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The population biology of the spider crab, (Maja brachydactyla) in north Wales

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The population biology of the spider crab (*Maja brachydactyla*) in north Wales

A thesis submitted to the School of Ocean Sciences, Bangor University, in fulfilment for the requirements of the degree Master of Science by Research (MscRes)

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Prifysgol Bangor University

I hereby declare that this thesis is the results of my own investigations, except where otherwise stated. All other sources are acknowledged by bibliographic references. This work has not previously been accepted in substance for any degree and is not being concurrently submitted in candidature for any degree unless, as agreed by the University, for approved dual awards.

Yr wyf drwy hyn yn datgan mai canlyniad fy ymchwil fy hun yw'r thesis hwn, ac eithrio lle nodir yn wahanol. Caiff ffynonellau eraill eu cydnabod gan droednodiadau yn rhoi cyfeiriadau eglur. Nid yw sylwedd y gwaith hwn wedi cael ei dderbyn o'r blaen ar gyfer unrhyw radd, ac nid yw'n cael ei gyflwyno ar yr un pryd mewn ymgeisiaeth am unrhyw radd oni bai ei fod, fel y cytunwyd gan y Brifysgol, am gymwysterau deuol cymeradwy

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Abstract

The Atlantic Spinous Spider Crab (*Maja brachydactyla)* has increased in abundance in the coastal waters of North Wales over recent decades. Despite an array of anecdotal reports regarding the species in this region, there is very little research providing an insight into this, and substantial knowledge gaps regarding the ecology of the species. There is presently a low commercial market for the species in North Wales. This study uses local knowledge alongside 3 key sampling methods; one static gear (local pot fishery bycatch), and two mobile gear surveys (Newhaven dredge and 4m bottom trawl), to provide the first species-specific study in North Wales, with a total of 1118 individuals sampled from April to November 2022. This study found the highest abundances of *M. brachydactyla* from southern Cardigan Bay to North of the Llŷn Peninsula, with lower numbers of individuals in Liverpool Bay to the north. Estimated sizes at maturity for this study are 101mm (L_{50}) and 115mm (L_{90}), with ovigerous females present throughout the sampling period (April to September 2022). Gear type had a significant impact on the ratio of sexes caught, with baited pot fishing presenting significantly more male crabs than in mobile gear surveys. It is recommended that further research uses non selective gear types for population sampling. Using information voluntarily provided by industry partners, this study found that spider crabs are generally perceived negatively by fishers, viewed as a bycatch species. There are concerns the increased abundance of *M. brachydactyla* may be impacting benthic communities and commercially important species in North Wales. Observations of in-pot depredation of small lobster (*Homarus gammarus*) may indicate the possible impacts of spider crabs within the local crustacean fishery.

1-Introduction

The Atlantic spinous spider crab, *Maja brachydactyla (Brachyura, Majidae)*, is a large decapod crustacean that inhabits the waters of the Northeast Atlantic, from Northern Africa to the United Kingdom (Neumman, 1998). The species occurs across a variety of habitats, including rocky ground, kelp forests and sandy seabed, often utilising different habitats at different life stages (Corgos et al., 2011). A commercially-important species in European fisheries, *M. brachydactyla* was previously believed to be conspecific with *M. squinado*, a sibling species found throughout the Mediterranean (Neumann, 1998; Freire, 1999,). However, phylogenetic analysis by Sotelo et al. in 2008 using mitochondrial DNA (16S and COI) confirmed that the two are distinct species. Whilst range overlap occurs in the western Mediterranean, it is evident that the only species present in U.K. waters is *M. brachydactyla* (Rodriguez-Pena, 2020).

Despite this, oftentimes non-scientific literature and species guides can be unreliable, frequently still referring to *Maja brachydactyla* as *squinado,* for example in the Marine Conservation Society Good Fish Guide (2022). Older research papers also cite the former species name (*squinado*), and thus understanding of regional distribution is needed to determine which species is being referred to.

In comparison to other large crustaceans in British waters, the life cycle of *M. brachydactylya* is relatively truncated. Sexual maturity can be achieved ~2 years after initial hatching (García-Flórez and Fernández-Rueda, 2000; Andrés, 2010; Pazos et al., 2013), whilst in comparison, *Cancer pagarus* (brown crab) can take up to ten years to reach sexual maturity (Bennett, 1979; Brown and Bennet 1980). Spider crabs exhibit determinate growth, a characteristic not uncommon to crabs of the family Majidae (Ng and de Forges, 2015; Pazos et al, 2018). At sexual maturity, *M. brachydactyla* undergoes the terminal (sometimes called pubertal) moult at which point all ecdysis and external growth ceases fully (Sampedro et al. 1999; Hébert et al. 2002).

M. brachydactyla is known to exhibit strong seasonal changes in abundance, and population density. In regions where movements have been studied in detail, it has been shown that they undertake migrations in relation to mating and gonad maturation (Corgos et al, 2007). Spider crabs will mature and undergo the terminal moult in a region with a high abundance of food, before developing body condition for 2-3 months, at which stage a migration takes place to breeding grounds, often in deeper waters between 40-100m (Corgos et al, 2006).

1.1-Observations and current understanding

Well established, residential populations of *Maja brachydactyla* can be found from Angola to the South of the U.K and Ireland (Sotelo et al., 2007; Kergariou, 1984; Guerao et al, 2016). Around the U.K, the species exhibits a southerly distribution, with higher frequencies at lower latitudes, such as the South of England and the Channel Islands (Trundle et al., 2018, Blampied, 2022). North Wales and the surrounding waters historically have had some of the northernmost records of the species' range (Sotelo et al., 2008, Abelló et al., 2014). The earliest available reports of spider crab present in North Wales date from the early 1900s in northern Cardigan Bay, where the crab was believed to be 'rare', whilst the same source commented that it was "abundant" in more southerly waters (The Cambrian News and Merionthshire Standard, 1917).

Since the late 1900s to present day, a notable increase in abundance has been observed in north Wales (Fig. 1). Commercial fishers have reported that initially, 'a couple' of spider crab were present during the warmest months of summer, during the late 1980s - early 1990s (pers. comms, information volunteered by a pot fisherman involved in data collection, Llŷn peninsula). In the years following initial observations, numbers have increased considerably and spider crabs are now one of the most frequently occurring catches in the pot fishery at certain times of year (Moore et al., 2023). In recent decades, spider crabs have been reported to be most abundant during spring and summer months, exhibiting a clear fishing "season", a characteristic shared with other populations across the species' range (García-Flórez and Fernández-Rueda, 2001; Fahy and Carroll, 2009). Local fishers have reported that very recently, there has also been a change in temporal range and seasonality, particularly on the Llŷn peninsula (Fig.1), with some reports that the crabs were still present inshore throughout the winter months (as of 2022-2023). During the same year, it was reported that total catches of spider crabs were lower in the summer than previous years, an unanticipated change with little explanation thus far (pers. comm., 2023). The 'first' spider crab one fisher had personally caught in the Menai Strait was in 2022 (Moore et. al, 2023), after over 3 decades potting the area. This was followed by more individuals. These observations appear to be indicative of a further northward shift in abundance, from the aforementioned population increase in the waters around the Llŷn peninsula. However, most characteristics of the population in this region, and possible impacts of *M. brachydactyla* on the ecosystem and fishery are unknown and warrant further investigation.

From a fisheries perspective, the recent abundance of *M. brachydactyla* in north Wales creates a complex situation. Alongside its sibling species *Maja squinado*, *M. brachydactyla* is a significant target of the pot and tangle net fishery in Spain, Portugal and the South of France (Sampedro et al., 1999) with annual continental landings of around 6299 tonnes (as of 2010 FAO report). *M. squinado* is even classified as 'scarce' and 'endangered' in some parts of the mediterranean (Durán et al.,2013). In the U.K., *Maja brachydactyla* fisheries exist in the Channel Islands and the south coast of England, (Rodhouse, 1984; Trundle et al., 2018), whilst small-scale, commercial exploitation is also carried out in South Wales and the Republic of Ireland (Fahy, 2001).

In north Wales specifically, *M. brachydactyla* is generally perceived negatively by fishers, with some referring to the crabs as a 'pest' at times, but 'better than nothing' when fishing for target taxa is poor (pers. comms.) Spider crab has a low market value, currently reported as around £4.00 per kg when sold to restaurants, and only £15.00 per 'box' (~50kg), when sold as bait. There is little demand for spider crab as a food item, with local buyers showing preference towards brown crab (*Cancer pagarus*) and lobster (*Homarus gammarus*). Spider crabs do not survive well when being transported, particularly in comparison to brown crab and lobster, as reported by fishers who have previously had issues distributing spider crab, when trialling standard transport methods. As a result, exporting abroad or shipping to buyers in other regions of the country is difficult to accomplish successfully. Furthermore, for the same meat yield, the processing of *M. brachydactyla* takes up to twice as long than that of brown crab (reported by both fishers and wholesalers). Due to this, demand, and pricing must be high to make fishing for the species a commercially-viable venture. In a survey conducted by Bangor University in 2013, using fishers' local ecological knowledge across Wales, only one fished area for spider crab was reported in north Wales (region unknown for fisher anonymity), compared to a total of 20 fished areas in Mid and South Wales (Pantin et al., 2015). Although not the case in other fisheries, attitudes and resulting lack of market mean that spider crabs in north Wales can be labelled as a bycatch species, as reported by Moore et al. (2023). As a generalist forager (Bernardez et. al. 2000), *M. brachydactyla* are drawn to the same bait types used to fish for brown crab and lobster, meaning little can be done to prevent their attraction to pots. In some areas of the U.K., re-branding of the species is currently being undertaken to enhance local sales (i.e. Cornish King Crab in Cornwall, via the Cornish Fish Producers Organisation), although no such approach has yet been undertaken in Wales.

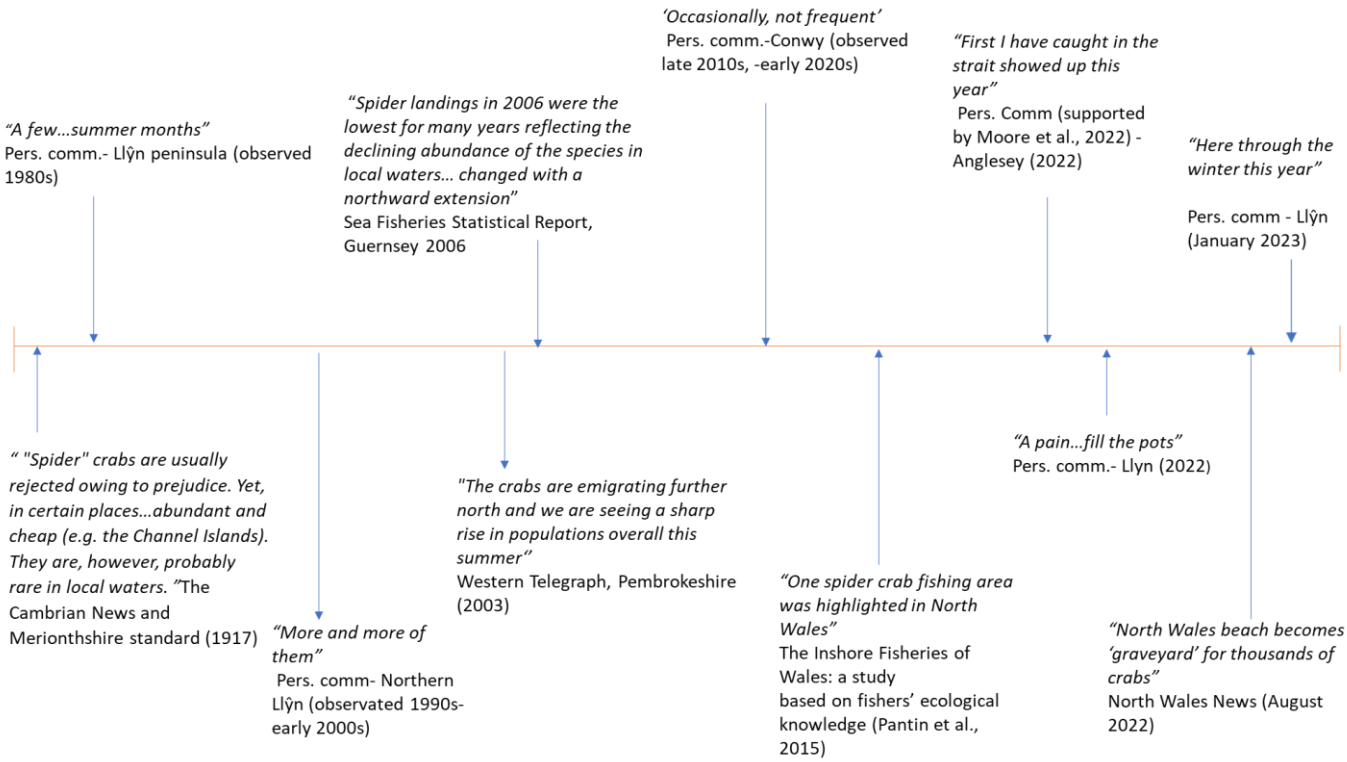


Figure 1. Timeline of observations of *M. brachydactyla* in Wales, through personal communication and reports via mainstream media, as well as reports and publications

The abundance of spider crabs is not only evident to stakeholders working in the fishing trade but has become clear to those who use beaches and inshore waters recreationally. Large aggregations of *M. brachydactyla* are often observed in shallow sandy waters. These aggregations, known as 'heaps' or 'pods', occur during both moulting and mating processes, in which large, hardened males will be found around the edges of the pods, to deter predation attempts (Degoursy, 1992; Sampedro et al., 2004, as *squinado*,). These aggregations are presently frequently observed in shallow, sandy waters off north Wales beaches, to such extent that they are highlighted in mainstream news (Fig.1, North Wales News, 2022).

1.2-Study aims

Despite the recent increase in abundance of *Maja brachydactyla* in the commercial fishery of north Wales, there has been no in-depth study of the population in north Wales. Evidence presented regarding the species in the region often refers to spider crabs as bycatch or as a secondary catch of the crustacean fishery. As described in Section 1.2, the Irish Sea is at the northernmost limits of the species' range, and the current reports from North Wales appear to indicate a range expansion outside of historical populations.

Existing knowledge of the species indicates that *M. brachydactyla* exhibits plasticity in breeding cycles across populations in its known range. In north-west Spain, *M. brachydactyla* regularly produce 3 broods in a single year, (González-Gurriarán 1998). In areas off France, this is often 2 broods a year (Kergariou, 1984), and it is believed that in the South of Ireland the crabs only produce one brood annually (Fahy, 2001). Due to this high variability across regions, assumptions about ecology, particularly breeding and migratory cycles of the species cannot be made using evidence from other areas, and thus region-specific data must be collected. As the study region (north Wales) is at the upper limits of the species' range, therefore it is likely that this population exhibits differing behaviours and ecology to populations found at lower latitudes.

This study will provide the first species-specific research into the population of the spider crab *M. brachydactyla* in north Wales. Sex ratios, female size at maturity, regional distribution and relative seasonal abundance are assessed, providing a basic understanding of the status of the population in the study area, and possible reasons for the recent range expansion into these waters.

Using the aforementioned anecdotal reports as a basis from which to begin data collection, data was gathered through 3 key sampling methods (See section 2.3). Using different sampling techniques is key for understanding how methodology can influence sample composition, as no established technique is in place for sampling the species in the study area. An analysis of data collection types, as well as communications with fishers, will help establish a protocol for sampling populations and understanding changes in the future. If, in the future, a commercial fishery for spider crab develops in north Wales, studies such as the present will provide a valuable insight into the opportunities and limitations this fishery may provide. Understanding abundance and behaviour of *M. brachydactyla* will also shed light on

possible impacts on presently commercially-important species, such as brown crab and lobster.

2-Methods

2.1-Data collection

Spider crabs used in this study were captured using multiple fishing techniques. Sampling was carried out opportunistically, through both commercial fishing activities and alongside other research fieldwork. *M. brachydactyla* is not usually targeted but often caught as bycatch in both commercial and research surveys. Pot fishing was the primary source of data (Section 2.1.1) and data collection was also carried out on two independent surveys aboard the R.V *Prince Madog*, (Section 2.1.1), in which spider crabs were a frequently-caught species. Study areas were Cardigan Bay, north Llŷn Peninsula and Liverpool Bay (Fig. 2).

Data collected in this study was supplemented by pot fishery bycatch data from 2020-2022 on the north Llŷn peninsula, as part of a survey assessing bycatch in the Irish Sea static pot fishery (Moore et al., 2023). These data enabled an enhanced temporal range to be surveyed in order to explore seasonal changes, however, often this data only provided total catch per unit effort with no sex or maturity status reported.

1- Liverpool Bay- Most northerly sampled sites during dredge and trawl surveys

2- Menai Strait- New reports from 2022 of *M. brachydactyla*

3- North Llŷn Peninsula- Pot fishing sites sampled April-September 2022

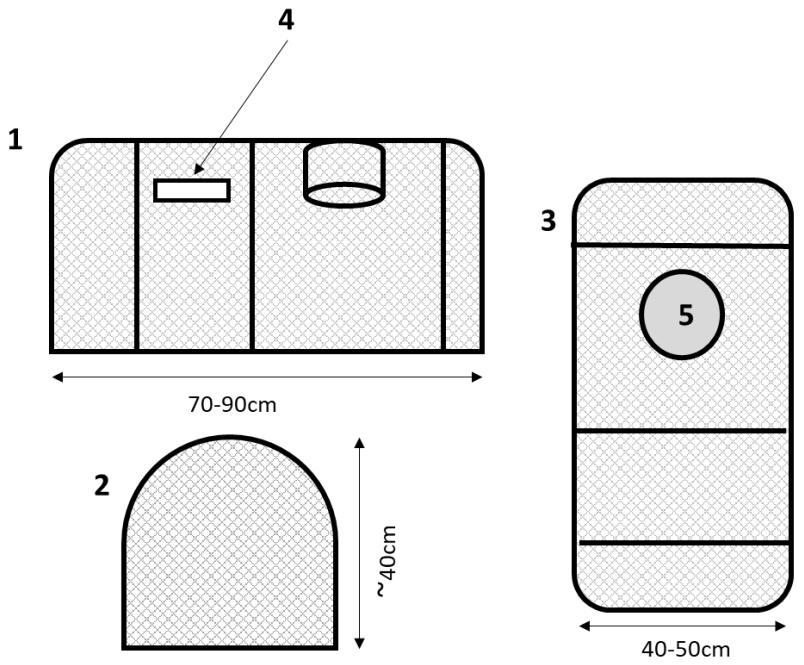
4- Cardigan Bay- key sampling site for trawl and dredge surveys and historical reports of spider crab

Figure 2- Key sites of sampling and reports of spider crab in north Wales. Note broad study area within Cardigan Bay. Map source Veemaps.com.

2.1.1-Pot fishing

Sampling was carried out during commercial fishing activities of fishermen off the north coast of Wales, from two sites on the Llŷn Peninsula, an area in which the species has increased in abundance in recent years (pers. Obs., comms w/ fishers). The crustacean fishery in the region primarily targets brown crab (*Cancer pagarus*) and lobster (*Homarus gammarus*), although spider crabs are a frequent bycatch (and may be termed 'secondary catch' if retained). Fishing was carried out using baited static gear, weighted traps (hereafter 'pots') with an array of baits, either salted herring/mackerel, or bycatch species such as bull-huss and catshark. Due to high variability and difficulty recording bait type after pots had been 'soaked', bait type was not recorded as a variable. The style of pot used is primarily the D-shaped parlour pot (Fig. 3). 'Soak' time of pots varied but was generally between 2-5 days in normal fishing procedures.

The sampling period (in which sex, carapace length, and maturity was assessed), ran from April to September 2022. Data collected was opportunistically, as an invited observer aboard potting vessels therefore this was often weather-dependent, but at the least was bi-monthly from April-September 2022. The number of crabs were recorded per pot and per string, allowing for a Catch per Unit Effort (hereafter CPUE), to be established. CPUE refers to the average number of crabs caught per pot in a denoted fishing period or effort, usually over a single day of hauling. Observations regarding weather, changes in bait or fishing style and other patterns described by fishers were noted.



1- Side view of pot in an upright position with broadest side visible- parlour located inside pot itself

2- End of pot- D-shaped with flattened, weighted base.

3- Topside of pot- 'eye' (5) may be on top or side of pot.

4- Escape gaps-not present on all pots but majority used in this study (generally 80mm x 40mm).

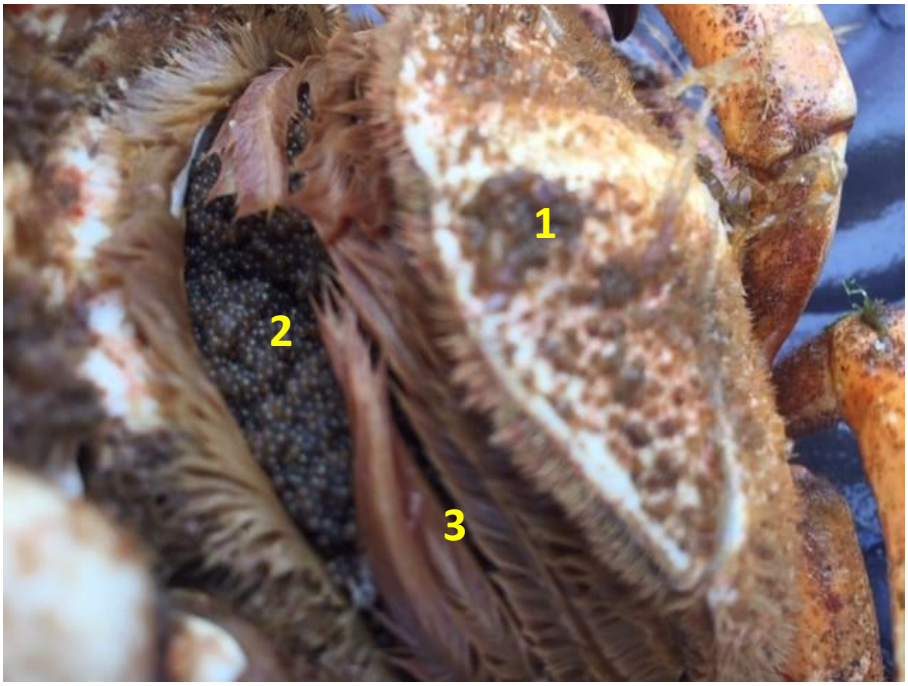
5- 'Eye'-entrance point of pot, can be hard plastic or soft meshing. Either top or side of pot.

Figure 3. Generalised crustacean pot (D-shaped) used to sample spider crabs. These are the most prevalent pot style in north Wales and specifically target brown crab and lobster.

Carapace lengths (measured to 1mm) of all caught individuals were taken using callipers on the dorsal side, from between the two rostrum spines, to where the carapace joins the abdomen at the posterior. Measurements using the tip of the rostrum may be inaccurate due to wear and erosion with age of the individual after the terminal moult (Corgos, 2006; Fahy et. al., 2009) and thus this method was avoided. For similar reasons regarding erosion and damage, as well as variability in spine lengths, carapace length rather than width is deemed a more reliable measurement for assessing size consistently (Corgos, 2007).

M. brachydactyla exhibits clear, easily observable sexual dimorphism. Both mature and immature male crabs possess proportionally larger chelipeds, and have a pointed, narrow abdominal flap that lies flat against the underside of the body. Females have proportionally smaller chelipeds, a domed, raised abdomen once mature, with well-developed pleopods under the abdominal flap, Immature females have a flattened abdominal flap, but comparatively much broader and less pointed than males (Teissier, 1933, 1935; Hartnoll, 1963; Sampedro et al., 1999). These characteristics allowed for immediate and reliable identification of individuals to be carried out, even when processing high numbers of crabs during busy fishing operations.

M. brachydactyla is a species that exhibits determinate growth, and at the terminal moult, females undergo a change in abdomen morphology, in which the abdominal flap changes from flattened to raised and domed, with well-developed pleopods, capable of retaining a clutch of eggs. (Fig 4). This morphological maturity is accepted to be a suitable estimate for female maturity (Baklouti et al., 2015), as the onset of gonadal maturity occurs within two months of the terminal moult (Hartnoll, 1963), and mating occurs once the individual is fully hardened (Verisimio et al., 2011; Corgos et al., 2010). Females maintain the carapace length attained during the terminal moult (Chang, 1995), and thus this study uses female abdomen morphology as an indication of maturity status. As with identification of sex, this allows for relatively large numbers of female crabs to be assigned a maturity status, with little likelihood of observer error, whilst processing large numbers of crab onboard during sampling efforts.



1. Domed abdomen structure used to retain eggs.

2. Fertilized eggs between ~125 000–~530 00 per brood (Verisimio et al., 2011)

3. Pleopods used to hold eggs in place, only visible in females (Guerao and Rotllant, 2009).

Figure 4. Eggs under the abdominal flap of an ovigerous female *Maja brachydactyla*. Domed abdomen morphology varies from flattened juvenile.

Ovigerous (egg-bearing) females were identified by lifting the abdominal flap to observe the eggs held by the pleopods (Fig 4). When initially fertilised, eggs exhibit a bright orange colouration, but in later development stages, the eggs change to dark brown and black, before becoming 'eyed' just before hatching development stages (García-Flórez and Fernández-Rueda, 2000). Eggs are fully covered by the abdominal flap, and so unless this is lifted it is very difficult to differentiate a non-egg bearing mature female from an ovigerous individual. After individuals were measured and identified, it was left to the fishers' discretion to release or retain the catch, if of landing size (130mm for males and 120mm for females).

2.1.2 Dredge and trawl surveys

Further data was collected from the annual RV *Prince Madog* scallop survey (methodology outlined in Lambert et al., 2012), carried out during April 2022. The gear used was four Newhaven spring-loaded dredges, two of 80mm belly ring size and two of 60mm ring size. Sites were selected based on previous data from scallop surveys, with a mix of sites, open and closed to dredging, around the coast of Wales. Sites stretched from southern Cardigan Bay to Liverpool Bay north of Anglesey. Due to this selection of sites, sampled areas were random in relation to known spider crab abundance. A total of 45 sites were sampled (Table 1), with the order of sampling based on ships' directional movements and windows in weather. Each site was dredged for 20 minutes at a time.

Using a similar approach, crabs were also sampled from a Welsh Government funded Skate survey conducted by Bangor University in August of 2022. Gear used was a 4m beam trawl, designed to target demersal fish towed for 3o minutes A total of 7 sites were sampled across Cardigan Bay, the Llŷn Peninsula, around Anglesey and Liverpool Bay (Table 1). As with the scallop survey, sites were random in relation to known spider crab abundance.

After removal from the trawl or dredge, all individuals were measured with callipers to the nearest whole millimetre using the carapace length measurement protocol explained in section 2.1, and sex and female maturity status was identified. During the scallop survey, each individual crab was weighed (to one gram), using motion-compensated scales for accuracy at sea. Recently damaged or killed crabs (during dredging) were recorded but crabs with severe damage to main body were identified and removed from further analyses, as this can impact total length data. All but 10 crabs from the scallop survey (retained for later

stomach content analysis, unpublished data) were discarded with other bycatch according to survey protocol and requirements of discards at sea.

Table 1. Summary of regions and dates sampled during mobile gear surveys on the R.V *Prince Madog* conducted in April 2022 and August 2022.

Location	**Dates sampled**	**No. sampling efforts***	**Method**
North Llŷn	25/04/2022 + 30/04/2022	3	Newhaven Dredge
Liverpool Bay	26/04/2022-27/04/2022	7	Newhaven Dredge
Cardigan Bay	20/04/2022-26/04/2022	35	Newhaven Dredge
North Llŷn	12/08/2022 + 14/08/2022	3	4m beam trawl
Liverpool Bay	19/08/2022	2	4m beam trawl
Cardigan Bay	12/08/2022 + 14/08/2022	3	4m beam trawl
South Llŷn	12/08/2022-13/08/2022	2	4m beam trawl

***20-minute dredge or trawl, timed from moment gear is on the seabed.**

2.2-Data analysis

Total observations from fishery-dependent and fishery-independent surveys were combined for analyses such as female size at maturity and overall abundance and carapace length, as these conclusions were not reliant on frequency of observations and collated data will produce reliable outcomes. However, representations of distribution were constructed only

from the fishery-independent observations, due to the limited spatial distribution of fishery-based data collection and the necessary requirements of anonymisation of fishers. Catch per unit effort denotes number of spider crabs per 20-minute dredge or per each hauled pot when using each method respectively.

Maps of distribution observed during each survey were creating using ArcGIS pro software, using total counts of males and females in each sampling effort (30-minute bottom trawl or dredge), and based off starting coordinates of the sampling effort. Four key areas were identified across both sampling methods, Cardigan Bay, South Llŷn, North Llŷn, and Liverpool Bay. These areas were established in order to allow for a comparison of abundance across latitudes.

For other analyses of data, results of length frequency, sex ratios and variation between gear types, analysis was carried out using R studio (R Core Team, 2023), with packages *plottrix*, *ggplot2*, and *rstatix* being key for statistical approaches and data organisation.

Size at maturity ogives were constructed for female crabs using proportions of morphologically-mature females within 5mm carapace length size classes. Proportions of mature female crabs were then plotted against the median value of each size class, fitted with a line (*geom_line)* and smoothed using *geom_smooth*, to create an S-shaped curve. From this, size at 50% maturity (CL_{50}) and 90% maturity (CL_{90}), could be estimated from the X intercept of the resulting plotted curve.

3-Results

3.1 – Distribution

During dredge surveys in March 2022, *Maja brachydactyla* was present in 36 of the 46 sampling sites (78% occurrence). Using CPUE, based off the number of crabs caught per 20-minute dredge or trawl period, as a measure of abundance, a high abundance was found across Cardigan Bay (average CPUE of 9.0) and North Llŷn, (average CPUE of 8.3) but ~~in low~~ abundance was low in Liverpool Bay (Average CPUE of 0.43) (Table 2). The bottom trawl survey conducted during August 2022 exhibited similar patterns, with the majority of crabs being caught in central Cardigan Bay and the north Llŷn peninsula (average CPUEs of 12 and 10.7 respectively), with the only site containing no crabs found on the Southern edge of Liverpool Bay, and the area having a CPUE of 0.5 on average. The highest number of

crabs identified in a single trawl from this survey was 29 (6 Males and 23 Females) caught in the south of Cardigan Bay, the most southerly point in which data was collected for this survey. Similar to the dredge survey, most sites presented both male and female crabs (Fig 5).

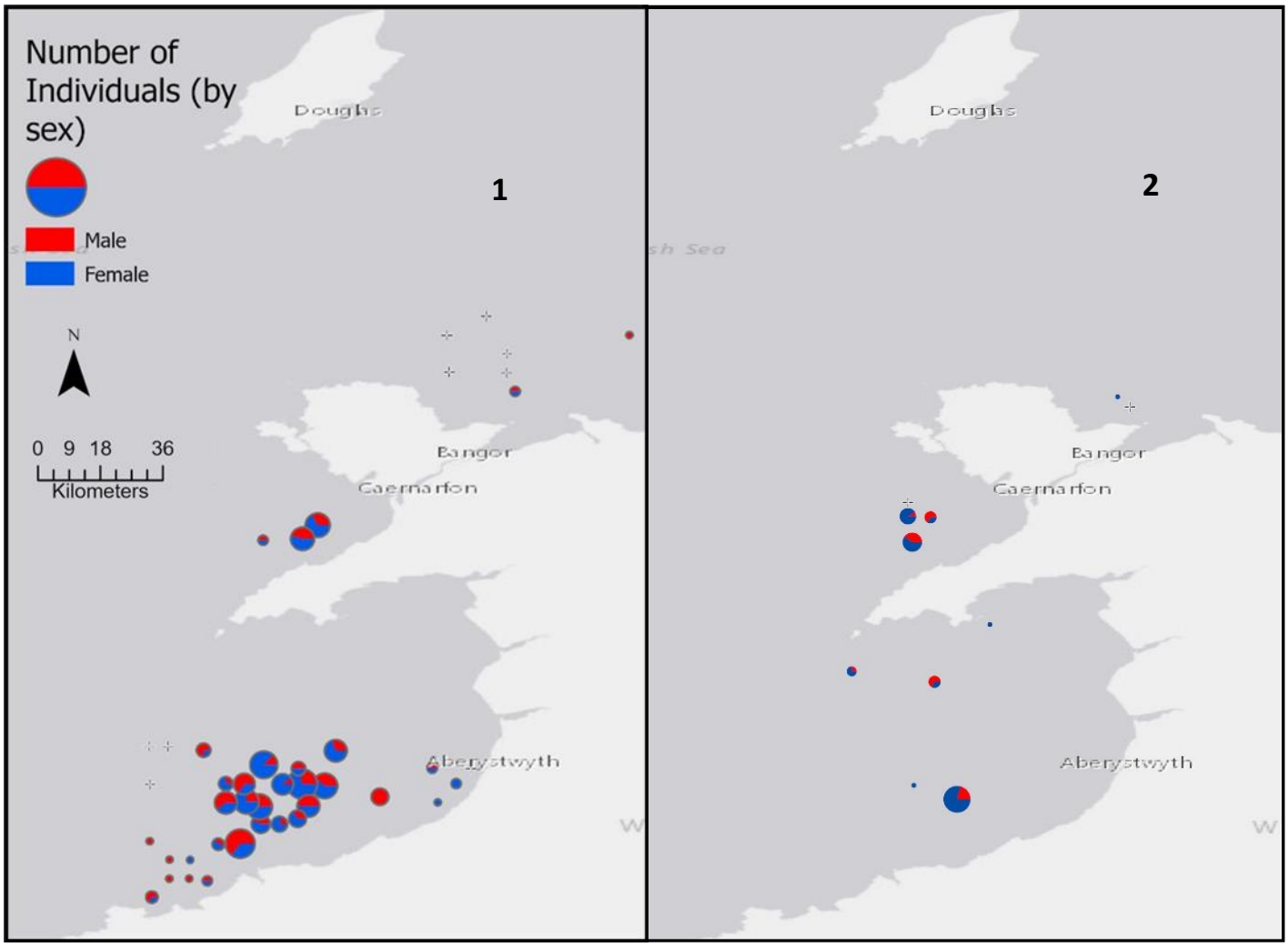


Figure 5. Total numbers of male and female *M. brachydactyla* sampled from a Newhaven style dredge survey in April 2022 (1) and 4m beam trawl survey in July 2022 (2).

Table 2. Catch per unit effort (CPUE) of *M. brachydactyla* during dredge and trawl surveys conducted in the Irish Sea in April 2022 and August 2022.

Location	Gear type	Total no. individuals	CPUE
North Llŷn	Dredge	25	8.3
Liverpool Bay	Dredge	3	0.43
Cardigan Bay	Dredge	316	9.0
North Llŷn	Bottom trawl	32	10.7
Liverpool Bay	Bottom trawl	1	0.5
Cardigan Bay	Bottom trawl	36	12
South Llŷn	Bottom trawl	5	2.5

***Unit effort: 30-minute dredge or trawl, beginning when gear reaches the seabed.**

3.2 Seasonal abundance

Fishery-dependent data from 2020-2022 to the north of the Llŷn Peninsula, using pots, appears to indicate generally higher abundances during spring (1.15 ± 0.15) and summer (1.93 ± 0.42) than those observed in winter (Fig 6). However, due to low numbers of sampling events, only one observed trip in winter and 3 in Autumn (often because of less weather windows), it is difficult to establish a clear conclusion from the observed data, although anecdotal data regarding seasonality is readily available from fishers (see 3.5).

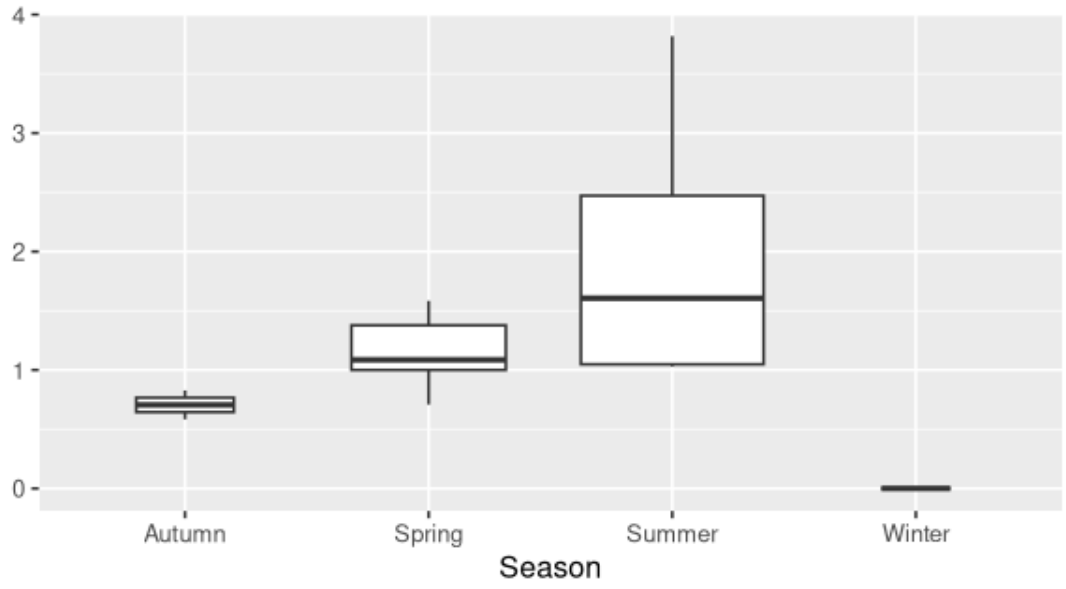


Figure 6. Seasonal catch per unit effort (CPUE) of *M. brachydactyla* caught in pots on the north Llŷn Peninsula, using bycatch data from 2020-2022. [Autumn n = 3, Spring n= 5, Summer n = 7, Winter n = 1]

3.3- Catch composition

3.3.1-Sex ratios

A total of 1118 crabs were caught across all methods (Table 3), comprising of 706 males and 412 females (Fig.7).

A Pearson's chi square test showed there was significant association between frequency of each sex caught, and fishing methodology ($X^2_{(2)} = 125.2$, $p < .05$). Pot catches consisted of 78.8%, male crabs, and only 21.1% females (of *n*=547). Dredges yielded a catch ratio of 58% female to 42% male (*n*=325), with trawl-caught samples at 57% male and 43% female (*n*=246).

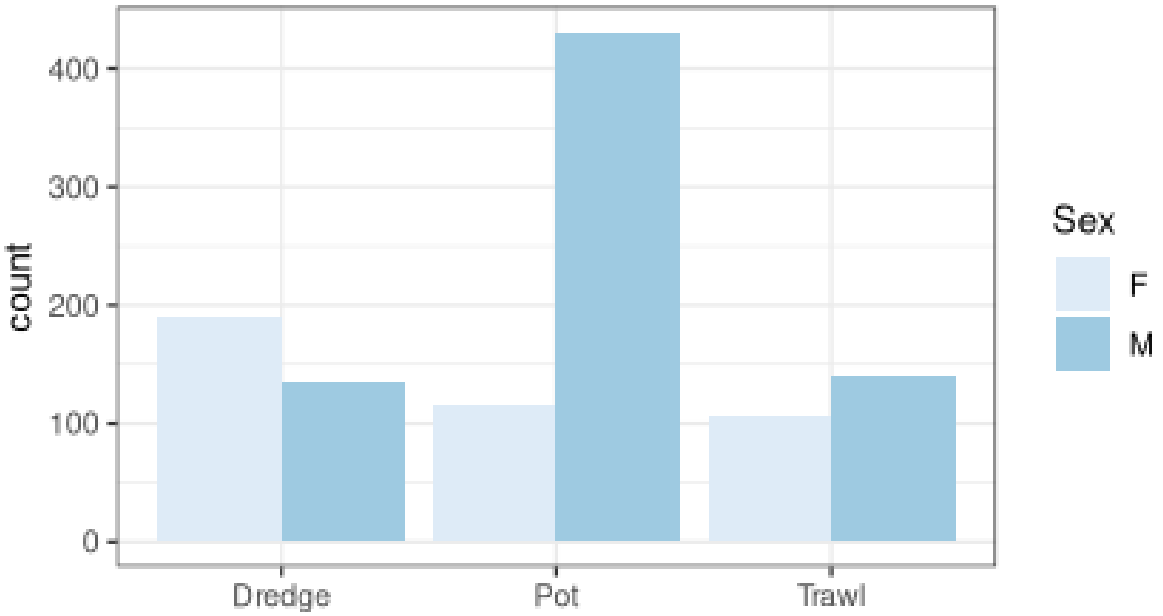


Figure 7. Total catches of male and female *M. brachydactyla* caught using Newhaven dredge, 4m beam trawl and baited pots**.**

Table 3 Total numbers of male and female *M. brachydactyla* caught using 3 different gear types, and percentage of overall samples. Surveys conducted from April to September 2022**.**

Gear Type	**Total *n* caught**			**Percentage of total crabs caught across all gear types**		
	Male	Female	Total	Male	Female	Total
Newhaven Dredge	136	189	325	**12.16%**	**16.91%**	**29.07%**
Pot	431	116	547	**38.55%**	**10.38%**	**48.93%**
4m Bottom Trawl	139	107	246	**12.43%**	**9.57%**	**22.00%**

3.3.2- Carapace length distribution

It was found that overall carapace length of caught crabs was normally distributed. (Shapiro-Wilk, *W = 0.96038, P> 0.05*) Using a two-way ANOVA with interaction effects, it was found that, independently, neither sex of crabs nor gear type had a significant impact on carapace length of caught crabs, (*P>0.005),* however, the interaction between these variables

was significant (*p= 0.021*). Following this, a Tukeys HSD test was conducted across groups of gear type and sex (Table 4).

When samples are combined from all gear types, there is no significant difference between mean carapace length of males (*M*=123.0 mm, *SD*= 18.7) and females (M= 122 mm, *SD=20.5)*, obtained during this study (t (797) = -1.02 p = 0.31). Whilst there was no significant difference in carapace length of males or total crabs between survey methods, the carapace length of females caught in pots, 128.5mm ± 0.97 SE, was significantly (t_{302} = -5.26, p <0.05) larger than those caught in dredges (119.8 ±1.31mm). Pot-caught females were also significantly larger (t_{130} = 3.53, p <0.05) than those caught in trawls (Table 5).

Trawl surveys exhibited the largest range of carapace lengths, with crabs ranging from 50mm to 225mm present in these catches. Pot fishing returned crabs from 72-158mm and dredge surveys 13-179mm (Fig. 8). The most common size caught in both pots and trawls was the 125-130mm size class, when both sexes are taken into account (Fig. 9).

Figure 8. Carapace length (mm) of male and female *M. brachydactyla* caught using in the Irish sea dredge surveys (April 2022) trawl surveys (August 2022), and pot fishery bycatch (April-October 2022).

Table 4. Mean carapace length (mm) of male and female *Maja brachydactyla* caught using dredge, pot and trawl surveys. T test result compares carapace length of males and females caught using each gear type independently.

Gear type	Female Mean CL ± SE	Male Mean CL ± SE	t-test of male and female Carapace length
Dredge	119.8 ± 1.31	123.6 ± 2.12	**NS**-(*t* (234) = -1.49, *p* = 0.136)
Trawl	117.9 ± 2.84	123.1 ± 2.29	**NS**-(*t* (218) = -1.44, *p* = 0.151)
Pot	128.5 ± 0.97	122.8 ± 0.59	***-(*t* (208) = 4.99, *p* = <0.005)

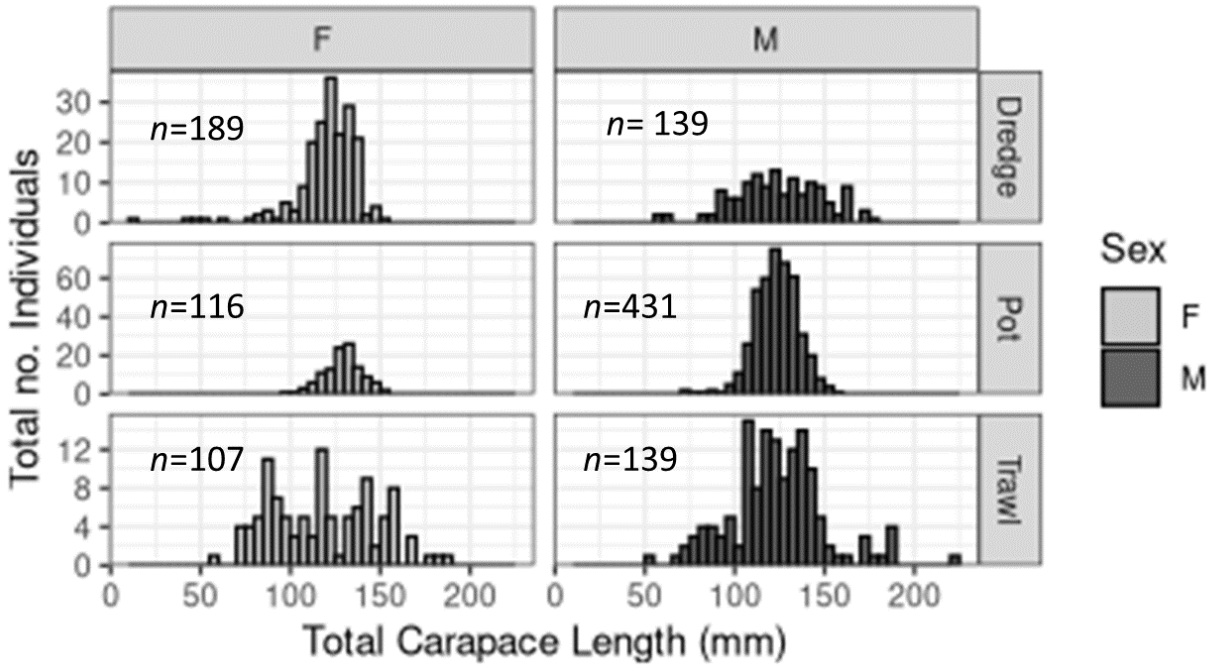


Figure 9. Size-frequency distributions of male and female *Maja brachydactyla* caught using dredge, pot and trawl surveys (bin size 5mm).

Table 5- Results from Tukey HSD test of carapace length of male and female *M. brachydactyla* caught using pot, dredge and trawl surveys

Gear Types	**P Value (adjusted, Tukey's HSD test)**		
	Male	**Female**	**Combined**
Dredge vs Pot	0.998	*0.002	0.259
Pot vs Trawl	0.999	*0.001	0.122
Trawl vs Dredge	0.999	0.955	0.880

3.4-Size at maturity and breeding status

Female crabs ranging from 13-186mm carapace length were assessed for size at maturity. This study found the size range of mature crabs was 83mm-186mm CL, with immature crabs ranging from 13-132mm CL, showing a broad range of sizes at which terminal moult may be undertaken (Fig 10). Mean carapace length of mature female *M. brachydactyla* was 121mm, whereas means of immature individuals was 95mm. Female size at morphological maturity was estimated to be 101mm for CL_{50} and 115mm for CL_{90} respectively (Fig 11).

Ovigerous females were caught in pots on all dates when an observer was present, from April to September in 2022. Eggs varied in developmental stage, however, it did not appear that developmental stage correlated to seasonal catches. Ovigerous females ranged in size from 98mm-186mm CL, with a mean of 129.6 ± 2.1 mm. This was larger than the mean CL of all mature females caught (116.4 ± 1.4 mm). Twenty three percent of all mature females caught over the survey period were ovigerous.

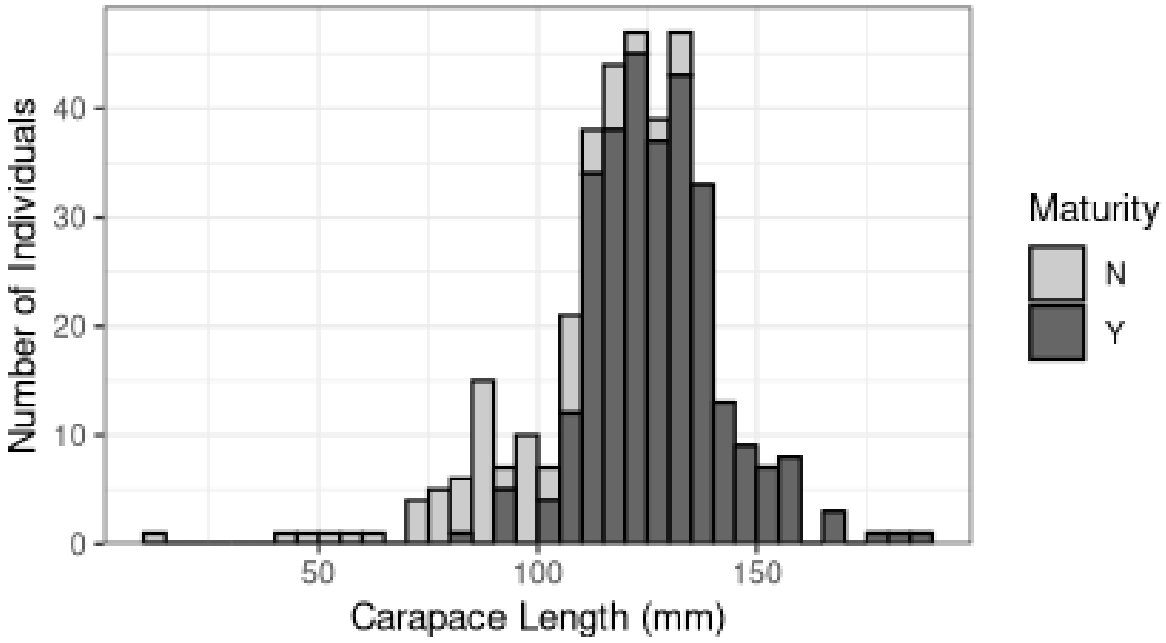
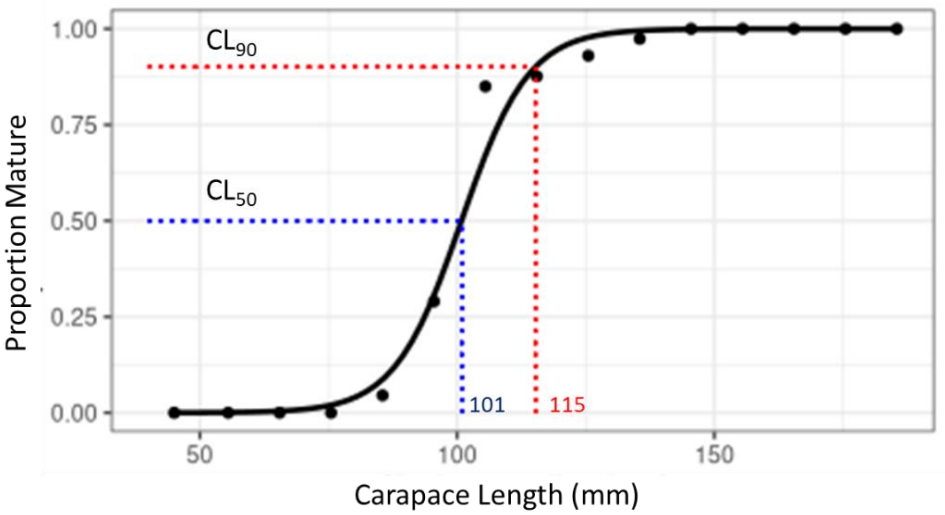


Figure 10- Stacked size-frequency of mature and immature female *M. brachydactyla* (*N*=373) observed in north Wales/ Cardigan Bay from April-September 2022. Note significant overlap between immature and mature females at the same carapace length.



CL_{90} -Estimate of size at which 90% of individuals are mature

CL_{50} -Estimate of size at which 50% of individuals are mature

Figure 11. Estimated size at maturity for female *Maja brachydactyla* in north Wales/ Cardigan Bay sampled from April-September 2022, based on abdomen morphology.

4-Discussion

4.1-Regional and seasonal abundance

The observed regional abundance of *M. brachydactyla* in this study supports the theory of a northward range expansion of the species in the Irish Sea. The frequency of individuals caught during mobile gear surveys within southern Cardigan Bay in the present study is to be expected as historically there has been a targeted and successful fishery for the crabs in this region (gov. Wales, 2014). In some regions of South Wales, the fishery has declined in recent years, with stakeholders holding the belief that the crabs were in fact likely moving north due to climate change and fishing pressures (Pantin et al., 2015). However, the results of this study show that the most southerly regions sampled (Southern Cardigan Bay) held a higher CPUE of crabs, for both dredge and trawl surveys than the northernmost regions (Southern Liverpool Bay/ North Anglesey). These catches support reports from fishers in northern regions, and it is clear that the large numbers of crabs observed off the Llŷn peninsula are now commonplace. The observations from the mobile gear surveys support the results by Moore et al. (2023) that report a lower bycatch per unit effort (BPUE) of spider crabs in Liverpool Bay compared to the Northern Llŷn peninsula. Similarly, a bycatch study focussing on Isle of Man pot fishing activities deemed the bycatch rates of *M. brachydactla* 'unimportant' (Öndes et al., 2017) and trawl bycatch surveys from 2014 (Bloor et al., 2015) recorded no *Maja brachydactyla* bycatch in a scallop dredging bycatch survey, in which all invertebrate bycatch were identified. It may be concluded from the information gathered from sparse literature and in this study, that species' range extends as far north as the Isle of Man, although in limited numbers beyond the Isle of Anglesey and into Liverpool Bay.

Poleward range expansion of temperate-distributed species is known to occur with warming global temperatures (Booth et al., 2011; Heath et al., 2012; Engelhard et al., 2013; Goodman et al., 2022), and climate change induced range shifts may occur up to 1.5 times faster in oceans than terrestrial environments (Burrows et al., 2011). However, it can be difficult to determine velocity of species' range shift based on climate patterns alone, and it has been determined that a multi-factor approach is necessary for estimating and understanding reasons for range expansion (Perry et al., 2007; Dulvy et al., 2009; Pinksy et al., 2013). In the northern hemisphere, it is understood that southerly-distributed species will more readily undertake a northern range expansion than northerly-distributed species will decrease their range, leading to changes in community composition and species interactions (Sorte et. al.,

2010; Bates et al., 2014). It may be true that warming ocean temperatures combined with lower fishing pressures in north Wales have led to the northwards range expansion of *M. brachydactyla*, resulting in large numbers in regions that historically only held brown crab and lobster. Competition between range-extending crustaceans and established crustacean species are believed to favour range-extending species, even more so than invasive species, especially in the long term (Lauchlan et al., 2019). Whilst *M. brachydactyla* occurs alongside the two key commercial crustacean species in multiple regions of the U.K, many of the benthic communities in north Wales have existed without the presence of large numbers of *Maja brachydactyla.* Therefore, the long-term impacts of the species' foraging behaviours are presently unknown.

Seasonally, observations seem to indicate that the species is most abundant in the inshore fisheries of north Wales during the warmer months of the year. As described (section 1.1), within its established range, *M. brachydactyla* is known to undertake migrations between depths, related to breeding and moulting cycle (Corgos et al., 2007). The patterns observed in this study and reported by fishers may be indicative of the same process in the waters of north Wales. The recent reports of a temporal change in abundance are possibly indication of a year-round inshore population (i.e. reports from January on the Llŷn peninsula, pers. Comms.). Climate change can influence residency time of migratory marine species, increasing time spent in one area if the conditions remain favourable (Poloczanska, 2013; Langan et al., 2021). It may be a possibility that *M. brachydactyla* is increasing inshore (shallow water) residency time and limiting migratory behaviours in accordance with beneficial water temperature conditions, however, lack of long-term catch data makes this difficult to quantify and more research is needed to understand temperature-related behaviours of spider crabs.

4.2- Influence of gear type and implications for future study

Gear type and sampling methodology are known in fisheries science to have significant effects on catch compositions (Tuda et al., 2016; Humphries et al., 2019; Anders, 2023). The results of the present study show that variation in gear type may lead to variations in both size-frequency distributions and sex ratios in spider crab catches. This is particularly evident due to the unintentional selectivity of both static gear (pots) and mobile fishing gear (dredges and trawls) used during the survey.

Behavioural traits of male and female *M. brachydactyla* in the presence of baited pots may have affected sex ratio of catches. Both unpublished labratory studies and *in-situ* field observations of the species by the author appear to indicate that males are more aggressive and active foragers than females of the species, exerting agonistic behaviours towards conspecifics in the presence of prey sources, deterring other males and climbing over the bodies of females. In contrast, females do not deter, nor are deterred by other crabs, either male or female. These observations are supported with findings by Rodhouse (1984), in which male crabs were observed as being more likely to enter pots than females. Furthermore, studies on a related species of crab (*Paralithodes camtschaticus,* the red king crab) indicate that males are less likely to attempt escape from baited pots, once entered (Zhou and Shirley, 1996). Therefore, the higher frequency of male crabs caught in pots (where bait is a coercing factor) in this study may be partially explained by sex-specific behavioural characteristics. The mobile gear surveys were not selective towards bait-motivated or explorative individuals and may provide a more accurate insight into the relative abundance of each sex in a given area.

Whilst males and females overall exhibited no significant difference in total carapace length, changes in gear type yielded variability in sizes caught (Table 4). The shape and size of the 'eye' of parlour pots used in the crab and lobster fishery in north Wales are often not wide enough to allow entry of the largest spider crabs, particularly males. Smaller crabs can also escape the pot through the mesh itself, or deliberately designed escape gaps, present on many of the pots used in this survey (fisher's discretion).

The pot styles frequently used in north Wales may mean that the largest and smallest individuals of *M.brachydactyla* are often not caught in the pot fishery itself. For this reason, it can be recommended that bycatch from the pot fishery alone may not provide a representative sample of population structure and relative abundance of *M. brachydactyla* in an area.

Large males, with long chelipeds and pereopods, can however reach through the mesh of pots, and are occasionally observed clinging to the outside of the pots when hauled (pers. obs.). In this study, females caught in pots were larger than those caught in dredge and trawls, and this may be due to their inability to reach through pot mesh, and so must enter to access the food source. There is little competition between females, nor are they deterred from pots by males, and so can freely enter the pot if able to fit through the entry point. It may also be

true that the proportionally smaller appendage size in females compared to males means that the constraints of a pot entry point do not have the same influence. Dredges and trawls possess entry points for the crabs, and thus larger individuals (over 200mm) can be caught using these gear types. In areas in which spider crabs are a key target, fishers often use a different style of pot, with a larger opening for access of larger males (Fig. 7) or use static tangle nets which are effective at capturing a wide range of sized individuals, dependent on mesh size (Fahy, 2001; Corgos and Freire, 2007).

Ideally, any future studies would assess the impacts of other gear types, such as nets or other static pot types, used for the commercial fishery. An opinion provided by fishers involved in the study, is that static tangle and gill nets yield the largest range of sizes of spider crabs inshore. Due to availability of weather windows for netting, only one sampling period was carried out in this study, which caught two female crabs, an unexpectedly low catch. This data was not included in the results due to lack of replication. For future research, tangle netting should be included alongside potting and mobile gear, to fully encompass the abundance and size distribution of female and male spider crab and sex ratios in the local population.

Figure 12. Inkwell style of pot used to target spider crab (Seafish, 2023), note large opening (eye) and conical pot shape, different to those used in this study (section 2.5).

4.3-Size at Maturity estimates and reproductive status

The size at maturity estimated in this study (for both CL_{50} and CL_{90}) appears to indicate that the present minimum landing size (120mm) for female spider crabs is appropriate. Size at maturity analysis using proportional maturity within binned size classes is beneficial due to the wide variation in size at which individuals may mature. Previous work has suggested that estimated size at maturity for female crabs can be inferred from mean carapace lengths of all morphologically-mature individuals, as *M. brachydactyla* ceases further ecdysis after undertaking this moult retaining this final size (García-Flórez and Fernández-Rueda, 2000). Therefore, these authors state that mean size at morphometric maturity is equal to the mean carapace length of all mature individuals. This approach results in 126.5mm mean carapace length at maturity, in this study, larger than the estimated size at maturity for CL_{50} and CL_{90}. In order for mean size at maturity to equal mean CL, researchers would have to be confident that the caught sample is fully representative of the size distribution of a population and does not contain a high frequency of larger-sized females, whilst underrepresenting smaller mature females. In this study, using proportions of mature crabs within size classes eliminates the chance of a skewed mean CL, and may be a more effective method of assessing size at maturity. The ranges of immature (13-132mm) and mature (83-186mm) sizes observed at which females attain maturity, show similar overlap to those described by Corgos et al., 2006, who find 25-169mm immature and 99-188mm mature.

It is notable that the only previous work regarding spider crab life history and abundance in north Wales was based on fishers' local ecological knowledge and in that study less than half of fishers surveyed reported that they had never seen berried spider crabs (Pantin et al., 2015). It is possible that reports using fisher observations may result in an underrepresentation of the numbers of ovigerous females, as it is unlikely that fishers would specifically check for eggs under the abdominal flap. The abundance of ovigerous females caught in pots in the present study, combined with aquaria-based observations (unpublished data) seems to provide evidence that egg carrying does not heavily impact the female's foraging tendencies, unlike other species such as *Cancer pagarus* (Naylor et al., 1999, Edwards, 1979., Haig et al., 2015). Although this will require further analysis using different gear types, it is likely that pot fishing can provide accurate estimations of ovigerous females within a population.

4.4- Fishery and ecosystem implications

The high abundance of *M. brachydactyla* observed in fishing pots in this study supports anecdotal observations by fishers that the species is impacting fishing activities. At the very least, high numbers of a non-target taxa increase pot sorting time (Page et al., 2013), reduce bait retention and attraction (Catchpole et al., 2006), and may increase rate at which pots become damaged (pers. comms). Furthermore, the observation of in-pot depredation on lobster confirms that *M. brachydactyla* is a predator capable of killing commercially-important species. In-pot predation of crustacea can be a significant driver of economic losses in static gear fisheries (Briceno et al., 2015; Milburn et al., 2023). However, in cases in which this was observed, the pot had been left 'soaking' for extended periods of time. From these observations it appears unlikely that spider crabs enter pots to feed on a captive lobster, and instead preyed upon the lobster when no other food sources were available within the pot. This may in fact be a scavenging behaviour on a deceased lobster. Due to the low number of these instances observed, it is not likely that the frequency of these predation events presently causes significant losses to fishermen in north Wales, although as-yet unknown future changes in abundance may affect this.

Male spider crabs exhibit agonistic behaviours towards conspecifics when presented with a food source (Rodhouse et al., 2006) and it is likely this behaviour also influences other species. Competitive interactions between benthic scavengers are rarely fatal, however, if strong defensive behaviour is exhibited, this is likely to impact total catches of conspecifics as well as deterring other species attracted to the bait source (Boudreau and Worm, 2012, Davenport et al., 2023). It is more likely that high numbers of spider crab consuming the bait in pots, and possibly deterring other species through agonistic behaviours, will be a more significant driver of the CPUE of target taxa than the aforementioned depredation within pots.

Alongside inter-specific interactions within the fishery, other impacts regarding established benthic fauna in the region are also a concern for fishery stakeholders. Large foraging crustaceans can have significant impacts on the composition and functioning of benthic ecosystems. As an opportunistic species, *M. brachydactyla*, and its sibling species *M. squinado*, have been observed feeding on a variety of prey sources, including hard-bodied organisms and bivalves with robust shells such as clams and mussels (Pers. comm.; Bernardez and Freire., 2000). In Jersey, reports of 'voracious' spider crabs having 'negative impacts on other species

such as brown crab and lobster', have made headlines (Jersey Evening Post, 2022). It is understood that during early benthic phase of development (EBP), crustaceans are particularly susceptible to predation (Ball et. al., 2001; Butler et al., 2006), and there is concern amongst fishers in north Wales that spider crabs may be predating on EBP brown crab and lobster. Studies on invasive species, (such as the shore crab *Carcinus maenas* in the United States) show that an abundance of an opportunistic forager can impact native populations due to predation upon post settlement juveniles (Macdonald, 2001).

The abundance of *M. brachydactyla* in north Wales offers an opportunity for an exploitable fishery for the species in the future. In comparison to the two main targets of the north Welsh pot fishery, brown crab and European lobster, spider crabs grow and mature significantly faster. From hatching, *M. brachydactyla* can attain sexual maturity within two years (Gonzalez-Gurriaran and Friere, 1994., García-Flórez and Fernández-Rueda, 2000) whereas it may take brown crab (*Cancer pagarus*) over ten years to attain maturity (Bennett, 1979., Brown and Bennet 1980), and lobster over 6 years (Sheehy et al., 1999). Currently, due to the low market values, targeting only spider crab is not commercially sustainable for most fishers in north Wales. However, the abundance and accelerated growth of *M. brachydactyla* may mean that, if managed and exploited effectively, spider crabs could be a comparatively more environmentally sustainable target than brown crab and lobster. Further understanding of fishery impacts on the population would need to be developed, the species is listed as 'OK' in the MCS Good Fish guide (Rating 3-4), with pot and creel methods earning higher sustainability rating than tangle nets. Only 6 sources of spider crab are listed, all in the south of England. The species is also classified as 'data limited'**.** Furthermore, if larger scale targeted exploitation were to be undertaken, drastic changes to marketing, distribution and elements of processing would need to be carried out. If issues regarding distribution and survival of spider crabs in transit could be managed, then this could open up a European market for export, one which may command higher prices than the current demand in Wales. However, it is more likely that the development of a local market, focussing on selling spider crab within north Wales, would be the more feasible option for future exploitation.

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Appendix

Table 1- bycatch data from crab and lobster pot fishing on the northern Llŷn peninsula, as part of a study by Moore et al., 2023.

Month	Season	No. pots bycatch recorded	CPUEtotal	CPUEM	CPUEF	Date
October	Autumn	81	0.8271605	0.53116049	0.296	17/10/2020
April	Spring	137	0.7080292		0.583942	21/04/2021
July	Summer	133	1.037594	N/A	N/A	07/07/2021
October	Autumn	36	0.5833333	N/A	N/A	06/09/2021
December	Winter	83	0	N/A	N/A	16/12/2021
April	Spring	108	1.5833333	1.15740741	0.425926	20/04/2022
April	Spring	106	1	0.57407407	0.425926	21/04/2022
May	Spring	140	1.0857143	0.72142857	0.364286	05/05/2022
May	Spring	122	1.3770492	1.13114754	0.245902	19/05/2022

June	Summer	33	3.8181818	3.61958182	0.1986	15/06/2022
June	Summer	32	3.125	N/A	N/A	23/06/2022
July	Summer	33	1.8181818	N/A	N/A	01/07/2022
July	Summer	33	1.6060606	1.48	0.12	06/07/2022
July	Summer	33	1.030303	0.79500891	0.235294	19/07/2022
July	Summer	34	1.0588235	N/A	N/A	28/07/2022

Table 2- Sites and total male and female crabs observed during the R.V *Prince Madog* scallop assessment survey during April 2022.

Site	Total Crabs	Male	Female	Long	Lat
27	17	11	6	-4.73743	52.19555
65	12	4	8	-4.53497	53.04368
61	11	5	6	-4.57468	53.00745
64	2	1	1	-4.67767	53.00345
75	0	0	0	-4.09463	53.59967
79	0	0	0	-4.09463	53.59967
76	0	0	0	-4.19762	53.54992
73	0	0	0	-4.04007	53.5
77	0	0	0	-4.19118	53.45167
72	0	0	0	-4.04168	53.44985
80	2	1	1	-4.01918	53.39997
74	1	1	0	-3.72043	53.55007

60	0	0	0	-4.97343	52.35322
43	0	0	0	-4.97595	52.45487
31	0	0	0	-4.92632	52.45452
36	4	3	1	-4.83317	52.44453
11	6	6	0	-4.3724	52.32038
46	2	1	1	-4.23588	52.39618
26	2	1	1	-4.23588	52.39618
47	0	0	0	-4.13418	52.39497
45	2	0	2	-4.17322	52.35545
48	1	0	1	-4.22127	52.30548
5	13	5	8	-4.51673	52.34935
33	18	5	13	-4.5758	52.35433
14	9	1	8	-4.6265	52.35347
6	10	5	5	-4.55922	52.29595
59	6	2	4	-4.5875	52.26203
57	5	1	4	-4.6348	52.24743
32	7	3	4	-4.68373	52.24798
9	13	5	8	-4.6872	52.29407
10	11	3	9	-4.72123	52.30728
53	10	6	4	-4.77508	52.30428
17	4	1	3	-4.77498	52.3552
25	9	6	3	-4.72678	52.35451
22	15	2	13	-4.67572	52.40565
40	4	2	2	-4.58517	52.39538
2	10	3	7	-4.48798	52.44282
7	3	2	1	-4.9685	52.05318
16	1	1	0	-4.92283	52.102
34	2	1	1	-4.82342	52.09642
51	3	1	0	-4.87097	52.10233
1	1	0	1	-4.86848	52.15205
27	1	0	1	-4.73743	52.19555
52	3	1	2	-4.7947	52.19387
44	1	1	0	-4.97398	52.20202
58	1	1	0	-4.92215	52.153

Table 3- Sites and total male and female crabs observed during the R.V *Prince Madog* skate and ray survey during August 2022.

Station	Long	Lat	Male	Female	Total
4	-4.52427	52.31727	6	23	29
5	-4.63807	52.3543	0	1	1
6	-4.62652	53.06713	4	2	6
1	-4.43755	52.7821	0	1	1
101	-4.58335	52.62967	4	2	6
6A	-4.64205	53.04733	6	9	15
7	-4.8016	52.65755	1	3	4
4B	-4.65358	53.06997	1	10	11
3	-4.10113	53.3877	0	1	1
77	-4.0688	53.36037	0	0	0
2	-4.65358	53.10692	0	0	0