability to view daily landings and effort by ICES Rectangle. Since the Isle of Man TS is composed of several ICES Rectangles, none of which are captured entirely within DEFAs jurisdiction (see Figure 1), resolving landings inside and outside the management jurisdiction (Isle of Man TS) is problematic. The fishery is not currently subject to HCRs and there are no agreed BRPs, though there are pot allocation limits in addition to technical measures such as a minimum-landing-size (MLS) of 130 mm carapace width (CW) for crab and mandatory escape gaps fitted to pots fished within the 3 NM zone.

Table 5.1. The data reporting requirements imposed on the Isle of Man static-gear sector by length category.

| Sector | Spatial Data (iVMS/VMS) | Electronic Reporting | Effort Data | Legislation |
|---|---|---|---|---|
| < 10 m | NO (ICES Rectangle) | NO (Monthly paper logbook) | YES | IOM/UK |
| 10 – 12 m | NO (ICES Rectangle) | NO (Daily paper logbook) | NO | UK/EU |
| > 12 m | YES (2 hr poll) | YES (Daily e-logbook) | NO | UK/EU |

### 5.2.2 GIGO and EERS technology

In September 2018, a sentinel fleet of Isle of Man licensed static-gear vessels were invited to participate in a trial to improve data collection and reporting in Isle of Man static-gear fisheries. The technology used in the trial was developed by Zebra-Tech© (www.zebra-tech.co.nz). The technology offered an integrated EERS that is centred on a 'Decklogger' (DL) device (Figure 5.2). The DL is designed to be able to collect and store data through manual input and by automatically synchronising with wireless ancillary devices such as "gear-in gear-out" (GIGO) sensors called wet-tags (WTs) (Figure 5.2), which are small submersible data storage tags that are attached to pots. Data offload is from the DL via USB or mobile data connectivity.

Figure 5.2. Left: The zebra-tech© decklogger and right: zebra-tech© wet-tag (Zebra-tech, 2019).

The custom firmware installed on the DL devices was designed and tested prior to the trial to ensure that users (fishers) could easily navigate the data-entry process. The firmware determines what each screen displays, what happens when each button is pressed and what data is logged. The firmware was carefully designed to ensure data entry is simplified and operation is intuitive. The number of required keystrokes is minimised to ensure accurate data entry within time limited working environments (Zebra-Tech, 2017).

Fishers were asked to attach a single WT into the central pot within each of their fishing strings (i.e. a series of pots attached to a single line weighted with anchors at either side). When submerged, WT devices begin recording pressure, temperature and duration. Upon surfacing (during a haul in a fishing trip), this data is wirelessly transferred to the DL. The DL registers the data as depth (m), minimum, maximum and average temperate (°C) and soak-time (mins). The information is appended with geo-positional data so that it is referenced with time, date, latitude and longitude. The DL presents the data on the screen and prompts the skipper to acknowledge the data with a single 'YES' push-button, as well as highlighting whether a tampering event has occurred (i.e. the pot has already been hauled previously by another vessel). After the fisher has finished hauling a string, stored their catch and re-deployed the fishing gear, they then navigate the DL to manually enter the total number of pots in that string (string specific effort) along with quantities of retained catch (landings). For the purposes of this trial, the firmware was designed to capture the same information as demanded by existing mandatory logbooks (landings and effort only) in addition to the automatic sensor-captured (WT) data. We acknowledge the pertinence of additional variables such as pot-type (volume) and discard data. Our approach was to develop a system requiring only the same data variables as statutory logbooks in the first instance in agreement with skippers and crew within the fishery. DL's can be updated with future versions of the firmware, which can include additional data entry requirements.

At the beginning of each fishing trip, the fisher is prompted to enter information on sea-state and wind-direction, after which the DL searches for a valid GPS signal. At the end of the fishing trip, which typically lasts 7-9 hrs in the Isle of Man edible crab fishery, the fisher is prompted to review a 'catch summary' page on the DL. If the data are accurate, the skipper offloads the data from the device via cellular mobile signal. The data is sent as a '.csv' file to a specified email address. Each DL and WT record has a unique identifier, which is appended to each data so that vessel and string can be identified day-by-day.

### 5.2.3 EERS data analysis

All data analyses were run in 'R' (R Core Team, 2017). In order investigate whether there were distinct patterns in spatial data, cluster analysis techniques were adopted. The latitude and longitude, hereafter referred to as 'geolocation', of each WT record was mapped and analysed using Euclidean geometry. The total 'within cluster' sum of squares value was calculated from the Euclidean distance between haul-events and a range of clustering scenarios, ranging from 1 to 10 cluster-centroids (K). An 'elbow plot' was visually inspected to determine the value of K at which the total within sum of squares value asymptotes, i.e. additional cluster-centroids do not identify statistically different groups of haul-events. The 'elbow plot' method was supported by 'silhouette' analysis, which determines how well each haul-event location fits into its K-means determined cluster group. For each clustering scenario, the Silhouette Width, S(i), was calculated for each haul-event. Values range from -1 to 1, where value of 1 indicates that the observation is well matched to the assigned cluster, 0 indicates it is on the border between two clusters and -1 indicates that a better cluster assignment is possible. S(i) is calculated using the Cluster Distance (the average Euclidean distance of each observation to every other observation within the same cluster; C) and the closest Neighbour Distance (the average Euclidean distance from each point to the closest neighbouring cluster; N) and is described using the formula:

$$S(i) = \begin{cases} 1 - \dfrac{C(i)}{N(i)} & , if\ C(i) < N(i) \\ 0 & , if C(i) = N(i) \\ \dfrac{N(i)}{C(i)} - 1 & , if\ C(i) > N(i) \end{cases}$$

Visual interpretation of the average S(i) value over a range of K values was used in conjunction with the ‘elbow plot’ to estimate the number of spatial clusters in the data. Each haul-event was then assigned to a colloquially named fishing ‘area’.

Prior to statistical comparisons of observations between fishing areas, data were tested for normality using the Shapiro-Wilk Test for normality and inspected visually using Kernel Density and Normal Q-diagnostic plots. Heteroscedasticity was tested using Levene’s test and outliers identified using the Cook’s distance plot. All data that failed to conform to normality assumptions were transformed and re-tested for normality. If data still failed to conform to normality assumptions, non-parametric testing alternatives were adopted for analysis. Kruskal-Wallis rank sum tests were used to test for differences in SBT, soak-time, depth and LPUE by fishing area with post-hoc pairwise comparisons conducted using Wilcoxon rank sum tests (R-package: stats).

Crab CPUE data were modelled assuming a Gaussian distribution of errors using geolocation within a generalised additive model (GAM) in the ‘mgcv’ package in R, whereby a 2-Dimensional smoothed interaction term (Latitude and Longitude) was used to characterise geolocation data. The smoothed interaction term within the GAM (‘s’) therefore takes into consideration the complex spatial structure of the data, where Crab CPUE ~ s(Longitude, Latitude). Smoothing parameterisation within the GAM was reached via the restricted maximum likelihood method (REML). Crab CPUE was also modelled using a GAM approach incorporating all predictors, including the 2-dimensional smoothed term for geolocation, before reducing model complexity using a backward selection approach by comparing AIC values.

## 5.3 Results

The EERS was used by sentinel fleet over a 12 month period from September 2018 to September 2019 generated a total of 340 daily records of haul-events; 190 and 150 days were reported by the under-10 m and 10-12 m respectively.

In total, 812 individual string-lifts were reported, with a total of 29,826 pot-hauls. The total harvest from these pots was approximately 50 tonnes of edible crab and 5 tonnes of European lobster. By comparison, the total number of pot-hauls estimated in the entire fishery for the same period (based on logbook data) is 450,000 and the total harvest was 516 tonnes of edible crab and 47 tonnes of lobster. The sentinel fleet therefore reported an approximate 7% of effort and 10% of landings during the period for the whole fishery.

### 5.3.1 Spatial Data

The geolocation was successfully appended to each haul-event recorded by the DL. During the 12 month trial, a total of 3,260 GPS co-ordinates were recorded. Of these, 59% are precise fishing locations where skippers entered the catch data of the pots they had most recently hauled and re-deployed. A further 20% of the spatial data were records of GIGO sensors (WTs) with measurements of temperature, depth and soak-time, which were 'joined' to the catch data (effort and landed weight) for analysis. The remaining 21% of records were relating to system status (important for managing hardware) and not useful for fisheries analysis.

Analysis of the 665 WT data using the elbow plot (Figure 3a) indicates that there are a three discrete spatial clusters within 37E5 identified by the activity of the sentinel fleet. Similarly, visual interpretation of the average Silhouette Width shows S(i) = 0.62 and 0.57 for K = 2 and K = 3 respectively, indicating that spatial data are well matched to several cluster groups. Where data are assigned to four or more cluster groups, analysis suggests that spatial data become less well matched to assigned clusters centroids (Figure 5.3b). Despite this, silhouette width values remain above 0 for K values up to 10, suggesting that spatial data are well matched to fine-scale clustering even when using many cluster groups (Figure 5.3c). However, since the asymptote is evident in figure 5.3a it is only clear that there are three discrete fishing grounds from the data resolution at present, which can be more colloquially categorised as 'East', 'Inshore Southwest' and 'Offshore Southwest'. Though spatial data points cannot be presented for commercial reasons, Figure 3a shows the relative position, density and spread of the three fishing grounds identified by cluster analysis. The number of WT records logged in each fishing ground through the 12-month trial is shown in Figure 5.4.

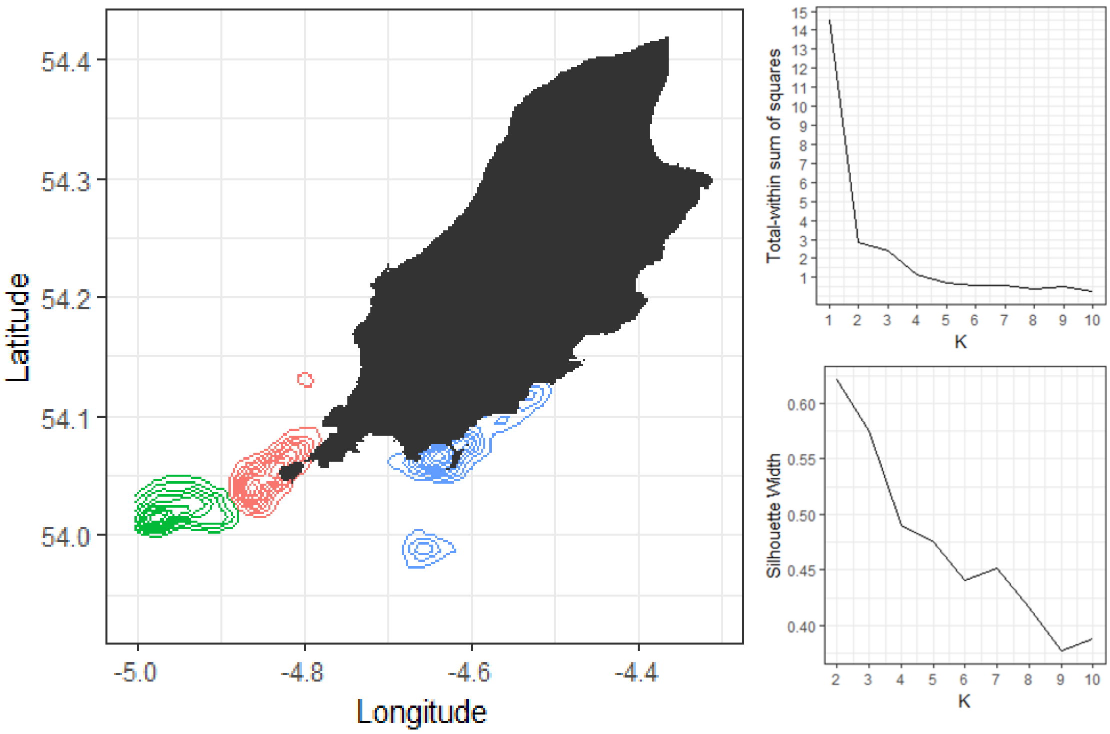

Figure 5.3. a) the southwest offshore (green), southwest inshore (red) and east (blue) fishing areas with landings of *C. pagurus* recorded by the sentinel fleet; b) the total within sum of squares value for different K values, and; c) the Silhouette-width of cluster assignment at different K values.

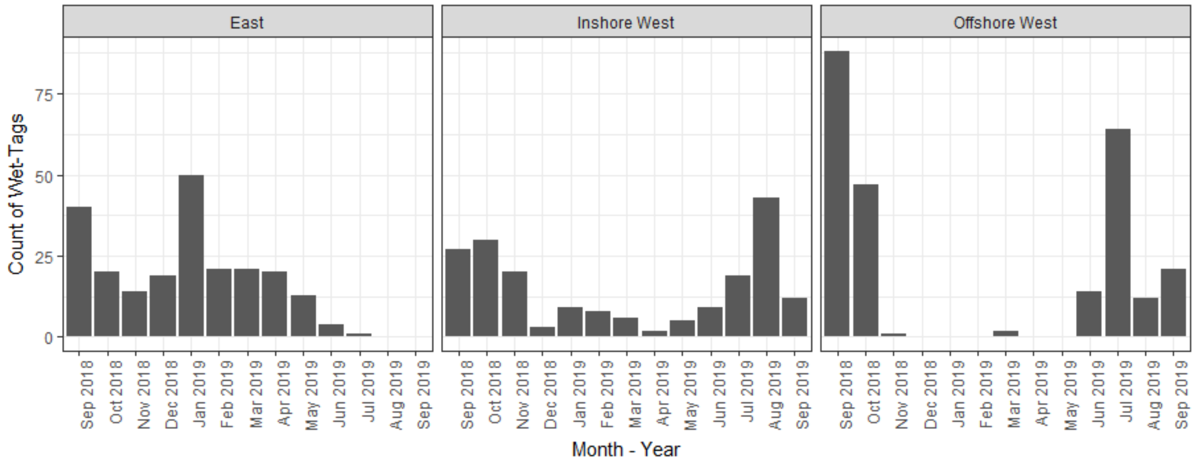

Figure 5.4. The number of wet-tag (pot-hauls) recorded by the sentinel fleet in each fishing area throughout the trial.

### 5.3.2 Wet-tag Data

Temperature data from WTs show that the summer maximum occurred in later summer (August / September) whilst the coolest water temperature records were observed during late winter / early spring (February – April) (Figure 5.5). No significant differences were observed in SBT between areas through the majority of the 12 month period, including the months of January through to June as well as November. However, pairwise post-hoc Wilcoxon rank sum testing revealed a number of significant difference in average SBT observed between areas within the same month, shown in table 5.2.

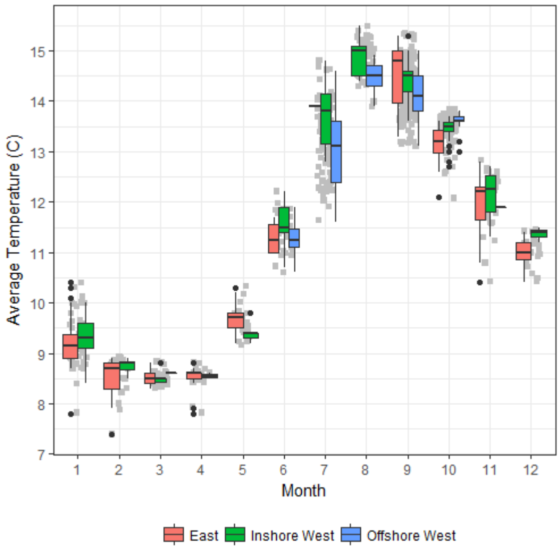

Figure 5.5. The sea-bottom-temperature (°C) by month in each fishing ground.

Table 5.2. Sea-bottom-temperature differences between two areas by month, recorded by Wet-tags during the EERS trial.

| **Month** | **Warmer Area** | **(°C)** | **Cooler Area** | **(°C)** | **Difference** | **p-value** |
|---|---|---|---|---|---|---|
| July | Inshore W | 13.9 | Offshore W | 13.1 | 0.7 ± 0.1 | 0.002 |
| August | Inshore W | 14.9 | Offshore W | 14.5 | 0.4 ± 0.2 | <0.001 |
| September | East | 14.5 | Offshore W | 14.1 | 0.4 ± 0.1 | <0.001 |
| September | Inshore W | 14.4 | Offshore W | 14.1 | 0.3 ± 0.8 | <0.001 |
| October | Offshore W | 13.6 | East | 13.1 | 0.5 ± 0.1 | <0.001 |
| October | Offshore W | 13.6 | Inshore W | 13.4 | 0.2 ± 0.1 | <0.001 |
| October | Inshore W | 13.4 | East | 13.1 | 0.3 ± 0.1 | 0.008 |
| December | Inshore W | 11.4 | East | 11.0 | 0.4 ± 0.2 | 0.023 |

Crab and lobster pots were soaked for 2-3 days on average in the fishery, though there was a significant difference in average soak time between different areas (Kruskal-Wallis rank sum test; $\chi^2 = 15$, $p > 0.001$). Pots were soaked for shorter periods in the Offshore West (median = 2.1 days) ground compared to both Inshore West (median = 2.9 days; Pairwise Wilcoxon rank sum test; $p = 0.012$) and East fishing grounds (3.1 days, Pairwise Wilcoxon rank sum test; $p < 0.001$). There was no significant difference between Inshore West and East fishing grounds (Pairwise Wilcoxon rank sum test; $p = 0.20$) (Figure 5.6a). The three fishing grounds were also characterised by significantly different depth profiles (Kruskal-Wallis rank sum test; $\chi^2 = 455$, $p < 0.001$), with the deepest fishing areas in the western grounds, which were generally deeper in the offshore cluster (Figure 5.6b).

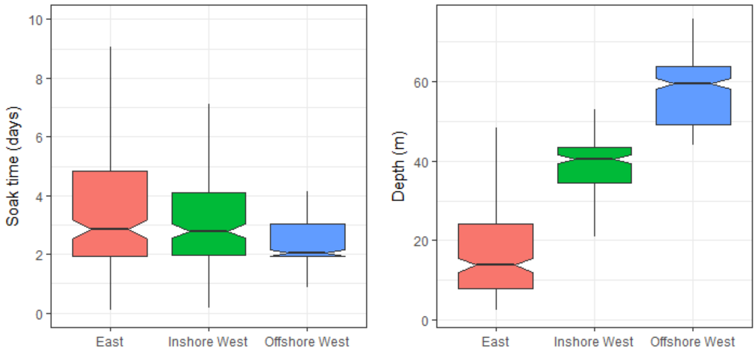

Figure 5.6. a) The soak-time of pot-hauls, by area (left), and b) the depth of fishing grounds (right) recorded by EERS wet-tags.

### 5.3.3 Landings-per-unit-effort (LPUE) model

Across the 12-month time series, crab LPUE data ranged from 0.02 to 8.25 kg pot$^{-1}$, with an annual mean of 2.4 kg pot$^{-1}$ (figure 7a). The average weight of edible crab at MLS (130 mm CW) is approximately 0.5 kg (Emmerson, *unpublished data*), suggesting that at least five crabs were caught every pot-haul on average and the fishing capacity of an individual creel may saturate at 16 crabs. The temporal trend in LPUE data shows a clear seasonal pattern with a peak occurring in September and October and depressed catch rates from December through to April. Monthly average LPUE peaked during the autumn fishery (3.5 kg pot$^{-1}$) corresponding to a 45% increase from the annual average catch-rate (Figure 5.7a). LPUE varied significantly between all fishing grounds (Kruskal-Wallis rank sum test, $\chi^2 = 135$, $p < 0.001$), with the greatest catches recorded in the Offshore West area and poorest recorded catches in the East (Figure 5.7b). Catch rates showed a significant difference of 0.5 kg pot-1 between Inshore and Offshore Southwest areas (Pairwise Wilcoxon rank sum test, $p = 0.011$).

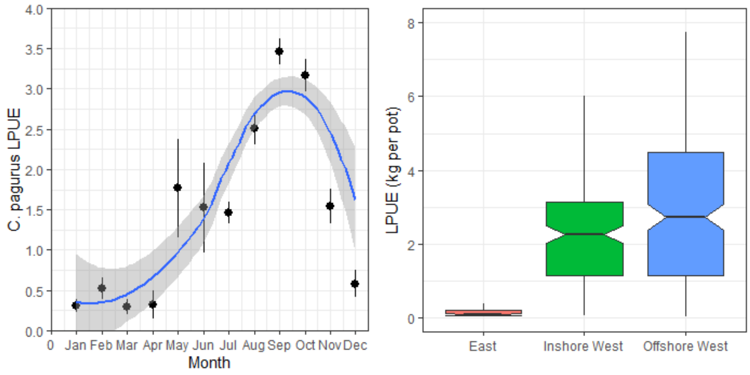

Figure 5.7. a) The landings-per-unit-effort (LPUE) of the crab, *Cancer pagurus*, fishery through the 12-month sampling programme undertaken with EERS (left). Data show mean ± standard error; b) the LPUE recorded by EERS by fishing area (right).

Geolocation, characterised by a smoothed interaction term within a GAM; s(Longitude, Latitude), was found to have a significant effect on Crab LPUE (GAM; $p < 0.001$). GAM outputs showed that the relationship between geolocation and Crab LPUE is both significant and highly complex (edf = 15.92, $p < 0.001$). The model was able to explain 47.7% of the deviance in Crab CPUE ($R^2 = 0.48$) using solely geolocation as the explanatory variable. The effect of geolocation on Crab LPUE, with a 10% extrapolation, is shown in Figure 5.8. By comparison, a GAM using solely cluster-group assignment (i.e.

fishing ground) without precise latitude and longitude data explained 21.2% of deviance ($R^2 = 0.21$) in LPUE.

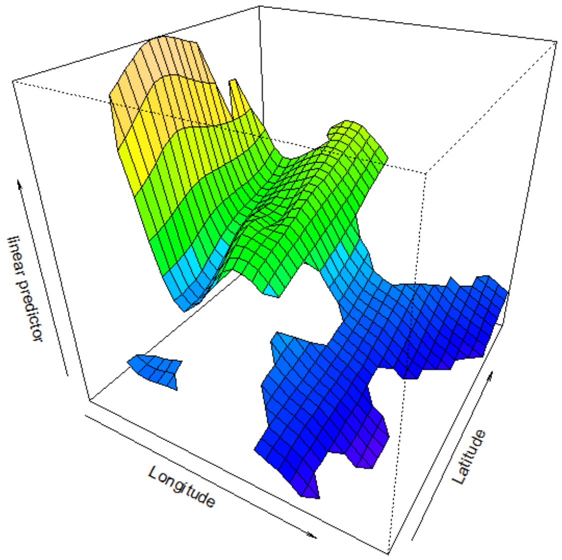

Figure 5.8. The effect of latitude and longitude (geolocation) on the linear predictor of *C. pagurus* LPUE. Output from Generalised additive model of LPUE and a smoothed interaction term of latitude and longitude.

Opportunistic sampling of environmental data via the WTs attached to commercial strings allowed GAMs to consider the fishery response (LPUE) against additional observations alongside geolocation, including SBT, depth, tidal coefficient, soak time, month, Vessel ID and bycatch of lobster (lobster LPUE). The full model revealed Vessel ID, geolocation, SBT and lobster bycatch as significant variables, whilst depth, tidal coefficient and soak time showed a linear non-significant effect on Crab LPUE (edf = 1.00, $p > 0.05$), whilst month was near-linear and non-significant (edf = 1.44, $p = 0.37$). The full model explained 68.2% ($R^2 = 0.64$) of deviance and had an AIC value of 469.5. Backward selection of model components based on a stepwise improvement of AIC value produced the final model described as; Crab LPUE ~ s(Geolocation) + s(SBT) + s(Lobster Bycatch) + Vessel, which explained 68% of deviance in Crab LPUE (adjusted $R^2$ value = 0.64) and an AIC value of 467.1. The smoothed terms (Geolocation, Average temperature and Lobster LPUE) were significant (F(14.9) = 5.77, p = < 0.001; F(2.2) = 4.22, p = 0.009; F(2.3) = 3.69, p = 0.023 respectively) as well as the categorical variable ‘Vessel’ (Figure 5.9, Table 5.3).

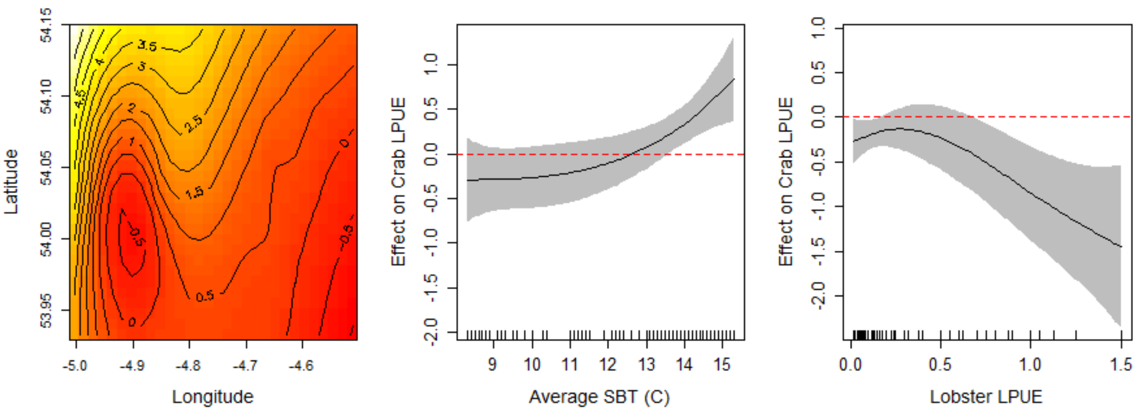

Figure 5.9. Generalised Additive Model (GAM) smoothed term outputs; Crab Model: $\text{Crab}_{\text{LPUE}} = s_1(\text{Geolocation}) + s_2(\text{SBT}) + s_3(\text{Lobster LPUE})$ + Vessel.

Table 5.3. Generalised Additive Model (GAM) factor variable outputs; Crab Model: CrabLPUE = s1(Geolocation) + s2(SBT) + s3(Lobster LPUE) + Vessel.

| Area | Est. | SE | t-value | p-value |
|---|---|---|---|---|
| Vessel A | 0.52 | 0.18 | 2.86 | 0.004 |
| Vessel B | 1.78 | 0.45 | 4.00 | <0.001 |

## 5.4 Discussion

This trial demonstrates the utility of an EERS that allows skippers to easily submit effort and catch data electronically to a central database on a daily basis, which was developed in co-operation with the fishing industry. By successfully integrating GIGO and mobile technologies, the catch and effort data submitted through the Isle of Man sentinel pot-fishery EERS are available at a much greater spatial-temporal resolution than the current mandatory reporting requirements and proposed logbook solutions for many data-poor fisheries (e.g. MMO, 2019). EERS data can be resolved to the time and geolocation of individual haul-events, which is a step-change in data resolution compared to aggregated daily reports resolved to ICES Statistical Rectangles (30 NM$^2$ areas), at little extra burden on the fishing vessels standard operating procedures. The high geospatial resolution of the catch and effort data together with passive monitoring of additional variables with sensor technology has enabled statistical modelling of LPUE using a generalized modelling approach, within which several variables have been identified as having a significant effect on LPUE in the *C. pagurus* fishery based upon this 12-month study of a sentinel fleet, including; i) location, ii) SBT, iii) rate of lobster bycatch per string and iv) vessel ID. Other observations (e.g. month, depth, tidal coefficient and soak-time) showed non-significant relationships with LPUE according to the model. The GAM was able to predict 64% of variance in LPUE ($R^2$ value = 0.64) suggesting that further data collection and parameterisation is required, which may be achieved through further firmware development, but also that the ancillary data-storage tags are a valuable tool in modelling LPUE for use as a stock abundance indicator in *C. pagurus* baited-pot fisheries in particular. More generally, the precision and modelling capacity of the fisheries-dependent data collected through this trial demonstrates the utility that GIGO and mobile technologies can offer to management of data-poor fisheries that lack fisheries-independent stock assessment approaches.

The inclusion of SBT within the LPUE model has provided valuable insight into the thermoregulatory dynamics of the fishery, where a clear positive effect on LPUE detected at approximately 13 °C, which increased linearly to the maximum observed temperature of 15°C. A thermal preferendum of around 13 °C for this species has been documented elsewhere (Bakke, et al., 2013), whilst non-critical lower and upper thermal limits (i.e. pejus temperatures) are thought to be around 5 °C and 16 °C respectively (Karlsson & Christiansen, 1996; Pearson, et al., 1999; Metzger, et al., 2007; Hyde, et al., 2015). Understanding the thermoregulatory dynamics of this species are important for stock assessments to consider, particularly those that are based upon fishery-dependent indices, since the effect of temperature on ecological processes such as moulting, mating and migration (Bennett, 1995; Tallack, 2007; Bakke, et al., 2018) are linked to fishery performance (LPUE) and fishing activity (seasonally dictated effort). We have shown that SBT can exhibit subtle but significant differences on local spatial scales, which in addition to other factors, drives variation in LPUE data. Fisheries managers that rely on fisheries-dependent LPUE data in order to set HCRs for *C. pagurus* stocks must seek to incorporate SBT monitoring and parameterisation, since SBT can be measured with ease as part of commercial activities, thereby making the corrections of effects on relative abundance indices within assessments practical. Such an approach has been recommended for stock assessments of baited fishing gear for some time (see Stoner, 2004) but has yet to be adopted in any formal assessments of *C. pagurus* stocks specifically to our knowledge. Similarly, utilisation of LPUE as part of an inter-annual abundance survey for crustacean stocks using baited traps (e.g. for the assessment of impacts of offshore developments; Roach, et al., 2018) should also seek to incorporate in-situ monitoring of SBT to accurately perform post-hoc adjustments of LPUE indices. For data-poor fisheries more generally, the inclusion of SBT monitoring as part of EERSs may assist scientists, FAs and industry to develop an understanding of specific thermo-regulatory dynamics that effect variable fisheries performance and also to develop management plans that consider environmental triggers and thresholds effecting stock abundance, which will be particularly important within the context of ocean warming (Cheng, et al., 2019).

The EERS automatically recorded geopositional data when the GIGO technology surfaced and has provided a high-resolution spatial-temporal distribution of fishing activity over the 12 month trial. Cluster analysis of haul-events has identified three distinct cluster groups, although cluster assignment analysis suggests that the geopositional data could be well matched to a higher number of cluster centroids, i.e. there are more fine-scale clusters within the identified three fishing grounds described as ‘East’, ‘Inshore southwest’ and ‘Offshore southwest’. In terms of fisheries management, the refinement of spatial data from fishing activity into smaller geographical components (management areas) has to be balanced against the quantity (and quality) of useful information in each area to inform analysis, recommendations and decision making processes. As opposed to data being aggregated to ICES statistical rectangle under existing logbook reporting systems, fishing activity can now be accurately described by fishing ground based on exact haul locations. The characteristics of the three grounds (including depth-profile, fishing intensity (soak-time) and temperature) differed significantly.

Understanding the heterogeneity of fishing locations is an important factor in fisheries-dependent assessments since temporal trends in catch data need to be isolated from unobserved variations in spatial geographies. For example, the Isle of Man FA (DEFA) may record a significant drop in *C. pagurus* LPUE within ICES Rectangle 37E5 if more fishing effort is diverted from one area to another, since there is a negative effect on Crab LPUE as fishing activity moves from the west coast to the east coast, which is in agreement with previous studies of this fishery (Öndes, et al., 2017) as well as anecdotal reports from the industry and is likely a function of habitat preferences associated with specific life-history stages (Bennett, 1995), such as migration (Hunter, et al., 2013) and reproduction (Edwards, 1996). Such a situation could easily arise in response to economic conditions (e.g. a drop in £ $kg^{-1}$ for *C. pagurus*) as well as exclusion from favourable fishing grounds due to competition with mobile gear or other marine users (e.g. offshore developments). In the absence of appropriately resolved spatial data, a BRP based on LPUE threshold for the whole of 37E5 may 'trigger' HCRs (e.g. total-allowable-catches; TACs) that are not necessary or appropriate for protecting specific stocks or populations of *C. pagurus* since the LPUE data that triggered the HCR reflects aspects of behavioural change in the fishery rather than that of stock decline. This hypothetical example highlights why best-practice would require FAs to use multiple indicators when interpreting fisheries-dependent indices and setting HCRs (Probst, et al., 2013; Miethe, et al., 2016) and why highly-resolved spatial data should be incorporated into indices to inform area-based assessment and management (Babcock, et al., 2005). Whilst identifying heterogeneous fishing grounds within greater management areas enables area-based fisheries management, 'area' alone was able to explain only 21% of the variation in LPUE in this fishery. If spatial data can be resolved to exact fishing locations (latitude and longitude) using GIGO technology, the modelling power increases so that 47% of the variance in *C. pagurus* LPUE data can be explained, highlighting the utility of GIGO technology in data-poor fisheries with highly variable spatial interactions.

Previous studies investigating spatial data in data-poor pot fisheries have examined the utility of GPS and iVMS systems (Mendo, et al., 2019; Mendo, et al., 2019a) and found that an optimal polling interval of 1 min is required in order to accurately estimate effort metrics such as the number of hauls, total area fished per trip and spatial extent of fishing activities in static-gear fisheries. This is 120-times greater than current EU VMS requirements for >12 m vessels (EC, 2011) and greater than trials in other data-poor fisheries (e.g. Shelmerdine & Leslie, 2015), some of which required an especially high-frequency poll-rate to monitor potentially damaging fishing activity within sensitive European Marine Sites (ICES, 2016). Mendo et al. (2019) found that iVMS/GPS with a low polling frequency made it increasingly challenging to detect discrete hauling events in pot fisheries, as well as producing increasingly erroneous estimates of the spatial distribution of fishing activity since many data are recorded during transitory activity. Further, Mendo et al. (2019) identify that iVMS polling intervals ≥ 2 mins significantly underestimates the effective area fished per haul-event compared to high-resolution on-board-observations as the length of the string calculated from geopositional data becomes increasingly erroneous.

Clearly, the use of VMS-type data for approximations of effort introduces error unless poll-rates are set at very high frequencies and poll-rate requirements are likely to vary between fishing vessel métiers

(Mendo, et al., 2019; Mendo, et al., 2019a). Alternatively, an EERS that integrates GIGO technology can overcome many of the approximation issues associated with VMS data. For example, in the case of a pot-fishery as used in this case-study, each GIGO record represents the exact location of a haul-event associated with a declared number of pots, which could more simply and accurately be used to calculate the effective area fished with basic assumptions of fishing gear configuration (e.g. distance between consecutive pots), information that can be very easily acquired from EERS users. In addition, Mendo et al. (2019) suggest that a high-poll rate VMS system could potentially facilitate calculations of soak-time through machine-learning algorithms trained to identify spatially overlapping hauling events as well as estimating the number of pots in a string, however the accuracy, precision and computational requirements of this level of spatial-temporal analysis was not tested in the study. By comparison, the GIGO technology incorporated into the EERS trialled in the Isle of Man automatically appends soak-time to each haul alongside other observations, including depth and SBT, as well as haul-specific catch rates, further reducing analytical complexity and scope for error. Although the modelling based on the data collected during the 12-month reported in this study did not identify soak-time as having a significant effect in estimating *C. pagurus* LPUE, it may be significant in other important static-gear fisheries that target other crab species (e.g. *Necora puber, Carcinus maenas*), molluscs (*Buccinum undatum, Sepia officinalis*), prawns (*Palaemon spp., Nephrops norvegicus*) and lobster (*Homarus gammarus, Palinurus elephas*). Beyond static-gear fisheries, the integrated EERS-GIGO technology can also be configured for use within data-poor mobile gear fisheries, where soak-time would correspond to tow-duration and GIGO technology deployment and recovery could initiate high-frequency records of geopositional data on the DL (i.e. exact tracks of vessel position during tows), whilst similarly recording depth and SBT during the tows as well as tow-specific catches of multiple species after hauling and sorting catch (*pers comms.*, Zebra-tech).

The EERS trial has also demonstrated the utility of highly resolved spatial-temporal fisheries-dependent data within the context of data-poor mixed-species fisheries, since haul-events are associated with catches of multiple species as opposed to aggregated daily catch logbook reports. Modelling haul-specific EERS data collected during this trial has shed light on a long-term issue in the management of *C. pagurus* fisheries using fisheries-dependent data specifically; that *C. pagurus* and *H. gammarus* populations are often targeted within a mixed fishery owing to their overlapping spatial distribution (Smith, et al., 2001) with significant interspecific effects on catchability (Skerrit, et al., 2020).

Historically, fisheries-dependent catch analysis has failed to address the probability that concurrent capture of these species distorts estimates of relative abundance using LPUE data due to inter- and intra-specific interactions (Skerrit, et al., 2020). Skerrit et al. (2020) highlighted the potentiality for error when using fisheries-dependent LPUE as an index of abundance if landings data originate from a mixed fishery without first qualifying the complex relationships that determines catchability. Trials off the Northumberland coast found that pots pre-loaded with *H. gammarus* had significantly lower catchability of *C. pagurus* compared to control pots with no pre-loaded animals (mean average of control pots = 1.15 individuals; treatment pots = 0.09 individuals). Interestingly, the mean size (carapace width) was not significantly different between treatment and control pots, which suggests that the inter-species interaction is one where *H. gammarus* dominate *C. pagurus* in an attempt to monopolise food resources and guard the entrance to baited pots (Skerrit, et al., 2020) irrespective of competition size. Inversely, Skerrit et al. (2020) found no evidence to suggest that pots pre-loaded with *C. pagurus* significantly effects the catchability of *H. gammarus*, reflecting the less defensive feeding behaviour of *C. pagurus*, which have been observed to feed in the presence of conspecifics (Lawton, 1989) and occur at relatively high densities compared to *H. gammarus* (Bell, et al., 2003). Having qualified the inter-dependency issue within mixed crustacean fisheries, Skerrit et al. (2020) highlight that the ability of current and proposed monitoring systems fail to capture the level of detail to allow for fisheries-dependent LPUE analysis that must necessarily correct for inter-species interaction. Skerrit et al. (2020) argue that "location-specific data throughout the fishing year for individual vessels" including "the number of strings and traps that are hauled daily … in each sub-area, their mean soak-time and the resulting catch of lobster, crab and other species" would allow for the level of analysis required to stratify and accurately model fisheries-dependent LPUE by area, season and target species.

The EERS trialled in this study fulfils and exceeds the data-requirements that Skerrit et al. (2020) identify as fundamental pre-requirements for monitoring baited-pot fisheries targeting *H. gammarus* and *C. pagurus*. Using haul-specific catch data, LPUE modelling of the *C. pagurus* fishery identified that incidental capture of *H. gammarus* has a significant effect (Figure 5.9). Interestingly, the model suggests that the negative effect on *C. pagurus* LPUE is minimal until *H. gammarus* LPUE reaches 0.5 kg, which is approximately the average weight of a single lobster at MLS (87 mm carapace length) (*unpublished data,* J. Emmerson). Thereafter, the effect of *H. gammarus* LPUE on *C. pagurus* LPUE shows a negative linear relationship to the point where average *C. pagurus* LPUE is forced towards zero (maximum average effect on *C. pagurus* LPUE ≈ -2 kg) where lobster LPUE reaches 1.5 kg pot$^{-1}$, providing all other model components are kept constant (e.g. SBT). Although the data analysed in this research comes from a spatially and temporally limited ERS trial within a specific mixed fishery, the analysis and results have demonstrated that the interspecific effects within a mixed fisheries are possible to capture, model and estimate if the EERS is designed taking these effects into consideration. This level of analysis would otherwise be difficult using temporally and spatially aggregated reports of fisheries-dependent logbook data.

Increased application of area-appropriate fisheries science recommendations and management tools are needed in order to sustain stock abundance and fisheries harvests in data-poor fisheries (Hilborn, et al., 2020). If fisheries-dependent indicators are to be used as a foundation for the delivery of scientific recommendations and management in these fisheries (Miethe, et al., 2016), catch reporting systems must necessarily be sufficiently capable of capturing the relevant data at an appropriate resolution. Establishing area-specific baselines for fisheries-dependent BRP triggers, for example average LPUE dropping below the last-five-years mean ($LYM_5$) used by Probst, et al. (2013), will require a longer-term data series, highlighting the need for precautionary advice until sufficient data series are built. In the medium-term, and by adopting an EERS such as the one trialled here, FAs would be able to monitor area-based fishery performance indices against agreed baselines, BRPs and triggers through daily data submissions at an appropriate resolution whilst correcting for variability from other factors (e.g. SBT, interspecific effects). The EERS could enable highly responsive management where fisheries-dependent indices trigger HCRs in near-real-time, with the ultimate aim of supporting long-term harvesting strategies and management plans for specific stocks. Whilst EERSs can deliver the foundational data requirements for fisheries-dependent advice and management, the design and implementation of reporting and management systems will inevitably vary depend upon the fishery-specific issues and the goals of the FA. Nonetheless, GIGO technology and well-designed EERSs generally represent an opportunity for step-change in the management of data-poor fisheries with minimal additional data submission demands on skippers, whilst also being decisively cost-effective when considered against the resource requirements of collecting data with a similar spatial-temporal resolution using fisheries-independent methods (e.g. survey vessels and observer programmes). A hypothetical example of an area-appropriate management plan based on fisheries-dependent data for the Isle of Man *C. pagurus* fishery is described in table 5.4.

Table 5.4. A hypothetical fisheries management plan, based upon the EERS data collected in this trial

| | |
|---|---|
| Jurisdiction | Isle of Man territorial Sea |
| Fishing Administration | DEFA |
| Target Species | *C. pagurus* (edible crab) |
| Gear-type | Baited-pots |
| Fleet | All static-gear vessels |
| Stock indicator | Fisheries-dependent LPUE (kg pot$^{-1}$) |
| Area | Offshore southwest |
| Season | September – November |
| BRP Type | LPUE threshold |
| BRP Trigger | Average weekly LPUE falls below LYM$_5$ (e.g. 2 kg pot$^{-1}$) |
| Agreed HCR response | Implement temporary weekly total-allowable-catch (TAC)<br>Example: reduced harvest by 10% relative to previous week until LPUE recovery. |
| Significant co-variable effects on indicator | SBT (°C)<br>Lobster Bycatch (kg pot$^{-1}$) |

From a scientific and management perspective, a ‘minimum basic requirements’ approach to developing typical reporting/logbook systems (e.g. MMO, 2019) may be problematic if the regulatory requirements aggregate catch and effort data to arbitrary spatial scales as well as temporally for entire fishing trips, as opposed to the haul-specific resolution realised in this EERS trial. For example, it is not uncommon for a vessel to fish in several fishing grounds or multiple FA jurisdictions within a single ‘trip’ in the northern Irish Sea (see Figure 1). Best-practice guidance for scientific assessment should accommodate geographical variation in fisheries-dependent indices, however catch and effort are recorded at an aggregated daily scale that cannot be accurately spatially resolved, therefore compromising the ability for FAs to monitor fishery performance in specific areas and enact appropriate local area-based management. The amount of error resulting from the analytical process that attempts to disaggregate logbook data for management purposes presents a risk, whereby scientific stock advice may not be accepted by neither industry nor FAs due to the various levels of complexity, assumptions and approximations. By comparison, the EERS trialled in this study integrates co-operatively developed firmware with GIGO technology that delivers fisheries-dependent data a spatial-temporal precision that simplifies the analytical process, which also encourages data-stewardship and acceptance among industry and FAs for species-specific area-based management, particularly if stock advice is based upon the same fisheries-dependent data. Monitoring key environmental drivers by integrating sensors into the GIGO technology (e.g. SBT for *C. pagurus*) is expected to further encourage stewardship and co-management through the identification and correction of noise (i.e. variability) that may otherwise unnecessarily limit fishing opportunities under more simplistic interpretations of fisheries-dependent data.

There is a requirement to undertake a minimum-component-requirement analysis before wide-scale adoption of EERSs. For example, it may not be statistically essential to attach a WT to every string of baited-pots in areas if it is possible to identify a minimum spatial-temporal resolution of data collection from sensory GIGO technology (e.g. 1 WT per 500 $m^2$), to which catch data from proximal records of haul-events (without WT data) can be associated. Similarly, a cost-benefit analysis will also be necessary where, for example, international regulatory requirements specify exact reporting system designs (e.g. VMS units within the EU) yet local management systems could benefit from sentinel fleets adopting EERSs, incurring additional cost. The EERS used in this trial has similar costs compared to the hardware required for alternative VMS/logbook reporting solutions (e.g. Android OS platform, iVMS hardware), whilst yielding data with considerably more utility for area-based management built upon fisheries-dependent indices. Nonetheless, FAs often find it difficult to justify investment in data-poor fisheries due to lack of public and private resources available for re-investment in sectors that have, until recently, generated less economic contributions from an industry-wide perspective and subject to less regulatory requisites (e.g. stock assessment). However, data-poor fisheries represent considerable economic sectors of the fishing industry around the British Isles and elsewhere in the world and there is a risk that inadequate reporting systems may lead to either mismanagement or permanent absence of appropriate evidence-based management.

To summarise, although iVMS and mobile catch-app developments within data-poor fisheries will undoubtedly improve the resolution of catch-statistics available for monitoring purposes, we argue that it is unlikely analysts will be able to resolve the highly complex multivariate effects and spatial-temporal variations that are embedded within daily-aggregated catch data to the level of accuracy needed for reliable fisheries-dependent indices. Skerrit et al. (2020) suggest that commercial providers should be encouraged to develop on-board electronic data logging and retrieval kit as part of a fully documented strategy, which could be implemented on either a voluntary or statutory basis. In the Isle of Man, we have demonstrated that such ERSs are commercially available and functionally capable for moving fisheries away from a data-poor status towards fully-documented scenarios. Furthermore, the EERS system is capable of, and will continue to undergo, firmware version developments in order to achieve improvements in LPUE modelling power in consultation with both the fishing industry and the scientific literature (e.g. inclusion of haul-specific bait-type, pot-design, existence of escape gaps, estimates of discards, etc.).

Similarly to Skerrit et al. (2020), we recommend that FAs and fisheries scientists work with the fishing industry to co-develop fisheries-specific EERSs for trials, initially using sentinel fleets in key areas and fisheries, in order to utilise technological solutions capable of providing the data required for area-appropriate management in data-poor fisheries. Whilst we acknowledge the spatial-temporal limitation of the EERS trial reported here, results point to the considerable potential for EERSs to harness GIGO sensory technology and mobile communications to; (1) increase the spatial-temporal resolution of catch and effort data to exact locations of haul-events and identify discrete fishing and management areas without complicated analytical methods that introduce error; (2) monitor and model significant drivers of variation in fisheries-dependent LPUE with no substantial changes to standard fishing procedures and (3) provide high precision daily reports with little administrative burden, which could be used by FAs to facilitate fully-documented, responsive and area-based fisheries management using fisheries-dependent data in data-poor fisheries.

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# Chapter 6. Modelling the effects of increased minimum landing size for European lobster in the northern Irish Sea; assumptions of natural mortality impact cost-benefit outcomes.

This chapter was prepared as a supporting document for the Isle of Man Government consultation on the future management of crab and lobster fisheries in Manx waters;

Emmerson, J.A. (2020) Minimum Conservation Reference Size (MCRS) changes in the lobster (*H. gammarus*) fishery; expected short-term costs and long-term benefits. Evidence to support the crab and lobster consultation (2020). Sustainable Fisheries and Aquaculture Report No. IOM2. Bangor University, pp.1-8.

## 6.1 Introduction

At present, the Isle of Man lobster fishery is subject to a minimum conservation reference size (MCRS) applied to the length of the carapace (CL), and is set at 87 mm. By contrast, several other jurisdictions in the Irish Sea have increased the MCRS to 90 mm CL (Scotland, Wales, Northern Ireland, Republic of Ireland), whilst others have set a maximum landing size (e.g. 127 mm CL in the Republic of Ireland, and 155 mm CL in Scottish waters). These changes are associated with a general aim to improve stock status and increasing yield in the fishery. This document considers the likely short-term economic impact on fisheries in the Isle of Man from a similar increase in MCRS, as well as long-term benefits. Size-selective harvesting is a common approach to stock conservation in many finfish and shellfish fisheries. Regulators aim to manage the rate of fishing mortality (F) across the different size-classes of the stock (Beverton & Holt, 1957; Quinn & Deriso, 1999) and is a basic principle of good management for Crustacea (Bannister, 2008).

Lobster increase in size through a process of moulting (‘ecdysis’), where moult increments and intermoult period are temporally and spatially variable (Wahle & Fogarty, 2006). The ‘growth factor’ of an individual is a measurement of proportional growth (% increase in CL) from before and after a moult. For European lobster around commercial size (~80-90 mm CL) a growth factor of ~10% per year has been previously estimated using mark-recapture methodologies (Bennett & Lovewell, 1983; Agnalt, et al., 2007; Wahle, et al., 2013).

In the Isle of Man territorial sea, MCRSs are set for all commercial shellfish species and many have been revised and raised in agreement with scientific advice on biological reference points such as $L_{50}$ and reproductive output (see Hold, et al., 2013; Haig, et al., 2016; Emmerson, et al., 2018) as well as advice based on the economic benefits of harvesting larger animals (e.g. Brand, et al., 1991).

Recent estimates suggest that the size at maturity in some regions of the UK and Ireland is above the current MCRS for that area (see Free et al., 1992; Tuly et al., 2001 and Lizárrage-Cubedo et al., 2003). Regional variability in size at maturity suggests regional application of MCRS is appropriate. In the Isle of Man, maturity analysis based on dissection of the female reproductive organs estimates physiological maturity at 83 mm CL (± 3 mm), which is below the current MCRS. However, onboard observations have also noted that 50% of observed females carry eggs at a size 93 mm CL (‘functional maturity’). More information is available on this study in a separate report (see Garratt et al. 2020).

It is important to evaluate the short-term economic impacts of an increase in MCRS, as well as the assumption that an increase will eventually lead to yield benefits after two or three years (Bannister, 2008). Population modelling can assist with devising strategies to increase the efficiency of natural resource management (Sundelöf, et al., 2015). With respect to MCRS changes in fisheries, previous studies have shown some unanticipated consequences to shifts in havesting strategies; for example where increasing MCRS may lead to a significant increase in exploitation rate (Harley, et al., 2000) or decreases in yield when dicard mortality and natural mortality is high (Waters & Huntsman, 1986).

In this study, the potential economic consequences of increasing lobster MCRS to 90 mm CL are explored for the northern Irish Sea population by combining shoreside sampling with growth rates determined from mark-recapture data.

## 6.2 Materials and Methods

### 6.2.1 Data collection

Shore-sampling of harvested lobster took place between February 2018 and February 2019 with samples from all of the main fishing grounds in the Isle of Man territorial sea (Figure 6.1). The size (CL) and sex were recorded for all individuals and any damage to the animal's appendages noted. A subsample of animals, excluding those with missing limbs, were weighed (0.01 kg) in order to determine a length-weight relationship for the population.

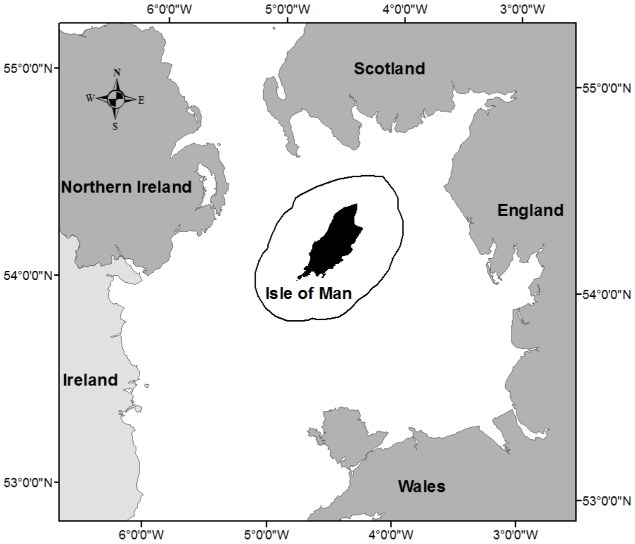

Figure 6.1. The Isle of Man (black) territorial sea (line) and surrounding fisheries administrations of the United Kingdom (dark grey) and the Republic of Ireland (light grey).

Lobster were also tagged opportunistically as part of a separate study between August 2016 and August 2018 in the Isle of Man. Captured lobster were tagged with a Hallprint© streamer-tag (as used by Agnalt, et al., 2007) with the unique ID attributed to each tag recorded along with the location and time of capture. Biological data including size, sex, damage and reproductive status were recorded prior to release. The time and location of the release site was kept as close to the capture location as possible and recorded electronically. Recaptures underwent the same data collection process and were voluntarily released again under the same procedure, with observations of CL increase (growth) noted.

### 6.2.2 Modelling assumptions and methodology

A simulation of the effects of increasing MCRS in the Isle of Man lobster fishery was undertaken in a number of scenarios under a specific set of assumptions that describes a static-environment model. Static-environment assumptions are applied to the recruitment, growth and mortality of the Isle of Man lobster population not affected directly by the MCRS change (i.e. lobsters that are not within the 87-90 mm CL size-class). In other words, the static-environment model assumes that these sections of the population (under 87 mm and above 90 mm) continue to make up the same proportion of the overall harvested population as observed in the shore-sampling data, since recruitment, mortality and growth do not change as a result of the change in MCRS.

With respect to the change in MCRS, the model focuses on the section of the population that measured 87 mm to 90 mm CL. These lobsters undergo a single moult during a season. The moult increment is assumed to be constant for all these individuals and equal to the growth factor determined by mark-recapture observations. The accompanying weight increase as a result of moulting is determined by a size-weight relationship modelled from data collected during shore sampling.

The moult induced mortality (‘natural mortality’; M) of this section of the population is unknown, though it is generally accepted to vary between 10% to 20% (Bannister, 1986). A low mortality value supports the idea that short term losses in the fishery brought about through an increase in MCRS will quickly return benefits as a large proportion of animals not captured the previous year are available the following year (Tully, et al., 2006). However, at a certain level, a high mortality rate will mean that the weight increase of those animals that survive is less than the total weight of those that die of natural mortality. In the model used in this study, we look at the effects of different levels of natural mortality, ranging from 0% to 20%.

Other model assumptions include;

- a closed population (i.e. no net-effect of migration on the catchability of lobster)
- effort and catch efficiency of static-gear lobster pots ‘creels’ in the fishery remains constant each year, and
- economic market conditions for lobsters remains constant between seasons.

The simulation is repeated for two different MCRS implementation scenarios, comparing the effects on recruitment and harvest of i) a single-step introduction of a 90 mm MCRS and ii) a phased-approach, whereby MCRS is raised to 89 mm for a period of one year followed by a second increase to 90 mm in the second year.

## 6.3 Results

### 6.3.1 Population and growth observations

Shore-sampling collected size data from 3,690 lobsters with a sex-ratio of 7:6 (M:F) (Figure 2). A subsample of 16% of individuals were weighed. Regression analysis (Figure 6.2) of log-transformed data determined the length-weight relationship as;

$$W = 0.00034\, CL^{3.16}$$

The estimated weight of an 87 mm and 90 mm CL lobster is 480 g and 510 g respectively, i.e. a 90 mm lobster is 6.2% heavier than a 87 mm lobster.

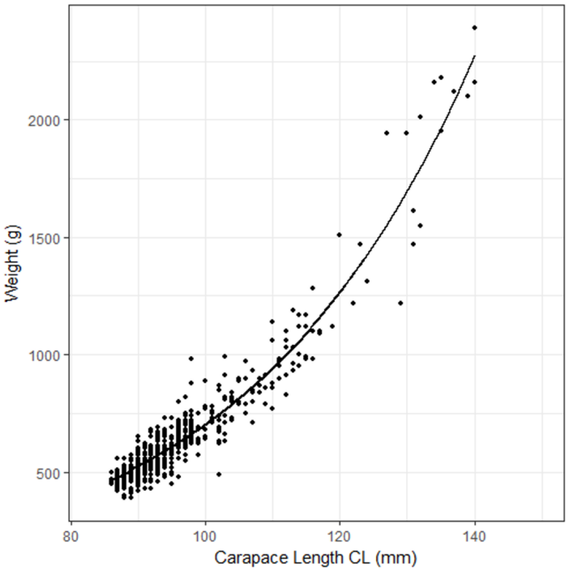

Figure 6.2. The size – weight relationship for lobster (H. gammarus) sampled in the Isle of Man 2018/19.

A total of 321 lobster were tagged during the period. A recapture rate of 31% was achieved (n = 97) with 26 observations of CL increase due to moulting. An average annual growth factor of 13%, was observed. This means that an 87 mm CL lobster will grow approximately 11.3 mm during the moult, and have a postmoult CL of 98.3 mm, and an estimated weight of 696 g (47% increase).

### 6.3.2 Model simulation: single step-change (87 mm to 90 mm)

Under a single step-change in MCRS from to 90 mm, lobsters between 87 mm and 90 mm CL would be excluded from the harvest in Year 1. The model estimates such a change would reduce the total landed weight by 12%, relative to 'Year 1: Status Quo' when the MCRS was 87 mm (Figure 6.3c). As the forgone catch in Year 1, i.e. individuals that were between 87 mm and 90 mm, moult and recruit into the fishery the next year, they will have increased in both size and weight. The model predicts that when natural mortality is 0%, the harvested weight in Year 2 is 6.5% greater than the status quo (Figure 6.3 b,d).The additional harvest weight of Year 2 relative to status quo will however decrease if an estimate of natural mortality rate is included in the model (as a portion of the unfished stock die). This means that harvest improvements reduce from +6.5% (with no natural mortality) to +4.1%, +3.2% and +2.4% when natural mortality rate is modelled at 10%, 15% and 20% respectively (table 6.1).

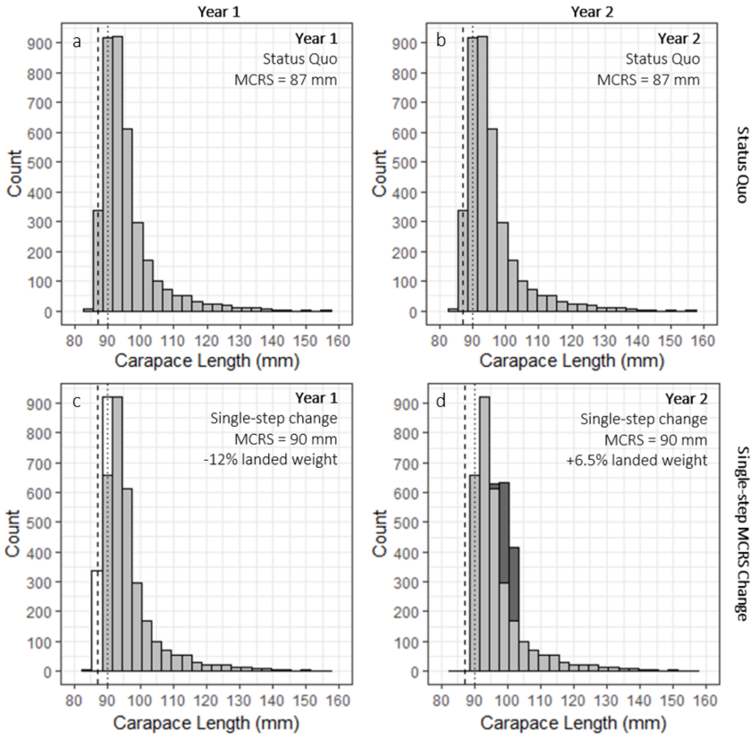

Figure 6.3. The data in these graphs are based on the size distribution of lobster (*H. gammarus*) sampled in the Isle of Man in 2018/19, which for the purpose of these models has been assumed to represent a standard year's harvest (i.e. for the purpose of this model it is assumed that, if fished under status quo conditions, the size distribution of harvested lobsters will remain constant among years) : (a) 'Year 1 Status Quo': which reflects the size distribution of harvested lobster for Year 1 under a status quo scenario (i.e. MCRS of 87 mm); (b) 'Year 2: Status Quo' which reflects the size distribution of harvested lobster for Year 2 under a status quo scenario (i.e. MCRS of 87 mm); (c) 'Year 1: Single-step MCRS Change' reflects the size distribution of harvested lobster for Year 1 assuming a single step increase in the MCRS from 87 to 90 mm (white bars represent forgone catch between 87 and 90 mm resulting from MCRS increase, which equates to -12% biomass relative to the status quo, under a natural mortality assumption of 0%); (d) 'Year 2: Single-step MCRS Change' shows the distribution of harvested lobster in Year 2 assuming a continued MCRS of 90 mm (dark grey bars represent the recruitment of the foregone lobster catch in Year 1 assuming a 13% growth factor and a natural mortality assumption of 0%, which equates to a + 6.5% increase in biomass relative to the status quo).

### 6.3.3 Model simulation: phased increase (87 mm to 89 mm to 90 mm)

Under a two phase step-change in MCRS to 89 mm (Year 1) and to 90 mm (Year 2) only lobsters under between 87 mm and 89 mm CL would be excluded from the harvest in Year 1, and additionally lobsters 89 mm to 90 mm in Year 2. The model estimates such a change would reduce the total landed weight by 6.7% , relative to 'Year 1: Status Quo' where the MCRS was 87 mm (Figure 6.4a).

In Year 2 (Figure 6.4e), the forgone harvest from Year 1 (i.e. lobster under 89 mm, Figure 6.4d) recruit into the fishery with postmoult increases in size and weight contributing to increased yield relative to status quo. The additional yield decreases as natural mortality increases, i.e. fewer individuals survive the additional moult (Figure 6.4e, 4f show the recruitment in dark grey when mortality = 0%).

In Year 2, there is a also a reduction in yield as a result of the second phase of MCRS increase from 89 mm to 90 mm CL (white bars in Figure 6.4e). The net effect of recruitment, mortality and increased MCRS on harvest in Year 2 relative to status quo ranges between -1.7% and -3.9% depending on mortality (see table 6.1). In Year 3, when MCRS is 90 mm, the increase in yield relative to baseline is the same as if the fishery had undergone a single-step increase in MCRS (see section 6.3.2).

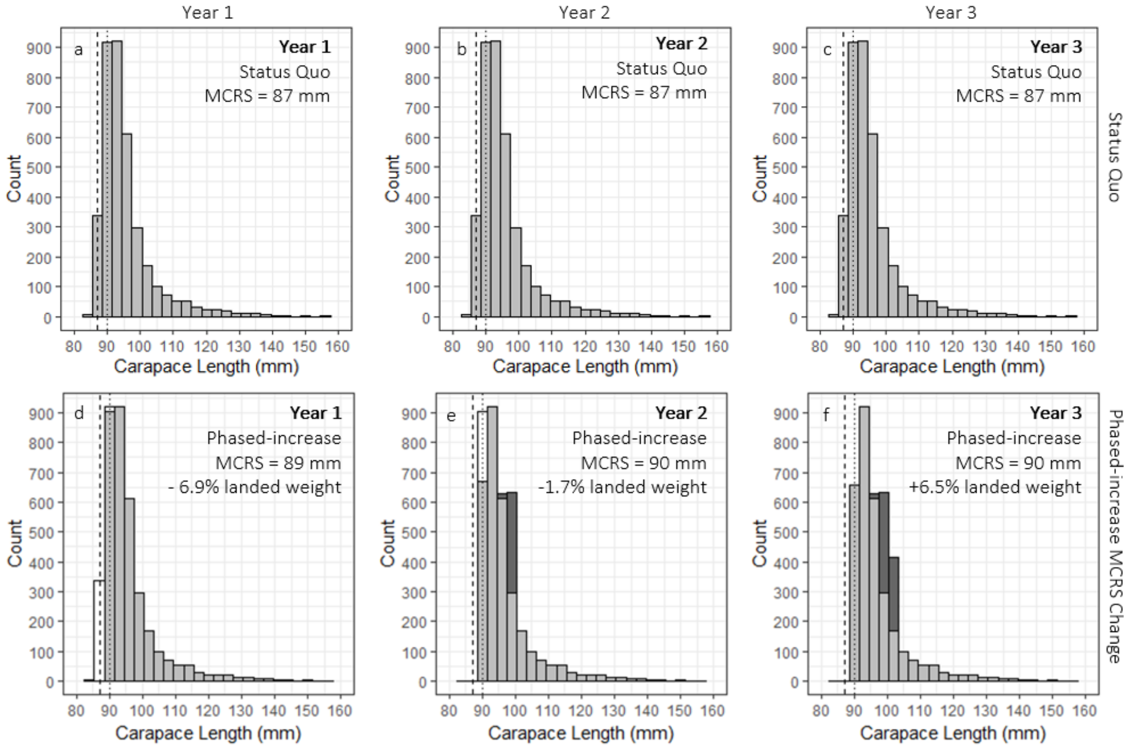

Figure 6.4. The data in these graphs are based on the size distribution of lobster (*H. gammarus*) sampled in the Isle of Man in 2018/19, which for the purpose of these models has been assumed to represent a standard year's harvest (i.e. for the purpose of this model it is assumed that, if fished under status quo conditions, the size distribution of harvested lobsters will remain constant among years) : (a-c) 'Year 1 Status Quo': which reflects the size distribution of harvested lobster for Year 1-3 under a status quo scenario (i.e. MCRS of 87 mm); (d) 'Year 1: Phased-increase MCRS Change' reflects the size distribution of harvested lobster for Year 1 assuming a step increase in the MCRS from 87 to 89 mm (white bars represent forgone catch between 87 and 89 mm resulting from MCRS which equates to -6.9% biomass relative to the status quo, under a natural mortality assumption of 0%); (e) 'Year 2: Phased-increase MCRS Change' shows the distribution of harvested lobster in Year 2 assuming a second increase in MCRS to 90 mm (white bars represent forgone catch between 89 and 90 mm resulting from MCRS increase from 89 mm to 90 mm. Dark grey bars represent the recruitment of the foregone lobster catch in Year 1 assuming a 13% growth factor and a natural mortality assumption of 0%. The net-effect of forgone lobster (white bars) and recruitment + growth (dark grey bars) equates to -1.7% decrease in biomass relative to the Year 2 status quo); (f) Year 3 where MCRS is 90 mm and lobster 87-89 mm and 89-90 mm have recruited into the fishery, which equates to a +6.5% biomass relative to Year 3 status quo.

Table 6.1. A summary table showing the short-term economic impact on harvest.

| | **Single-step** | | | | **Phased-approach (89 mm)** | | | |
|---|---|---|---|---|---|---|---|---|
| Natural mortality estimate | 0% | 10% | 15% | 20% | 0% | 10% | 15% | 20% |
| Year 1 compared to status-quo | -12.0% | | | | -6.7% | | | |
| Year 2 compared to status-quo | +6.5% | +4.1% | +3.2% | +2.4% | -1.7% | -2.8% | -3.3% | -3.9% |
| Year 3 compared to status quo | +6.5% | +4.1% | +3.2% | +2.4% | +6.5% | +4.1% | +3.2% | +2.4% |
| Number of years for net-benefit to be achieved | 2.8 | 3.9 | 4.8 | 6.0 | 3.3 | 4.3 | 5.1 | 6.4 |

Using the above data, we can also estimate that if natural mortality ≈ 31% (i.e. 31% of the forgone lobsters die before they recruit into the fishery at an increased MCRS), there would be zero benefit to an increase in MCRS and only a short-term loss, i.e. the weight gained by individuals that moult and survive is equal to the weight of the lobsters that do not survive.

## 6.4 Discussion & conclusion

An increase in the MLS for lobster in the northern Irish Sea from 87 – 90 mm CL is modelled to have a significant economic impact on fishery harvests (revenue) in Year 1, particularly if the shift in harvest strategy is a single-step change in MLS. The model showed that revenues reduced as much as -12.3 % relative to business-as-usual in the first season, though a phased approach can reduce the short-term impact (Δ) by ~44% if an interim 89 mm MLS is applied before increasing to 90 mm. Economic losses are not recovered for 2-6 years depending on the rate of natural mortality in the population and implementation strategy; where higher natural mortality and adopting ‘phased-approach’ prolongs the time taken to recover the losses from harvest regime shift ocurring in Year 1 (T).

Waters & Huntsman (1986) found that increases in MLS could result in decreased yield when discard mortality, fishing mortality or natural mortality was high in the red snapper (*Lutjanus campechanus*) fishery in the Gulf of Mexico. Our model suggests that for European lobster, yield-per-recruit can increase with an increase in MLS to 90 mm CL as natural mortality is assumed to be low (<0.15, Bannister, 1986; Sheehy, et al., 1999). However, the impact of the rate of natural mortality is an important consideration from an economic perspective for fisheries managers. Our model suggests that if $M = 0.31$, the yield-per-recruit benefit of increasing MLS declines to zero with no opportunity to recover the losses from forgone harvest in a static-environment model (i.e. no increase in recruitment and abundance in the stock). Despite the short-term cost of any shift in harvest strategy, the model shows that there is an oppotunrity to increase annual yield from lobster harvests by 2.0% to 5.5% per year depending on the rate of $M$, *ceteris paribus*.

The assertion that harvest will fall for one to two years (Bannister, 2008) after MLS change is true, but our simulations suggest it can take several further seasons to recover the initial forgone harvest if $M$ is high. There are many broad-scale and local factors that can affect $M$ in a population, including demographic bottlenecks created by habitat availability (Wahle, et al., 2013). The survivorship (1-$M$) of shelter-dwelling crustaceans such as lobster is hypothesised to be a function of size-specific shelter availability and size-specific predation risk (Caddy, 1986; Cobb, 1971; Wahle & Steneck, 1991, 1992; Beck, 1995, 1997). In other words, the real-world application of the change in harvest regime modelled in this study will only return the estimated benefits if there is habitat available to support a greater abundance of larger animals, though habitat enhancement has been shown to be a viable method of supporting lobster populations with a larger size-structure (Jensen, et al., 1994; Jensen, et al., 2000). The overall benefit of an increase in MLS is unlikely to be ~30% unless the existing demographic structure of the harvested population exhibits an extreme right-skew with most individuals harvested at 87 mm CL. Our model suggests that, with the size-structure and average growth factor observed in the Irish Sea, the maximum potential benefit of an increase in MLS in this region is +5.5%.

The net profit margin (total income minus total operating costs and finance costs as a % of total income) for <10 m and 10-12m static-gear vessels in the UK in 2017 was 19% and 26% respectively (Seafish, 2019). Therefore, a 12.3% reduction in revenue could create significant risk to business viability for those vessels that rely solely or principally on lobster for income. In particular, the small-scale (<10 m) inshore sector generated an average annual operating profit of only £16,320 in 2018 in the UK (Seafish, 2019) and is less capable of switching to alternative pot fisheries such as offshore brown crab (*Cancer pagurus*) and whelk (*Buccinum undatum*) to maintain income, unlike the 10-12 m potting sector. The <10 m sector is therefore particularly vulnerable to short-term economic impacts. The model suggests that fisheries administrations should consider a phased increase in MLS to 90 mm CL over two or more seasons to reduce the short-term economic impact on fishing businesses, as was highlighted to the Welsh Government following consultation (Welsh Government, 2014).

Many fishers view increased MLS as an ‘investment’ in lobster stocks with attractive rates of return (*pers comms*). In areas where 90 mm MLS has been informally adopted, fishers have shown that the number of animals needed to fill a 30 kg fish box has declined by ~20% (pers comms, 2018) with overall abundance remaining stable. However, in the absence of effort and harvest management plans for lobster fisheries more generally, the benefits of increased yield may be short-lived; landings-per-unit-effort (LPUE) can decline significantly, for example the Norwegian fishery collapsed between 1960 to 1980 to <10% of its pre-1960 level and has failed to recover (Agnalt, et al., 2007). Therefore, whilst an increase in MLS may offer a strategy to increase yield and protect functional maturity, it should not be seen as a panacea for sustainable management of lobster fisheries.

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# Chapter 7. Size-selective fishing for the common whelk, *Buccinum undatum* (L.), in the Isle of Man territorial sea; the effectiveness of ‘riddle’ benches for grading catch in relation to shell morphometrics.

## Abstract

Size-selective harvesting of marine fish and shellfish is often required by regulations in order to reduce the rate of mortality among juvenile populations. This can be a particularly effective measure in fisheries that can return undersize discards live to the sea with a low risk of subsequent mortality. Commercial fisheries for the common whelk, *Buccinum undatum*, are growing throughout north-western Europe and are subject to regionally variable minimum-landing-sizes (MLS), many of which have been increased in recent years in response to size-at-maturity estimates published in scientific literature. As regulations and technical measures are imposed on the fishing industry, technical solutions are sought by the skippers and crew of commercial vessels that comply with the law whilst maintaining efficiency. The bench-riddle that is employed in the whelk fishery in the Isle of Man was tested in field trials to assess the selectivity rate across a range of size classes for the species. We found that the size at 50% retention ($S_{50}$) is related to shell morphology, where the spacing between the bars of the riddle is more approximate to the maximum width of the shell ($SW_{Max}$) rather than the minimum shell width ($SW_{Min}$). The spacing of the bars in the riddle (35 mm) applies an $S_{50}$ value to the catch where $SW_{Max}$ is equal to 36.2 mm. Using linear regression, we show that a $SW_{Max}$ value of 36.2 mm corresponds to a value of 67.7 mm total shell length (TSL) whereas the MLS is specified to 70 mm. We therefore recommend that the spacing of the bars be increased to ~37 mm so that $S_{50}$ = 70 mm TSL. Finally, we suggest that the data presented in this work can be used to approximate the desired spacing in riddle devices elsewhere in order for fishers to comply with regionally variable MLSs, although we acknowledging that aspects shell morphometrics can vary between populations.

## 7.1 Introduction

The common whelk (*Buccinum undatum*, Linnaeus, 1758) is a neo-gastropod mollusc that is found in the subtidal waters of the North Atlantic to depths of 1200 m and is widely distributed on the Atlantic continental shelf; from within the arctic circle (76ºN) as far south as Delaware Bay, USA (39ºN) at the western-most extent (Borsetti, et al., 2018). Populations are most frequently observed in abundance in the northeast Atlantic, particularly in the waters of north-western Europe from the Celtic and Irish Sea through to Skagerrak and Kattegat Bay (Valtelinsson, 2002), including northern populations in Norwegian, Faroese and Icelandic waters (Gunnarsson & Einarsson, 1995).

The common whelk is the largest edible marine gastropod in the North Atlantic ($TSL_{MAX}$ ≈ 150 mm; (Hancock, 1967). It exhibits late sexual maturation (Hancock, 1963) and low fecundity (Martel, et al., 1986), rendering commercially targeted populations vulnerable to recruitment overfishing (Shrives, et al., 2015). The reproductive strategy, i.e the absence of a larval stage by which widespread dispersal of individuals to other areas is possible, combined with evidence of limited range of movement even after having recruited into the adult population (Morel & Bossy, 2004), means that populations may be isolated even within small geographic areas.

Within the north Irish Sea (ICES area VIIa), there is increasing commercial interest in prosecuting whelk stocks. The expansion of the fishery is most likely in response to increased economic returns resulting from the supply-chain opening lucrative markets in the Far-East, but also declining fishing opportunities in other sectors of the fishing industry (Emmerson, et al., 2018).

Throughout the majority of ICES Area VIIa, a minimum conservation reference size (MCRS) of 45 mm is enforced. However, within the Isle of Man territorial sea, a minimum landing size (MLS) of 70 mm is enforced. The former MCRS is a European-wide conservation measure that, although expedient for marketing purposes, is biologically inappropriate with respect to estimates of size-at-maturity in numerous areas in north-western Europe (see Valentinsson, et al., 1999; McIntyre, et al., 2015; Haig, et al., 2015; Emmerson, et al., 2018). The MLS enforced within the Isle of Man was raised in 2017 and is based on biological data published by Kideys et al. (1993) and Emmerson et al. (2018) and aims to protect immature individuals from harvesting prior to reproduction and spawning. Welsh waters increased the MLS for whelk in Welsh waters based on results from Haig et al. (2015) to 55 mm.

In order to comply with the MLS, fishers operating within the Isle of Man territorial sea have developed static riddle device that selects whelk based on shell morphology (Figure 7.1). The riddles are typically designed as a working bench with stainless-steel bars forming the base of the working area, which are spaced at 35 mm distance from one another. Underneath the bars is an angled sheet of mental directing those whelk small enough to pass between the bars towards a discard-shoot, after which they are returned live to the sea. Fishers are in need of a passive selectivity device to ensure compliance with the law as a single whelk pot, which is often in a 'fleet' of up to 90 pots, can frequently contain hundreds of individuals.

Figure 7.1. The whelk riddle used on Vagabond DO180 in the Isle of Man.

This work, which was conducted at the request of the fishing industry and aims to assess the effectiveness of riddle benches for compliance with the existing MLS in the Isle of Man territorial sea. The results can be used to inform fisheries management for this species elsewhere.

## 7.2 Methods

### 7.2.1 Field methods

Field experiments were undertaken on-board the FV Vagabond II DO180 on the 26th September 2017 during normal commercial operations. In each of the replicates, the contents of several whelk pots hauled on strings set within fishing ground E-2 (between the 3 and 6 nautical mile limits east of Douglas, Figure 7.2) were sorted. A subsample of 250 whelk spanning the typical size range (25 mm – 110 mm total shell length; TSL), reflective of the size-structure of catch in that fishing ground, were used in the riddle tests.

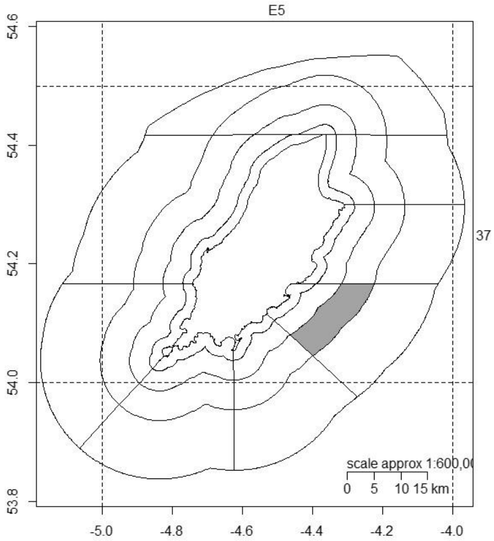

Figure 7.2. A map of the Isle of man territorial sea, highlighting the area (shaded) within which the whelk (*Buccinum undatum*) were sampled.

The total shell length of the subsample of whelks were measured using Zebra-tech© electronic measuring boards *in-situ* to the nearest 0.1 mm TSL (Figure 7.3). The whelks were then passed over the riddle and measured in the same way again if they were retained. Whelks that passed through the riddle were discarded to the sea. The process was repeated four times using a different sample of 250 whelks each time.

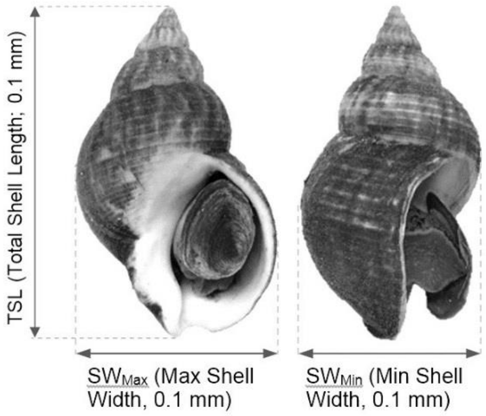

Figure 7.3. Shell measurements of whelk (*Buccinum undatum*) recorded on-board and again in the laboratory.

### 7.2.2 Laboratory analysis

As part of a routine assessment of size-at-maturity, a sample of 220 whelks were retained from the sample area and stored frozen for subsequent laboratory analysis. As part of that analysis, further shell measurements were recorded for each individual along with TSL, including the minimum and maximum shell width ($SW_{Min}$ and $SW_{Max}$, respectively). All measurements were made using callipers accurate to 0.1 mm.

### 7.2.3 Statistical analysis

All statistical analysis was carried out in R (R Core Team, 2017). Each TSL observation was assigned a categorical value, grouping measurements into 5 mm bins. The number of observations in each bin in both the unsorted and riddled sample was then summed and the selectivity value (S), i.e retention rate, in each category was calculated using the following formula;

$$S_{(X)} = \frac{\sum N^{Riddled}_{Category\ (X)}}{\sum N^{Unsorted}_{Catgroy\ (X)}}$$

where (X) represents the length category. The distribution of S values across the sampled population in each of the replicates was then plotted and modelled using a general linear model (GLM) with a binomial probability distribution (logistic regression), where;

Selectivity Model: $S_{(X)}$ ~ Length Category; family = binomial, link=”logit”

The size (TSL value) at which a whelk has a 50% chance of being both discarded and retained ($S_{50}$) was then calculated for each of the four replicates. The unsorted and retained size data was then aggregated and modelled in the same way to produce an average $S_{50}$ value for the four tests. The model derived from aggregated data across the four replicates was then used to estimate the average S value in each bin category.

Finally, the basic shell morphology for the sampled population was investigated using the measurements obtained in the laboratory. Using linear regression techniques, the relationship between

TSL and Shell morphology was investigated to assess whether bar spacing correlates to either of these easily identified measurements. The results of the regression was then modelled against $S_{50}$ to infer morphometric 'thresholds' that effect the selectivity-at-size of whelk within this population.

## 7.3 Results and discussion

Four replicate experiments were conducted at sea, with a total of 1000 whelks passed over a riddle table with a spacing of 35 mm. The smallest whelk in the unsorted catch measured 26.8 mm and the largest measured 113.1 mm (Figure 7.4).

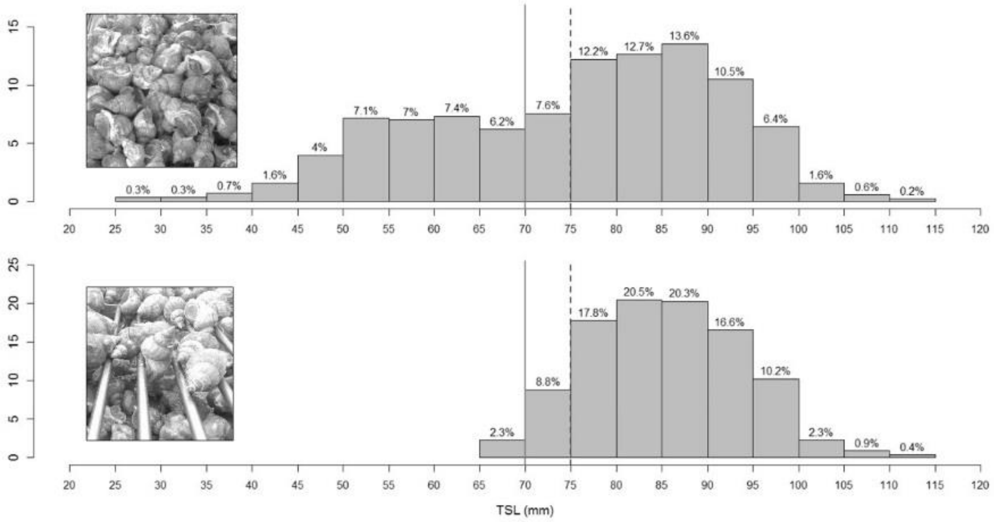

Figure 7.4. Frequency histograms showing the TSL distribution of unsorted whelk (top, n=884) that are retained after riddling with a 35 mm riddle device (bottom, n=567). The % above the bars indicates the relative contribution of each size-class to the overall catch before and after riddling. The solid line shows the current MLS (70 mm TSL) and the dashed line shows the estimated $L_{50}$ (75 mm TSL) from Emmerson et al. (2018).

The selectivity (S) increased with size in all replicate experiments from zero to one between categories 60-65 and 85-90 (i.e 100% chance of being discarded and 100% chance of being retained respectively). The results of the modelled aggregated data is shown in Figure 7.5.

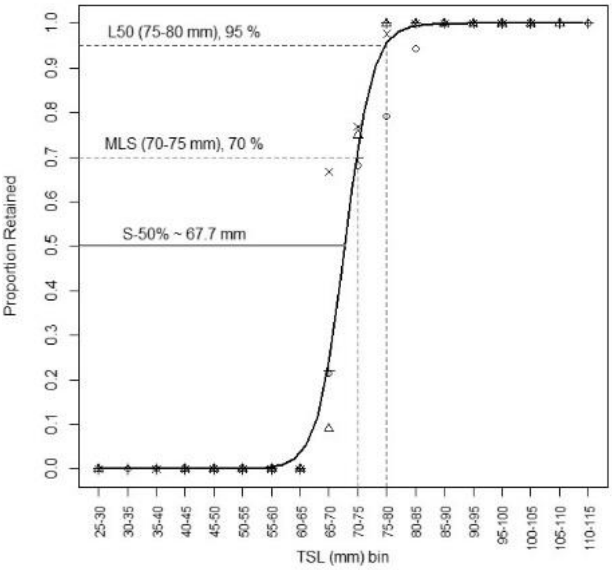

Figure 7.5. A selectivity curve (i.e proportion retained) for whelk (*Buccinum undatum*) in a 35 mm riddle spacing (combined data), The solid red line represents the size at which 50% of whelks are discarded or selected (S50). At the MLS (70 mm; dashed-red line) the retention rate is 70%. At the estimated size-at-maturity (L50; dashed-green line), the retention rate is 95%. The points represent the % estimates from each of the four replicates during the experiment.

The aggregated model indicates that, with current practices, the retention rate for whelk within the 65-70 mm category is approximately 20%. At the MLS (70 mm), the retention rate is 70% and increases to 95% for individuals within the 75-80 mm category. Whelks with a TSL ≥ 80 mm are fully selected by the fishery. The size at which the average whelk in this population is estimated to have an equal chance of being discarded or retained is 67.7 mm TSL.

Linear regression analysis showed a significant effect of TSL on $SW_{Max}$ and $SW_{Min}$ ($p < 0.001$) with R2 values of 0.93 and 0.95 respectively (Figure 7.6). The linear equations that describe both relationships are;

$$SW_{Max} = 0.55\,TSL - 0.2$$

$$SW_{Min} = 0.47\,TSL - 1.0$$

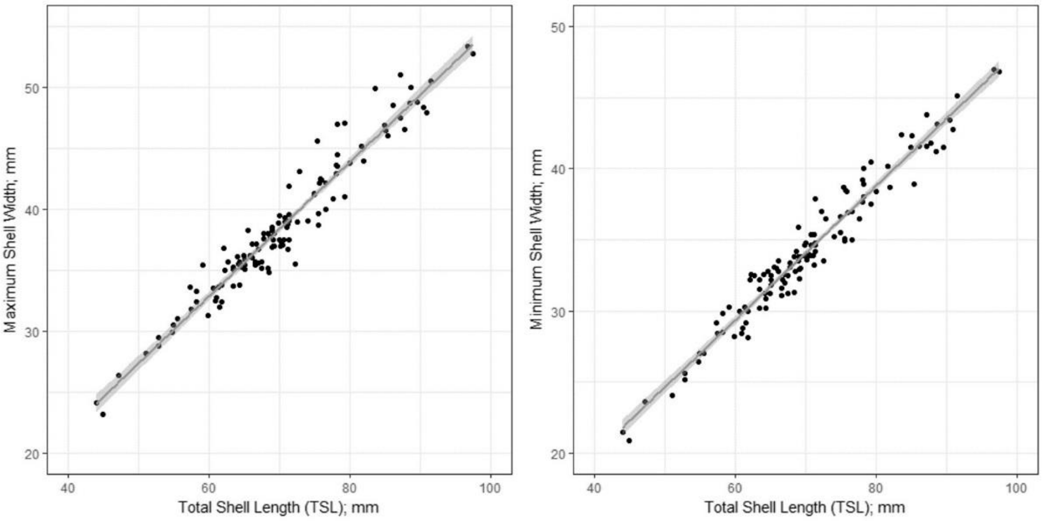

Figure 7.6. The relationship between total shell length (TSL) and maximum (left) and minimum (right) shell width (as described in Figure 3). The solid line represents the linear equations describing the relationship and the shaded band around the solid line shows the standard error of the relationship.

At a size 70 mm TSL, the $SW_{Min}$ $SW_{Max}$ of a shell is estimated to be 31.9 mm and 38.3 mm respectively. At the $S_{50}$ value of 67.7 mm selected by a 35 mm riddle, the $SW_{Min}$ $SW_{Max}$ of the average whelk is estimated to be 30.8 mm and 36.2 mm respectively. This suggests that the riddle is selecting to approximately the same width as the $SW_{Max}$, as opposed to $SW_{Min}$, i.e. the spacing of the riddle bar (35 mm) is selecting whelk at $S_{50}$ that have a $SW_{Max}$ 3.4% greater than the 35 mm spacing. It also suggests that in order to increase $S_{50}$ to 70 mm TSL, as might be preffered by fishers and enforcerment, the riddle bar width should be increased to ~ 37 mm according to shell morphology of whelk in the area.

Although not fine-tuned to the current MLS in the Isle of Man, the riddle design itself is very effective for releasing undersize individuals within a short period of time back to the sea, . The sharp increase in selectivity as shown in Figure 5 and 6 indicates that bench riddles go from 1.0 probability of discarding an individual to 1.0 probability of retention over just three size classes (15 mm TSL). Furthermore, the variation in $S_{50}$ between the four tests (Figure 5) was low, ranging between 65.4 mm and 69.3 mm (range = 3.9 mm) TSL suggesting that a single riddle design is effective between populations in the same fishing ground. If shell morphology, i.e the relationship between $SE_{Max}$ and TSL, varies significantly between populations then a pan-population specification for riddle design may not be a reliable tool for selecting to regionally variable MLS. Indeed, some aspects of shell morphology have been shown to vary significantly between populations, such as shell thickness (although this is unlikely to impact selectivity using riddles) (Thomas & Himmelman, 1988).

## 7.4 Conclusion

As technical measures such as MLS begin to be implemented for whelk fisheries in the UK and elsewhere, it is important to model shell morphology and design selectivity devices that have $S_{50}$ values in line with biological estimates of $L_{50}$ and harvest rules such as MLS. Shell morphology, specifically $SW_{Max}$, has been shown to approximate closely to the design of riddle devices in the Isle of Man. It is recommended that riddle bar spacing be set slightly under (0.97) $SW_{Max}$ of MLS for the population being targeted.

## 7.5 Acknowledgements

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# Chapter 8. General Discussion

Baited-pot fisheries in the Irish Sea target shellfish stocks, which are poorly understood and are typically characterised as ‘data-poor’ fisheries. Establishing a comprehensive evidence-base to underpin management of these fisheries requires research efforts to address;

- fundamental knowledge-gaps in species life history and population parameters;
- significant deficiencies in the quality of fishing activity data;
- methodological limitations in performing fisheries assessments, and
- any implications resulting from changes to current harvesting strategies.

This thesis aims to address elements of the above for particular shellfish stocks, including common whelk, common prawn, European lobster and edible crab. This final chapter provides an overview of key findings presented in the research and a discussion on the implication for management in the region. Finally, this chapter provides suggestions on the direction for future research in this area.

## 8.1 Summary of new contributions of this thesis

1. The basic population structure, reproductive biology and size-at-maturity are described for the common prawn in Welsh waters. Size-data exhibited a sexually dimorphic population structure, which causes the fishery to select for mature females when fishers operate a voluntary 10 mm CW minimum-landing-size (MLS) in pursuit of better market prices. Allomatric growth in females indicates a pubescent moult at ~12.5 mm CL (= 7.7 mm CW), whilst functional maturity ($L_{50}$) based on gravid status was estimate at 15.9 mm CL (= 9.9 mm CW). The voluntary MLS is therefore considered to be biologically appropriate at 10 mm CW by giving at least 50% of females the opportunity to reproduce. Nonetheless, temporal trends in sex-ratio of catches show decline in the presence of females through the fishing season, which may be indicative of either sex-overfishing or possibly migratory behaviour. The research suggests that whilst a 10 mm CW MLS should be applied, managers must consider additional tools (e.g. closed seasons and total-allowable-catch) in order to safeguard against recruit overfishing.

2. The basic population structure, reproductive biology and size-at-maturity are described for common whelk in Welsh waters and the Isle of Man territorial sea in the context of significant recent expansions in landings of the species in these areas. Using visual gonad analysis methods to estimate size-at-maturity should be used prior to spawning during ‘peak-aGSI’, i.e. when identification of gonadic development is most visibly clear. Estimates of functional maturity ($L_{50}$) were at a greater size (TSL) than the MCRS being applied to the fishery in Welsh waters (45 mm TSL) and the Isle of Man territorial sea (70 mm TSL) at the time of the study in all areas except from one site (Point of Ayre, Isle of Man). Gonadic development was analysed temporally and spawning season was defined for populations in the Isle of Man and Wales as being late winter to early spring. A mixed cohort analysis used size data to estimate age-at-recruitment and estimated that whelk recruit to the fishery at age 5.

3. Size-at-age relationships were established for common whelk populations sampled from throughout the latitudinal extent of the Irish Sea, and including a sample from the Celtic Sea in Swansea Bay. The methodology was adopted from previously published research in the region and uses measurements of rings visible within the statolith to estimate size-at-age. Data were fit to the Gompertz growth equation and the resulting parameters, including $L_\infty$, $K_G$, and Ti, showed a broadly latitudinal pattern, whereby northern populations grew slower, over a greater length of time and reached a larger maximum size compared to southern populations. This geographical trend was analysed in the context of sea-bottom-temperature for the sample locations. Regression analysis showed a clear significant relationship between temperature and $L_\infty$, as well as strong correlations with other growth parameters and $L_{50}$. It is hypothesised that sea-bottom-temperature may be able to predict important life history parameters in other areas of the northeast Atlantic using this relationship in order to establish approximated MCRS revisions in the absence of site-specific biological data.

4. Catch reporting requirements vary by size of vessel for the majority of fisheries in the EU, including those targeting shellfish using baited pots in the Irish Sea. In particular, spatial data and effort data requirements are largely absent from vessels under 12 m in length, although this does vary by region. Where they are available, the data are usually aggregated to daily totals and can fail to distinguish between pot-type (e.g. whelk pot, prawn pot, lobster creel etc.). The research presented in chapter 5 showed that enhanced electronic reporting systems (EERSs) that incorporate gear-in gear-out technology and combine observations of temperature, depth, soak-time and position of baited-pots with string-specific catch and effort data offers a step-change in fisheries-dependent data for these fisheries. Fisheries-dependent landings-per-unit-effort (LPUE) was successfully modelled for the Isle of Man edible crab fishery using a generalised additive model that incorporates temperature, latitude-longitude, intra-specific effects (bycatch of European lobster in what is regarded a mixed fishery) and vessel effects. The research demonstrated a direction in which fisheries-dependent reporting needs to go in order to develop area-specific fisheries management based on fisheries-dependent catch and effort data in baited pot fisheries.

5. A desk-based study utilising unpublished mark-recapture data and size-data from commercial landings indicates that changes to MCRS, from 87 mm CL to 90 mm CL, for European lobster in the Isle of Man will have a significant short-term impact on harvests if introduced in a single-step. A phased introduction over multiple season will reduce the short term impact on harvests. Depending on assumed rates of natural mortality, the long-term benefit of a moderate increase in MCRS to 90 mm CL can be substantial due to the length-weight relationship and growth-rate of European lobster at around the size-at-recruitment, where an 87 mm CL European lobster may grow to ~98.3 mm CL and increase in mass by 39%.

6. Vessels are able to effectively comply with common whelk MCRS using a ‘riddle’ device, which is a grid that allows some whelk to pass through gaps between bars depending on shell diameters. A selectivity curve was modelled using logistic regression on a typical riddle

employed in the Isle of Man territorial sea, which showed the size at which there is a 50:50 chance of capture is 67.7 mm TSL. Compared to the MCRS at the time of the study (70 mm TSL), the riddle can be viewed as an effective tool for compliance with regulations. Selectivity of riddle devices can vary depending on shell morphology of populations, which can vary locally. Site-specific riddle designs may therefore be required in order to comply with regulations, and vessels may need to have a changeable device if they operate in multiple jurisdictions that enforce different MCRS requirements.

## 8.2 Discussion

The research presented within this thesis by no means addresses all of knowledge gaps that preclude evidence-based management of baited pot fisheries in the Irish Sea. The data, analysis and results of the scientific investigations offer a baseline of evidence relating to a number of fishery-specific data limitations and direction for future research, however. The initial work (chapters 2 – 3) focus on biological parameters that are important for informing MCRS regulations in common whelk and common prawn fisheries. The aim of biologically informed MCRS regulations are to protect juvenile individuals from fishing mortality exerted on the stock, and therefore help safeguard fisheries against recruit overfishing. The method of capture and discarding in the common prawn and common whelk fisheries are similar, i.e. through the use of a riddle device that allows undersize catch to be returned live to the sea with minimal handling based on shell morphology. These studies did not investigate discard mortality, which can result from stress, physical damage and subsequent vulnerability to predation once discards return to the seabed. Discard rates and the rate of discard mortality are important considerations for most stock assessments, however.

Following the publication of chapter 3, both the Isle of Man Government and Welsh Government increased the MCRS of common whelk to a size that affords better protection to juveniles in those areas (65 mm TSL and 75 mm TSL respectively). Aside from some static input controls (effort limitations; capped licences and pot limitations) in the Isle of Man, Irish Sea common whelk fisheries continues to be largely unregulated throughout the region. Measures such as closed seasons, spatial management (temporary and/or permanent area-specific restrictions on fishing activity) and output controls (total allowable catches, quotas) are not yet applied for these fisheries, although both the Isle of Man Government and Welsh Government has undertaken public consultations with respect to additional management measures since the publication of Chapter 3.

Considering that recent landings data for whelk indicate that the overall fishery in the Irish Sea, and particularly in Welsh waters, is in decline it is strongly recommended that further research and policy considerations are directed towards this fishery. It is important to point out that there are currently no output harvest control rules for whelk fisheries in this region, and therefore declining landings are not being driven by restrictions, but more likely stock abundance. The data presented in chapter 3 can be seen as a valuable evidence-base from which to build upon, with strong evidence of reproductive biology (size-at-maturity and spawning seasons) that could be used to inform temporary spatial-temporal restrictions on fishing activity, particularly if that fishing activity is seen to cause damage or disturbance spawning (e.g. mobile fishing activity). Further work is required to formulate methodologies that lead to stock assessments of common whelk fisheries, either through fisheries-independent surveys, fisheries-dependent monitoring or a combination of both, which can be used to inform additional input (effort restrictions) and output (harvest limits) recommendations.

The common prawn fishery in Wales remains completely unregulated, other than the basic requirement of a UK Shellfish Licence. Nonetheless, the voluntary agreements within the catching and processing sectors of the industry remain largely consistent with those at the time of the research, including:

- minimum mesh size on prawn pots of 10 mm;
- grading catch at sea, either by hand or through the use of a riddle, to select individuals with a CW > 10 mm, and
- rejecting landings that are poor quality and below the size preferred by the market.

The data presented in chapter 2 indicate that these basic voluntary technical measures may protect juvenile individuals from fishing mortality. However discard rates are high in the fishery, particularly among male populations that exhibit a smaller size distribution. Similarly to common whelk, discard mortality remains unassessed for the fishery and should be quantified in order to determine the effectiveness of size-selective harvesting as a conservation measure. The voluntary size-selective harvesting regime is as much an economic concern as a conservation measure, however views should be sought on whether the quasi-MLS should be formalised and regulated throughout the Welsh fishery nonetheless through public consultation.

Annual landings of common prawn have varied considerably since the research presented in chapter 2 was undertaken, ranging from as low as ~11 t (2015) to over 25 t (2018). Although fishing effort data are unavailable and calculation of respective changes in LPUE are therefore not possible, it is likely that variable harvests are a reflection of changes in stock abundance rather than significant shifts in potting effort. Certainly, the number of days spent fishing has remained relatively constant since 2012, though the number of pot-lifts associated with these fishing trips is unavailable. In the absence of effort data and a stock assessment for this fishery, it is not possible to determine why landing trends are so variable. A general pattern is visible in the common prawn fishery where a productive year (landings > ~17.5 t) is succeeded by a less productive year (landings < ~15 t) (Chapter 1, Figure 5) and therefore resembles a ‘boom to bust’ situation in the fishery that has been evident since at least 2012. Indeed, the most recent data (2018/19) show the greatest inter-annual decrease (approximately 50%) in landings.

The sex-ratio of commercial catch samples, collected during the 2014/15 season presented in chapter 2 (Figure 3), highlight a possibility of sex-overfishing that could lead to an impairment of the sexually mature female population. The likelihood that the general boom to bust scenario is linked to sex-overfishing, reduced spawning output and subsequently poo recruitment is yet to be confirmed and should be addressed by future research. There is some evidence in the literature that these sex-ratio data are indicative of seasonal migrations into inshore and estuarine habitat, as opposed to decline in abundance. A greater understanding of the interlinking dynamics between the fishery and the stock is needed so that further management recommendations on input and output restrictions can be made, together with a consultation on the perspective of the fishing industry. However the short life-span (2-3 years) of the species together with the fact that fluctuating inter-annual harvests are dominated by mature females is indicative of a fishery that is highly dependent upon recruitment success. In such instances, output controls (e.g. TACs and prohibitions of landing egg-bearing females) and seasonal restrictions may be an effective tool in addressing boom and bust dynamics.

Chapter 4 highlights the relationship between species life history and the abiotic environment in common whelk populations, namely the effect that sea-temperature has on growth rates and maximum shell size. Understanding the drivers and variability of growth rates among common whelk populations is an important consideration for fisheries advice and management. As a result of these data and analysis, it is now understood that variable growth rates determine different age-at-recruitment values for whelk depending on the size-selective regimes in place for that fishery. For example in the Isle of Man, whelk recruit into the fishery (MCRS = 75 mm TSL) after 4-5 years, whereas whelk sampled near Saundersfoot recruit into the fishery (MCRS = 65 mm) after 2-3 years. Changes to management measures can now be better predicted, for example it is clear that the recent change in MCRS throughout Welsh waters (a phased increase from 45 mm to 65 mm) will have a significant effect in specific areas such as in Swansea Bay, where the fishery is likely to face significant declines in harvests since average $L_\infty$ is 59.9 mm. The significant range in growth parameters from whelk samples across Wales highlight the complexity and challenges associated with managing fisheries that target highly heterogeneous populations, in particular the challenge of how to sensibly enforce conservation measures (e.g. increased MCRS to protect juvenile individuals) that i) are pragmatic from a legal and enforcement perspective ii) reflect the biological reality of target populations, and iii) balances the disproportionate economic consequences of regulatory change across a management area.

If the relationship between growth and temperature is an association observed throughout whelk populations in the northeast Atlantic then it may be possible to estimate important stock conservation parameters (e.g. size-at-maturity, size-at-recruitment, $L_\infty$) in fishery management areas that operate the default EU-wide MCRS (45 mm TSL) for the species, which may not necessarily reflect size at functional maturity ($L_{50}$). It is predicted that most areas, particularly regions outside of the English Channel (ICES Area VIIe and VIId) and southern North Sea (ICES Area IVc), are likely to support whelk populations that display slower growing populations where $L_{50}$ is greater than 45 mm, for example there are significant fisheries in the Northern North Sea, Central North Sea, and West of Scotland (ICES Areas IVa, IVb and Via respectively) that still operate to 45 mm MCRS.

Chapter 5 highlights the improved data resolution, precision, and analytical insight from an Enhanced Electronic Reporting System (EERS) trialled within an edible crab fishery in the northern Irish Sea. The statutory requirements for this fishery vary according to vessel size. The requirements include logbook submissions (electronic daily submissions for vessels > 12 m, paper daily submissions for vessels 10-12 m, and monthly paper submission for vessels < 10 m), which report the total landings by species. Only the < 10 m vessels are required to report the number of pot-lifts for each daily record, whilst only

> 12 m vessels are required to carry VMS spatial polling equipment. All records are assigned to ICES statistical rectangle (30 $km^2$ areas) and < 10 m vessels also report daily landings and effort to scientific squares (5 $km^2$) in the monthly logbook.

Traditional stock assessments that employ fisheries independent survey data, e.g. length-structured or age-structured abundance indices, often utilise the basic logbook data described above (i.e. total landings) within the stock assessment model to estimate stock biomass, fishing mortality, spawning stock biomass and MSY, etc. However, many shellfish stocks, including edible crab, are characterised by limited biological data (e.g. size-at-age, stock boundaries, stock-recruitment relationship), which hampers stock assessment and scientific advice. The data-limited and unassessed status of edible crab stocks is compounded by a general acknowledgment, but lack of consensus, of how to accurately estimate stock abundance (individuals per $m^2$) using catch-per-unit-effort (CPUE) data from baited traps. Abundance indices from surveys depend on a critical assumption that CPUE is proportional to abundance, i.e. catchability is constant; however, the catchability of baited traps is highly variable and determined by a number of complex, inter-related, and random factors. Trawl and dredge-based surveys also encounter issues associated with variable catch efficiency yet are regularly incorporated and accommodated within traditional stock assessment methodologies since many of the effects on catchability can be observed, measured and controlled for within the survey design (e.g. tidal strength, habitat-type, etc.). By contrast, and despite the ability to control for some variables (e.g. soak-time, location, tidal-cycle strength), baited-trap CPUE can be significantly effected by uncontrollable factors; for example, the inter- and intra-specific behaviours of animals around and within the trap (e.g. guarding behaviour at the entrance of the pot), or even the strength, direction and duration of the chemical signal transmitted by the bait, which can vary depending on bait-type, local hydrodynamics and decomposition rate respectively.

An alternative approach to fisheries advice provision for data-limited stocks may therefore be to standardise fisheries-dependent CPUE and incorporating uncertainty into the decision making process, rather than attempting to produce an estimate of absolute abundance. However in the absence of additional information, the interpretation of trends in catches is generally difficult (Miethe, et al., 2016). The effects of observable factors on catch trends can be accounted for using models that accommodate random variables and smoothing functions, including generalised linear models (GLMs), generalised linear mixed models (GLMMs) and generalised additive models (GAMs).

The current reporting requirements in the edible crab fishery (outlined above) are undoubtedly insufficient for performing even the most basic fishery-dependent indices calculations due to the absence of effort data in > 10 m logbooks. The absence of high-resolution spatial data is also a barrier to geostatistical analysis of fishery-dependent data and, therefore, area-based fisheries advice other than to ICES statistical rectangle, which are arbitrary divisions from a stock boundary and jurisdictional perspective. Finally, and in addition to the absence of high-resolution spatial data, the daily summation of landings data does not allow for area-specific analytical insight of fisheries-dependent data. For example, edible crab and European lobster are concurrently targeted using the same gear but the catchability of each species varies depending on a range of parameters, including habitat type (i.e.

geolocation). A typical logbook entry within the fishery may report landings of both edible crab and European lobster with no delineation of the relative amount of effort targeting either species. For example, a typical logbook entry fails to capture the caveat that the majority of fishing effort being deployed on a given day is particular to edible crab, and that landings of European lobster reflect incidental bycatch; however, fisheries analysts would be unable to determine this from typical logbook data. Consequently, standard logbook LPUE data may underestimate and misrepresent the species-specific index of abundance and lead to inappropriate management advice. It is also common for skippers to target both crab and lobster within the same day, such that a proportion of daily effort and landings could be useful to develop separate species-specific LPUE indices; however, since logbook record requirements aggregate daily activity, and in the absence of high-resolution catch, effort and spatial data, the calculation and analysis of these indices is difficult.

The EERS trial presented in Chapter 5 demonstrates the application of high-resolution fisheries dependent data within a statistical model that could enable fisheries management advice in a fishery that is otherwise considered data-poor and lacking management. The model was based upon data that is collected at a very high resolution (string-specific data) including a number of additional variables (e.g. latitude, longitude, temperature, etc.). The results showed that abiotic factors (e.g. sea bottom temperature) had significant effects on LPUE in the edible crab fishery as well as geolocation and inter-specific interactions (Figure 5.9). Using the model outputs, it is possible to standardise LPUE data to take account of variation in these additional parameters that have significant and observable effects on fisheries-dependent data. Fisheries advice, based upon standardised LPUE data, can therefore be formulated providing that a continuous supply of high-resolution EERS data is available for fisheries scientists in areas of interest (i.e. specific fishing grounds) to fisheries managers.

The discussion section of the chapter proposes that a ‘sentinel fleet’ of EERS users is developed so that the supply of high-resolution data continues and a comprehensive fisheries-dependent dataset is assembled. Near real-time trends in standardised fisheries-dependent LPUE data could be monitored against historical reference points, which can instruct management responses through a framework of trigger reference points (e.g. if standardised LPUE declines below a certain threshold, increased data collection requirements are triggered) and limit reference points (e.g. if LPUE falls below a 5-year minimum, then real-time closures are imposed on the fishery). In addition to the development of an EERS sentinel fleet, the research highlights the requirement to improve and harmonise standard reporting requirements throughout the static-gear fleets irrespective of length-metier to include effort, landings, discards, and VMS/iVMS in order to effectively monitor and control fishing activity.

Chapter 6 combines unpublished mark-recapture data and length-based sampling of European lobster in the northern Irish Sea to assess the likely impacts on harvests following an increase in MCRS from 87 mm to 90 mm CL. The analysis and results were used to support the Isle of Man Government public consultation on ‘the future management of the Isle of Man Crab & Lobster fisheries in Isle of Man territorial waters’ in 2020. The length-structured model assumed a closed population (i.e. no net-effect of migration on the fishery) and constant recruitment across years, as well as a constant growth factor and size-weight relationship among individuals in order to estimate;

1. the weight of forgone catch during the initial MCRS increase, and
2. the weight change associated with growth (moult increment) of the above individuals when they recruit to the fishery the following year.

The model was run under a range of scenarios that considered a single-step increase in MCRS as well as a phased approach that increase MCRS over a two year period. The model was also simulated with several different values for natural mortality ranging from 0.0 to 0.2. The value of natural mortality in European lobster in the northern Irish Sea is currently unknown, but will have an effect on the harvest benefits of increased MCRS as a proportion of the forgone individuals will die before they become available to the fishery again following moulting.

The model found that there are significant short-term reductions in harvest following an increase in MCRS from 87 mm to 90 mm CL, particularly if a single-step increase is adopted as opposed to a phased-approach. Nonetheless, in the medium-to-long-term there are harvest benefits from selecting larger, and heavier, animals in the fishery. The results suggest that long-term benefits of 2.4% to 6.5% increased harvest weight are achievable depending on natural mortality, and correspondingly it may take 6.4 to 2.8 seasons to recover the short-term losses respectively. The model also suggests a natural mortality rate of 0.31 would result in no long-term benefit from increasing MCRS, i.e. that if ≥ 31% of individuals between 87 mm and 90 mm CL die before they recruit into the fishery at MCRS equal to 90 mm CL, then the increased weight of survivors is less than the weight of the individuals that die. Whilst the literature suggests that natural mortality for European lobster is <0.15, regional evaluations of natural mortality, and discard mortality, will be important for assessing local-scale benefits of MCRS change for European lobster and other shellfish species targeted by static-gear fisheries.

Chapter 7 continues to assess the implications of size-selecting harvesting in the northern Irish Sea and focuses on the whelk fishery. The research summarises a small experiment that assessed the effectiveness of a ‘riddle’ device for selecting whelks above a certain size (70 mm total shell length, TSL), and how this corresponds to shell morphology. The riddle that is typically used in the Isle of Man territorial waters is designed with 35 mm gaps spaced between stainless steel bars in a table design; the setup is designed to facilitate the discarding of undersized animals through a discard chute that releases individuals back into the sea. A selectivity curve was modelled for this specific design across a size-range of individuals measuring 25 mm TSL to 115 mm TSL. The model found that $S_{50}$, i.e. the value at which there is a 50% chance of being discarded and retained, was 67.7 mm TSL and 36.2 mm $SW_{max}$ (maximum shell width). In the context of a MCRS of 70 mm at the time the research was undertaken, and subsequent increase in MCRS to 75 mm TSL to better equate to $L_{50}$ estimates, the conclusion reached was that riddle spacing should be increased by 1-2 mm for the Isle of Man fishery, and that local-level studies may be required elsewhere due to subtle variations in shell morphology of common whelk.

Despite there being a correlation and close approximation between TSL, $SW_{max}$ and $S_{50}$, the regulatory preference for enforcing MCRS in whelk fisheries has been to stipulate a prohibition on retaining undersize animals with certain amount of tolerance for some individuals being accidentally retained, as opposed to stipulating a requirement for a certain specification of riddle design. Fisheries enforcement can nonetheless use the data and results presented within this chapter to *recommend* certain specifications of riddle design in the Isle of Man. Recommendations for riddle design elsewhere in the Irish Sea and northeast Atlantic will require similar studies using local samples in order to calibrate riddle design to local morphological characteristics.

## 8.3 Recommendations for future research and management proposals & conclusions

- Continue to develop an evidence base for common prawn fisheries management in Welsh waters, particularly with a focus on understanding discard mortality and a stock-recruitment relationship;
- Consider stock assessment and fisheries management approaches for short-lived common prawn fisheries in Welsh waters;
- Develop a more complete understanding of spawning areas and spatial-temporal variations in spawning season dynamic for common whelk populations in the Irish Sea, and consider spatial management approaches to enhance protections for populations in these areas at critical times;
- Consider stock assessment and fisheries management approached for long-lived common whelk fisheries in the Irish Sea, building upon baseline population data;
- Continue to assess the accuracy of a temperature related effects on whelk population parameters outside the Irish Sea region, and highlight areas of concern for existing conservation measures (e.g. where estimated $L_{50}$ is below the current MCRS);
- Continue to gather EERS data for static-gear fisheries and develop insights on the drivers of variability in fisheries-dependent data in baited pot fisheries;
- Explore fisheries assessment and management approaches that are based upon standardised fisheries-dependent data;
- Harmonise and improve the logbook reporting requirements for all static-gear fisheries in the Irish Sea to include harvest, discards and fishing effort for each species, and develop technological solutions to improve spatial monitoring of all vessels (VMS/iVMS);
- Increase the MCRS of European lobster in the northern Irish Sea to 90 mm in a phased-approach so that MCRS is increased gradually over a period of two or more years;
- Evaluate the effectiveness of riddle designs throughout whelk fisheries in the Irish Sea and wider northeast Atlantic in relation to $S_{50}$ and $L_{50}$, and develop regional advice on riddle-design.

## 8.4 Conclusions

The series of works presented in this thesis address a broad range of research questions and themes within baited pot fisheries in the Irish Sea region. Many of the issues and themes are not unique to the geographic area, and the research has wider implications for fisheries management elsewhere in the British Isles and globally, particularly chapter 5.

Baited-pot fisheries around the British Isles have often been viewed as the ‘poor cousin’ when it comes to fisheries science and management compared to EU TAC and pelagic fisheries. Even in the Isle of Man, where assessment and management approaches have been well developed for king scallop and queen scallop mobile gear fisheries that are not managed by EU TAC, baited pot fisheries remain relatively absent of input and output harvest control rules.

Recent trends in increased effort and landings continue to highlight the growing importance of these fisheries, and the urgent need for evidence-based approaches to management. Whilst this thesis is not an exhaustive compilation of the information required to align fisheries management of baited pot fisheries in the Irish Sea with a ‘gold standard’, it;

- is a foundation that addresses some important knowledge gaps;
- highlights residual species-specific knowledge-gaps and general data deficiencies in fisheries reporting, and
- suggests a management approach in data-poor baited pot fisheries through the instruction of an EERS within a sentinel fleet.

## 8.5 The future of baited pot shellfish fisheries in the UK

According to the United Nations, total worldwide marine capture fisheries production has stabilised at around 80 million tonnes over the 30-year period between 1988 and 2018, however the number of fish stock being overfished continues to rise (FAO, 2020). Fish stock that are allowed to deteriorate through poor management and weak regulation lead to less food from the ocean and more harm to the long-term survival of ecosystems, which is a clear contrast to intensively managed fisheries that generally see a reduction in average fishing pressure and an increase in stock biomass (Hilborn, et al., 2020).

In the UK, pots and traps accounted for £170 million of landings (first point of sale) in 2019, which represented 43% of the total value of all shellfish landings and 17% of all wild-capture marine fisheries landed into the UK and abroad by UK vessels (MMO, 2020). Given the economic significance of this sector in the UK, the absence of formal harvest strategies and harvest control rules based on area-specific scientific survey and fisheries data is unacceptable. The only notable exception are fisheries targeting *Nephrops*, which are managed under the umbrella of a total-allowable-catch (TAC) set for the species by the EU/UK quota system supported by advice from ICES, which is largely dominated by landings from mobile-gear sectors (Ungfors, et al. 2013). Furthermore, a high proportion of vessels engaged in these fisheries are under 12 m in length, and are therefore not required to carry spatial monitoring equipment that is routinely used for management in fisheries worldwide. The other target species of these fisheries (most notably European lobster, edible crab, common whelk, and velvet swimming crab) are poorly understood on a fundamental biological level with respect to the interaction between stock, ecosystems, and commercial exploitation.

Overall, the future of baited pot shellfish fisheries in the UK is (at the time of writing) underwritten with significant risk of overexploitation resulting from i) suboptimal controls on fishing effort and landings across most jurisdiction and management areas, ii) lack of scientific programmes that support sustainable harvest strategies, iii) inadequate fisheries-dependent data with which to inform appropriate area-based management, and iv) poor governance structures that would otherwise enable effective co-management of these fisheries. If these barriers are not urgently addressed, the likely outcome will be a failure to maximise fisheries and conservation benefits in the short-to-medium term (Rees, et al. 2021) and possibly even fishery collapse in the long-term.

These challenges are not insurmountable, particularly as technological solutions become increasingly available and affordable for industry, researchers, and managers (e.g. iVMS, gear-in gear-out technology, mobile recording and monitoring). Indeed, the application of these technologies in baited-pot fisheries could be of great assistance to wider environmental monitoring and climate change research, for example where fishers may be able to submit accurate records of sea-bottom-temperature profiles throughout the coastal waters where fishing takes place. However, technological innovation is only part of the potential solution. Effective fisheries management also requires a scientific evidence base that is delivered through secure, long-term funding aimed at addressing the most critical questions with respect to stock status and marine ecosystem interactions, and ideally delivered through partnership with industry.

Under the new UK Fisheries Act (2020), the UK Government has committed to the delivery of fisheries management plans (FMPs) for each stock. If scientific evidence is insufficient to enable the delivery of a FMP, then the relevant management authority must take steps to obtain the scientific evidence necessary to enable an assessment of the stock's maximum sustainable yield in line with the 'scientific objective', which states that:

- Scientific data relevant to the management of fish and aquaculture activities is collected,
- Where appropriate, the fishery policy authorities work together on the collection of, and share, such scientific data, and
- The management of fish and aquaculture activities is based on the best available scientific advice.

In the context of this new primary legislation, the disparity between the relative economic value of the UK baited-pot sector and the lack harvest strategies (FMPs) underpinned by robust scientific data strongly suggests that these fisheries require significant investment in scientific and monitoring resources, delivered through co-ordinated, collaborative, and pan-jurisdictional efforts.

## 8.6 References

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