A COLLABORATIVE STUDY TO DEVELOP AND FACILITATE A FISHER-DIRECTED STOCK ASSESSMENT OF *CANCER PAGURUS* IN THE INSHORE POTTING AREA, SOUTH DEVON.

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Thesis Abstract

The financial importance of the south Devon crab fishery was highlight by landings of 17,800 tonnes in 2010 (£18.9 million), approximately 59% of total UK crab landings. In recent years crab landings have increased and as such Bannister (2009) recommended 'a precautionary approach to future crab fishing' and 'the setting of management objectives to prevent any further increase in fishing mortality'. It is the responsibility of the MMO to achieve this as part of the EU target of setting catch limits to accomplish Maximum Sustainable Yield (MSY) in all fisheries by 2020. Despite this aims the authorities responsible for the enforcement measures to achieve MSY are grossly under-resourced. Thus an innovative and inexpensive method to create sustainable small-scale fisheries is a necessity.

Therefore the aim of this thesis, as part of the GAP1 and 2 Projects, was to devise a bottom up approach to create a sustainable fishery in south Devon using a fisher-directed stock assessment method and quota system, whilst working collaboratively with local fishers.

To achieve this aim we carried out the following objectives. We collected fine-scale data on catch, landings and discards gathered onboard fishing vessels over most of a year and 10 years worth of fisheries diaries this produced spatiotemporal mapping of crab distribution within the IPA. We performed semi-structured interviews answered by a subset of fishers to gather their Fisher Local Ecological Knowledge (FLEK). The results were then compared with empirical data and the scientific literature, which revealed that the FLEK was accurate and valid enabling its use in future management measures. Further we evaluated our approach of collaborative working, identifying the strengths and weaknesses of the style of research. We established guidelines for future researchers and fishers to work collaboratively.

The aforementioned data and knowledge was synthesised and evaluated as inputs to the Individual Based Model (IBM) of the fishery that was independently developed by P. J. B. Hart. The IBM currently enables its users to explore how the crab population and the fishery interact, as well as a tool that can be used to better understand the abiotic factors that affect the fluctuations in the fishery. In the future we hope the model will be able to output a sustainable quota of landings for the fishery. Finally, we produced a comprehensive plan of action to implement the future fisher-directed stock assessment and quota system into local management.

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Abbreviations

Abbreviation	Full Text
ABM	Agent Based Model
ANOVA	Analysis of variance
CEFAS	Centre for Environment Fisheries Aquaculture Science
CFP	Common Fisheries Policy
CFU	Crab Fishery Units
CPUE	Catch Per Unit of Effort
CSA	Canadian Sablefish Association
CSK	Conventional Science Knowledge
CW	Carapace Width
DAS	Days at Sea
DEFRA	Department for Environment Food and Rural Affairs
df	Degrees of Freedom
DFO	Canadian Department of Fisheries and Oceans
DNA	Deoxyribonucleic acid
DPUE	Discards per Unit of Effort
DSIFCA	Devon and Severn Inshore Fisheries and Conservations Authority
DST	Data Storage Tags
E-Logbooks	Electronic Logbooks
EC	European Commission
EMODnet	European Marine Observation and Data Network
EU	European Union
f	Fishing Mortality
FAO	Food and Agriculture Organisation of the United Nations
FAP	Financial Administrative Penalty
FD	Fishers Diaries
FDF	Fully Documented Fisheries
FIFT	Fishing into the Future
FLEK	Fishers Local Ecological Knowledge
FP7	EU's Seventh Framework Programme
GPS	Global Positioning System
HHM	Hidden Markov Model
IBM	Individual Based Model
IBM	Individual Based Model
ICES	International Council for the Exploration of the Sea
IDP	Inverse Distance to Power
IFCA	Inshore Fisheries and Conservation Authority
IPA	Inshore Potting Area
IVQ	Individual Vessel Quota
JAKFISH	Judgment and knowledge in Fisheries Management
KG	Kilogrammes
KLPUE	Kilogrammes Landings per Unit of Effort
KM	Kilometer

LCA	Length Cohort Analysis
LEK	Local Ecological Knowledge
LPUE	Landings per Unit of Effort
m	Mortality
m	Meters
MCS	Marine Conservation Society
MCZ	Marine Conservation Zone
MCZ	Marine Conservation Zone
MLS	Minimum Landing Size
MMO	Marine Management Organisation
MPA	Marine Protected Area
MPA	Marine Protected Area
MSARs	Monthly Shellfish Activity Returns
MSC	Marine Stewardship Council
MSY	Maximum Sustainably Yield
n	Sample Size
NAFC	North Atlantic Fisheries College
NTZ	No Take Zones
$^{\circ}$	Degrees of Arc
$^{\circ}C$	Degrees Celsius
ODD	Overview, Design concept and Details
PML	Plymouth Marine Laboratory
S.D	Standard Deviation
SCBCRABS	South Carolina Blue Crab Regional Abundance Biotic Simulation
SDCSA	South Devon and Channel Shellfishermen’s Association
SIG DIF	Significant Difference
SSMO	Shetland Shellfish Management Organisation
SST	Surface Sea Temperature
TAC	Total Allowable Catches
TEK	Traditional Ecological Knowledge
Tukey HSD	Tukey Honest Significant Difference
UK	United Kingdom
USA	United States of America
WEC	Western English Channel
wt	Weight
Z	Total Fishing Mortality

Chapter 1

Literature Review

A collaborative study to develop and facilitate a fisher-directed stock assessment of *Cancer pagurus* in the Inshore Potting Agreement, south Devon.

Introduction

In an attempt to reverse declining fish stocks and meet the requirements of the EU Marine Strategy Framework Directive and the reformed Common Fisheries Policy, scientists and managers should consider management systems that do not solely depend on top-down approaches (Blyth *et al.,* 2002). Only in recent years has there been a shift from top-down governance to the incorporation of fishers and other stakeholders into the design and implementation of fisheries management (Leite and Gasalla, 2013). In order to create and maintain sustainable fisheries, all stakeholders need to be educated to the necessity of management measures. Stakeholders should be helped to understand why management measures need to be implemented, and that the data used to assess the stock they fish is relevant. Most importantly, fishers need to be at least consulted on the construction of future management measures, which will ultimately govern the stock they exploit (Wilson *et al.,* 2006).

Despite the continual development and instigation of novel fisheries management measures and recovery of some stocks (Hilborn, 2012), the global trend of fish stocks has been in decline since the 1980's (Pauly, 2009). With exceptions, this decline continues, notwithstanding robust scientific knowledge of most aspects of fisheries science, industry involvement and management effort. The GAP Projects 1 and 2 recognised this disconnection between industry, science and management organisations and set out to bring cohesion between these stakeholders. The GAP Projects saw the development and implementation of 13 independent case studies around Europe, all with the focus of creating sustainable fisheries for the future.

The UK case study focused on the *Cancer pagurus* (Linnaeus, 1758) fishery in south Devon, and this thesis endeavours to develop and implement a bottom-up approach in which, fishermen participated in all aspects of the scientific and practical processes that contribute towards the establishment of a local and sustainable management regime.

Crab stocks and crab fishing around the UK

Cancer pagurus is distributed throughout the N. E. Atlantic from Norway to northern Africa, and from the sub-littoral zone to depths of 100 meters (Neal and Wilson, 2008). *Cancer pagurus* can be found throughout its distribution during all months of the year, however the abundance and composition of the catch can vary significantly through the seasons. Dense aggregations of *Cancer pagurus* support many fisheries around the UK, Ireland, Norway and France, with the major fisheries taking place around southwest England from Beachy Head to Lands End (Brown and Bennett, 1980).

Stock identification is an integral component of modern fisheries stock assessments, and in turn, is essential for effective fisheries management (Begg *et al.,* 1999). Stocks are notoriously difficult to delineate, but recently there has been a move towards defining crab stocks genetically. Logically, crab sub-populations which do not reproduce with each other will given time, develop genetic changes, which lead to the establishment of sub-populations or stocks (Ungfors *et al.*, 2007). Sub-populations are usually separated temporally or geographically and as result there is a degree of reproductive isolation and the appearance of differences in phenotypic and behavioural traits such as morphological differences, times of moulting and other life history differences. More importantly in terms of management, the structure and the fishing mortality of one sub-population does not impact another, and therefore management measures can be set for distinct stocks.

The Centre for Environment, Fisheries, and Aquaculture Science (CEFAS), the governmental agency responsible for fisheries science in the UK, bases the stock assessment of *Cancer pagurus* in English waters on 5 Crab Fishery Units areas (Celtic Sea, Western English Channel, Eastern English Channel, Southern North Sea, and Central North Sea) due to 'larval distributions and development, hydrographical conditions and distribution of the fisheries'. However, by their own admission CEFAS acknowledges that the defined Inshore Fisheries and Conservation Association (IFCA) management areas do not coincide with the biologically defined Crab Fishery Units, which can make management of the stocks 'challenging' (CEFAS, 2014).

Several studies mark-recapture tagging studies have reported that the *Cancer pagurus* in the English Channel are a separate stock from other populations around the UK. The first reports were from Brown and Bennett (1983), Cuillandre *et al*., (1984), Latrouite and Le Foll (1989), all arguing that 'tagging and landings data indicate that the areas of relatively high crab abundance in the Channel and in the North Sea are effectively separate'. Brown and Bennett (1983) stated that English Channel crabs did not move into the Celtic Sea. Later, Pawson (1995) reviewed the stock information for many species including *Cancer pagurus* and concluded 'that edible crabs in the Channel, northern Biscay and the Western Approaches should be treated as a single stock for management purposes.' Genetic analysis of nuclear and mitochondrial DNA by McKeown and Shaw (2009) concluded that there were significant differences between regional populations and that the '[English] Channel, and western and eastern North Sea regions should be considered as distinct populations'. These considerations reinforce the conclusion that the largest scale at which *Cancer pagurus* should be managed is the stock and not by arbitrary defined IFCA or ICES boundaries, as is the current situation.

The establishment of distinct stocks coupled with the large-scale movements of a species are factors to be considered during management decisions. Historically, mark-recapture studies have determined; migration and movement direction, speed of movement, time at liberty and mortality parameters (Brown and Bennett, 1979) and more recently Data Storage Tags (DST) (Hunter *et al.,* 2013), have elucidated parameters such as pressure (and thus tidal depth) and temperature experienced by crabs at liberty. T-bar tagging experiments by Brown and Bennett (1983) and more recently by CEFAS (2008-09) found overwhelmingly that female crabs migrate from east to west down the English Channel with 100% of the 49 recaptured DST tagged female crabs moving west at 14 out of 19 study sites (Hunter *et al*., 2013). Conversely, male crabs do not make the same migration and tend to move locally (Karlsson and Christiansen, 1996; CEFAS MF1103, 2008; Fahy and Carroll, 2008).

While CEFAS (2008) T-bar tagging data showed a predominant east to west migration of female crabs, the data can only reveal release and recapture locations and not add detail of the true route travelled by the crab to reach its recapture site. However, routes can be crudely reconstructed using DST tag data. These reconstructions demonstrated that, 'movement between release and recapture, does not depart appreciably from straight line movement' (CEFAS MF1103, 2008). However, the Hidden Markov Model (HMM) (Thygesen *et al*., 2008) used to reconstruct the crab routes, from temperature and tide profiles of the English Channel were designed for use with cod (*Gadus morhua*), therefore, the geolocations produced may not be reliable.

The mass migration of females is related to their reproduction (Pawson, 1995; Woll, 2006; Ungfors *et al*., 2007; Keltz and Bailey 2010) specifically their movements to the west, down the English Channel is explained by Sinclair (1988) and CEFAS MF1103 (2008) as a contranatant migration. CEFAS proposed that females migrate westwards against the prevailing northeast current, so the larvae released by females would drift north eastwards retaining the population in a favourable environment. To further support this finding, CEFAS MF1103 (2008) found that all (n=7) of the female crabs that were at liberty for longer than one spawning period, continued to move west with further spawning's, and none were recorded as making a return migration. These findings were possible as the crabs were caught while berried and re-released by fishers. Despite the small sample size these data gave a insight into the multiple years of migration for females. Eaton *et al.,* (2003) demonstrated that larval transport rates in the western Channel are insufficient to transport crab larvae from the western to eastern Channel, but are sufficient to disperse larvae within the western Channel.

Gear

A factor to consider when studying population dynamics in a fishery is the type of gear used to catch the targeted species and that species' interaction with the gear. UK crab fishermen use two main types of pots with local variations to catch *Cancer pagurus*: Inkwell and Parlour pots (Figure 1.1.). Inkwell pots are exclusively used to target crabs and parlour pots target crabs and lobsters (*Homarus gammarus*) simultaneously.

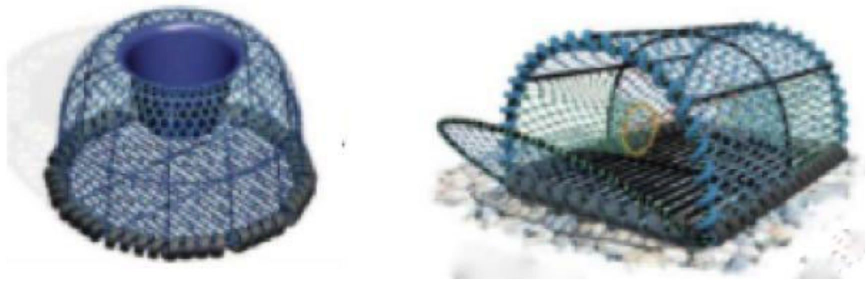


Figure 1.1. Inkwell pot (left) diameter approximately 0.66m, height 0.40m and a parlour pot length 0.66m, width 0.38m, height 0.38m (right). Source: Anon (2016).

The catch of a baited trap is the result of a series of interactions between the species attracted to the bait, the environment and the trap itself (Bennett, 1974a). There are other factors, which determine if a crab is captured, other than the individual's ability to detect and locate a baited pot. According to Watson *et al.,* (2009) these are 1) motivation to enter the pot i.e. level of hunger, moult stage, reproductive state and migration 2) interactions with other crabs, i.e. pot saturation, presence of other crabs and lobsters and dominance effects, 3) chances of escaping the pot before it is hauled.

Several experiments have set out to determine the range over which a baited pot attracts and captures crustaceans (Miller, 1978; Watson *et al*., 2009; Brethes *et al*., 1985; Skajaa, 1998). Watson *et al*., (2009), studied American Lobster (*Homarus americanus*) and found that 14 out of 25 lobsters approached a baited pot from a mean distance of 11.0m ± 0.7m. If the approach distance is treated as the radius of a circle then the range of a baited pot is 380m^2. Skajaa *et al*., (1998) used ultrasonic tracking to determine that *Cancer pagurus* began searching behaviour towards a baited pot from a distance of between 12 and 48m and 3 out of 9 crabs were captured when they began searching at a distance between 18 and 48m. All the above bait pot locating experiments used very low sample sizes. The distance range from which crabs are attracted to bait allows calculations of crab density to be estimated.

Passive crab pots exhibit a number of benefits; they capture live, high quality (undamaged) species (Cruz and Olatunbosun, 2013), and discards are widely thought to survive, as demonstrated in mark-recapture experiments e.g. Hunter *et al.*, (2013). There are few studies that solely focus on the impact of pots on the benthos *per se;* usually studies compare the impact of pots with other gear types (e.g. trawls). Nevertheless, Eno *et al.,* (2001) used video cameras and divers to established that potting gear had a low impact on the benthos. A criticism of this otherwise robust study is that the long-term effect of potting could not be established as the effect of pots on the benthos was only observed for between 3 days and 4 weeks. A negative impact of potting gear is the effect of ghost fishing. When pots are 'lost' at sea, due to bad weather or trawling, they self-bait and continue to fish for several years (Breen, 1990; Bullimore *et al.,* 2001; Arthur *et al*., 2014) until the netting degrades. Steps are being taken to develop biodegradable panels within pots to reduce the effect of ghost fishing to approximately 1 year (Bilkovic *et al.*, 2012).

There has been little research on the effect of pots on non-target species (Eno *et al.,* 2001) although Grieve *et al.,* (2014) stated that pots had a 'Minimal catch of non-target/non-commercial species' although he did not quantify 'minimal'. The non-target species captured by pots are predominately; European lobsters (*Homarus gammarus*), and other crab species, especially European spider crab (*Maja squinado*), green crab (*Carcinus maenas*), velvet crab (*Necora puber*) and common hermit crab (*Pagurus bernhardus*). Other species caught are: common whelk (*Buccinum undatum*), ballan wrasse (*Labrus bergylta*), pollock (*Pollachius pollachius*), pouting (*Trisopterus luscus*), cod (*Gadus morhua*) conger eel (*Conger conger*), and lesser-spotted dogfish (*Scyliorhinus canicula*) (Personal Observation).

Cancer pagurus is commonly caught as by-catch in other fisheries such as gillnets and trawls (Woll *et al.,* 2006). This is especially so in trawl and dredge fisheries with spring toothed dredges, demonstrating a catch efficiency of 19% for the target species King Scallop (*Pecten maximus*) yet a higher efficiency of 25% for the non-target species *Cancer pagurus* (Jenkins *et al.,* 2001). Further, *Cancer pagurus* is severely damaged when in physical contact with trawls and dredges but not actually caught (Jenkins *et al.,* 2001). These 'unobserved mortalities' are not caught and therefore are not recorded by any means as fishing mortality. This is a vital omission from stock assessments, as according to Jenkins *et al.,* (2001) as *Cancer pagurus* was observed by divers to be damaged nearly twice as often in the dredge track than captured in the haul. It is vital for a stock assessment to quantify these elements so as to be able to estimate the fishing mortality for a species from all gear types, such as catch, bycatch and 'unobserved fishing mortality'. This is especially important in areas where potting and mobile fishing gears are in operation in close proximity.

Current landings of crabs

In 2010, shellfish accounted for 25% (152,000 tonnes) of all fish landings in the United Kingdom by UK and foreign vessels with crabs contributing 30,000 tonnes (19%) of shellfish by weight. The English Channel has been the major crab producing area in the UK and Europe and accounted for 45% of the total European landings in the 1980s (Brown and Bennett, 1980). More recently, the financial importance of the south Devon fishery was highlight by reported landings of 17,800 tonnes in 2010 at a first sale value of £18.9 million (MMO, 2011), approximately 59% of UK total crab landings into the UK.

There has been a notable increase in the recorded UK crab landings from ~20,000 tonnes per year in 1994 to ~30,000 tonnes per year in 2010 (MMO, 2011). This rise in part can be attributed to the increase in voluntary landing reports submitted by the under 10m vessels. Before 2006, under 10m vessels were not obliged to declare their landings and therefore created an artificial rise in landings once they began to be reported.

Additionally, Bannister (2009) attributed the increase in landings recorded by the MMO to an increase in 'potting effort due to the modernisation of the inshore fleets, the advent of large mobile vivier crabbers, an extension of the inshore fisheries to offshore grounds and an increase in the number of pots.' Due to year on year increases in crab landings coupled with increased potting effort, and scarcity of scientific data on crab populations in the UK, Bannister (2009) recommended 'a precautionary approach to future crab fishing' and 'the setting of management objectives to prevent any further increase in fishing mortality in crab fisheries'.

Current management of UK crab fisheries

The EU legislation, which governs the seas of EU member states, is the Common Fisheries Policy (CFP). Within the UK this EU legislation was enacted as the Marine and Coastal Access Act (2009) and established the national body responsible for enforcing marine legislation including fisheries called the Marine Management Organisation (MMO). It is the ultimate responsibility of the MMO to achieve the EU target of setting catch limits to accomplish Maximum Sustainable Yield (MSY) for all fisheries by 2020 (http://ec.europa.eu/fisheries (2016)). This responsibility is delegated to the corresponding devolved administrations in England, Wales, Scotland and Northern Ireland. England has 11 regional Inshore Fisheries and Conservation Authorities (IFCA's), which are responsible, amongst other duties for managing the level of fishing effort applied to crab stocks within the 6nm limit. DEFRA and the MMO are responsible for the management of waters from the 6nm to the Exclusive Economic Zone (EEZ) limit at 200nm.

In UK waters *Cancer pagurus* stocks are managed by effort limitation and technical measures (Blyth *et al.,* 2002), although catch limits (called Total Allowable Catches (TAC)) or quotas are not used. To control the fishing effort of *Cancer pagurus* within the 6nm limit in English waters, local IFCA's use a shellfish-licensing scheme. A shellfish license is required by anyone wishing to fish with five or more pots, thus the IFCA could control the number of vessels and effort exerted upon the species. Currently, the scheme does not allow new entrants into English crab fisheries, and as a result new entrants must purchase licences and pots from fishers exiting the fishery or who want to reduce the number of pots they own. However, this method does not address the issue of latent capacity.

The technical measures that govern the management of *Cancer pagurus* within the 6nm limit of regional IFCA's jurisdiction are managed by over-arching national law set by the MMO and specifically designed local IFCA byelaws. In the Devon and Severn IFCA in which the south Devon fishery lies, there are six byelaws in operation to attempt to manage crab stocks to MSY.

1) The UK SI 2000 (No 2029): The Undersize edible Crabs Order 2000, decrees a Minimum Landing Size of 130 mm for crabs in waters around the UK to the 6nm limit, except for the following districts, where separate (larger) landing sizes apply: Eastern, Devon and Severn, Cornwall and the Isles of Scilly. It is therefore illegal to land *Cancer pagurus* below these sizes (apart from for scientific purposes). The Devon and Severn IFCA enforces a more stringent MLS for females at 150mm carapace width (cw) and 160mm for males. The implementation of these MLS's ensure that sexual maturity and 1 or 2 spawning(s) have occurred before the crabs are recruited to the fishery, in theory allowing time for the crabs to reproduce and 'replace' themselves before being vulnerable to fishing mortality.

2) It is illegal according to the Oyster, Crab, and Lobster Act of 1877 to land soft-shelled crabs, as female crabs can only copulate with males when they have recently moulted and are in a soft-shelled state (Fahy and Carroll, 2008). Both sexes of crab are not commercially viable when soft-shelled, as they have very poor meat yield (Edwards, 1979) and are consequently undesirable to fishermen, processors and consumers alike.

3) Legislation prohibits the landing of egg bearing females (called Berried), ensuring that females that have mated, and spawned eggs but have not yet hatched are not removed from the population along with their progeny.

4) UK legislation also limits the weight of crab chelae (claws) landed to a maximum of 1% of total weight of daily catch, and for mobile gear this can be no more than 75kg of crab claws per day. This legislation prevents the commercial declawing of *Cancer pagurus* for the lucrative, white meat, contained in crab chela. The de-clawing of crabs can reduce future growth increments (Bennett, 1973), as energy is diverted from overall body growth to the replacement of lost limbs. In addition these crabs are unable to protect themselves from predators, and are not able to easily catch and feed on prey.

The legislation for all discards stipulates that, they should be returned without injury into the water as near to where they were hauled as possible. This ensures that the natural spatial distribution of crabs is not distorted.

The current legislation that pertains to crab fishing gear and vessels states that:

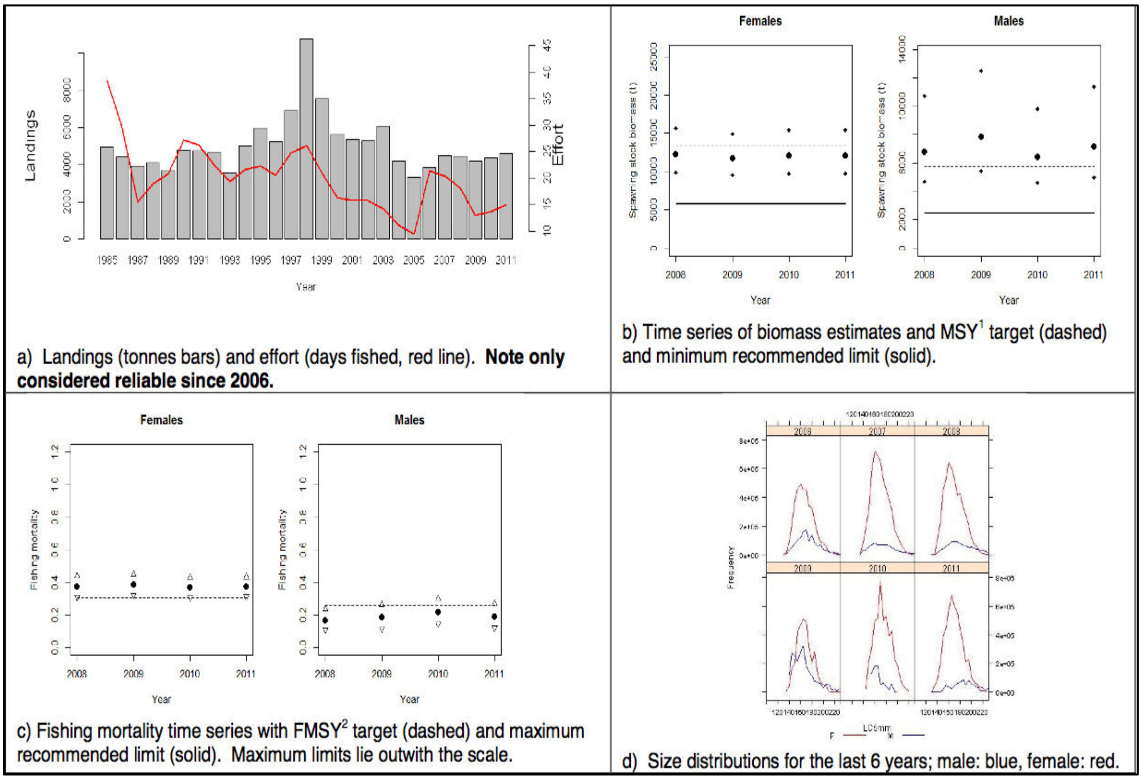
5) All parlour pots must contain escape gaps, to allow juvenile and undersized *Cancer pagurus* to escape the gear before it is hauled. Brown (1982) optimally designed the escape gaps at 38 x 74mm based on a MLS of 115mm (now 84mm x 46mm for a MLS of 150 and 160mm in the DSIFCA). The escape gaps are fitted on the lowest part of the exterior wall of the pot, and reduce the percentage of undersized *Cancer pagurus* in the catch by 34%, and increased the percentage of crabs over MLS in the catch by 125% (Brown, 1982). This increase of crab over MLS was attributed to pots being less saturated with undersized crabs. Therefore, fishers welcomed the use of escape gaps as they reduced the time that had to be spent sorting the catch and the measure also increased landed catch.

6) The Devon and Severn IFCA regulates the maximum overall vessel length to 15.24m within the 6nm limit. This restriction indirectly limits the effort within the district as the size of the vessels deck space restricts the number of pots, which can be hauled per string.

The most innovative byelaw in the management of *Cancer pagurus* in the IPA is the permanent and seasonal closures of fishing grounds to mobile gear (See 'The south Devon crab fishery').

As part of the shellfish licence obligation it is mandatory for all vessels to submit catch and effort information for each day at sea. Vessels under 10m in length are required to submit Monthly Shellfish Activity Returns (MSAR's) recording the kilograms of crabs landed by sex and by-catch per days fished. Whilst vessels over 10m must enter their catch details on to electronic logbooks (e-logs) at the end of each string of pots fished. These data are combined with data from a size-distribution sampling programme carried out by the IFCA and CEFAS to produce CEFAS Stock Status reports every 3-4 years.

The 2011 CEFAS Stock Assessment status for *Cancer pagurus* in the western English Channel, in which the IPA is located, was rated as 'green' for sustainable for all four factors that CEFAS use to assess a stocks sustainability: MLS, exploitation rates, discarding and stock size (Figure 1.2.). The assessment outlines that the current MLS enables 1-2 spawning's before crabs are landed, assumes that as discarded catch are returned to the sea alive, and there is a high level of survival. Further, the assessment advises that the exploitation rate and stock size of edible crabs in the western English Channel in 2011 generated catch levels around MSY, which is the aim set by the EU's CFP.



a) Landings (tonnes bars) and effort (days fished, red line). **Note only considered reliable since 2006.**

b) Time series of biomass estimates and MSY[1] target (dashed) and minimum recommended limit (solid).

c) Fishing mortality time series with FMSY[2] target (dashed) and maximum recommended limit (solid). Maximum limits lie outwith the scale.

d) Size distributions for the last 6 years; male: blue, female: red.

Figure 1.2. The 2011 CEFAS stock assessment outputs for the western English Channel (CEFAS, 2014).

Length Cohort Analysis (LCA) (Jones, 1990) is used by CEFAS to assess the status of *Cancer pagurus* in English waters. This model produces estimates of Maximum Sustainable Yield (MSY) and the fishing effort required to produce such a level.

The LCA uses fisher self-reported MSAR's as in index of abundance, combined with 'length' measured as carapace width, growth rate estimations and the rate of natural mortality, to establish population size and total mortality. The LCA was specifically developed for species such as crustaceans that cannot easily be aged, and are instead separated into length classes (Jennings *et al*., 2007). The advantage of employing LCA to manage *Cancer pagurus* fisheries is that in a single species fishery, exploited by one group of fishers, using the same fishing method, it can provide, in principle, a quantity of crab that could be removed from the fishery sustainably. Conversely, the disadvantage of using LCA is that many of the parameters employed in the model have high uncertainty. For example, CEFAS uses a fixed estimation of natural mortality in *Cancer pagurus* populations of approximately 20% (m=0.2). This value for natural mortality is used widely in fisheries management, but the scientific evidence for the use of this value is at best poor. Research by Sheehy and Prior (2008) found natural mortality to be 0.48 and the LCA does not accord for the aforementioned 'unobserved mortality' caused by trawling. Further, varying rates of natural mortality inputs into the LCA model have significant repercussion for predicted estimates of sustainability (Addison, 1989). Moreover, due to the discontinuous growth of *Cancer pagurus* and the lack of correlation between carapace width and age, the growth rates of the species (as well as all other crustaceans) are very difficult to determine (Sheehy, 1996). The establishment of accurate growth parameters are paramount to produce accurate stock assessments. Maximum Sustainable Yield treats recruitment as a constant and does not take into account changing environmental conditions and natural fluctuations in recruitment, resources or mortality. Furthermore, MSY treats all individuals within the model as identical and does not account for varying mortality, growth or rate of reproduction within different age classes. Estimating stock sustainability using LCA does not take into account any illegal, unregulated, unreported, or discard data and does not incorporate fisher knowledge.

CEFAS produced stock assessments in 2011 and 2014 (CEFAS, 2016) with 3 years between reports. It could be argued that this time frame between assessments is too long. Recruits enter the fishery at 4-5 years of age (Sheehy and Prior, 2008) and therefore at the current frequency of assessment, early changes in population size structure would not be detected. An additional criticism of CEFAS' stock assessment method is the number of crabs sampled to measure carapace width distributions (Table 1.1.). The total number of crabs sampled for the assessment in 2014 was 5669. This number of crabs would be caught by one vessel in approximately 3 days at sea during high season, so cannot be a representative sample of a 17,000 tonnes per year fishery, let alone the landings of the Western English Channel. Further, the 5669 individuals were sampled on just 43 separate occasions over 3 years and CEFAS does not disclose their sampling strategy, for instance as there is a correlation of carapace width with sea depth (Brown and Bennett, 1979) are samples stratified for the depth at which the crabs were caught?

Table 1.1. The number of crabs, number of samples and sampled weight (kg) recorded over 3 years for inclusion in CEFAS stock assessment 2014.

Year	Number of Crabs	Number of Samples	Sampled wt (kg)
2011	3412	34	3246
2012	2103	20	1659
2013	3566	23	2907

Once CEFAS has produced a stock assessment for each of its 5 Crab Fishery Units they are disseminated to the corresponding IFCA's, the MMO and DEFRA and used to design and legislate for local and national management measures. This process typically takes 1-2 years to complete. During this time the fishery could have collapsed, notwithstanding the time also necessary for new management measures to have an impact upon the crab population. CEFAS' approach to stock assessment could be improved by a fisher-directed stock assessment to collect a larger localised, real-time set of landing and discards data and FLEK.

The successful implementation of any management measures ultimately lies with the voluntary adherence to the measures by stakeholders and to a lesser extent with the prosecution of transgressors. As the voluntary adherence to management measures by the majority of fishers is paramount for ultimately attaining MSY (Wilson *et al.,* 2006), the communication and explanation of current stock assessment statuses to fishers and other stakeholders is key for their understanding of the importance of adhering to measures. The way in which the stock assessment is presented to fishers by CEFAS, could be improved upon (Personal Observation), an effectively communicated assessment (using non-fisheries science language) might help fishers understand the mechanics of the stock assessments and increase their level of engagement with the process.

The IFCA's are notoriously under resourced and as such are not able to prosecute a high percentage of transgressors. For example, in the last 5 years there have been just 11 fines issued in the form of a Financial Administrative Penalty (FAP) ranging between £250-3480, and four cautions, in the Devon and Severn IFCA. All transgressions, which were investigated during 2014 (n=6), are still on going (Personal Communication, Mat Mander, D S IFCA). These outcomes highlight the need for alternative management measures, which may be more successful than a top-down enforcement, in which fishers currently have no input.

To date, there has been minimal research into the sustainability of crab fisheries in UK waters on a more specific spatial scale than the 'western English Channel' or ICES area VIIe in which, one of the UK's major crab fisheries operates, the south Devon crab fishery. Therefore, the degree to which commercial crab exploitation is affecting crab stocks is difficult to quantify (Bannister, 2009).

Past studies on the dynamics of crustacean fisheries in the English Channel

The seasonal and spatial variation of catch, landings and discards of *Cancer pagurus* have been well documented (Edwards, 1979; Brown and Bennett, 1980; MF1103, 2008). To date the only edible crab population research specifically off south Devon was a 10-year long CEFAS study by Brown and Bennett between 1967-1977. At this time, 85% of the crab caught per year was landed between June and November (Brown and Bennett, 1980), with the highest mean monthly Catch per Unit Effort (CPUE) recorded in October at 265 kg per 100 pots, and the lowest CPUE in March at 24 kg per 100 pots (Figure 1.3.).

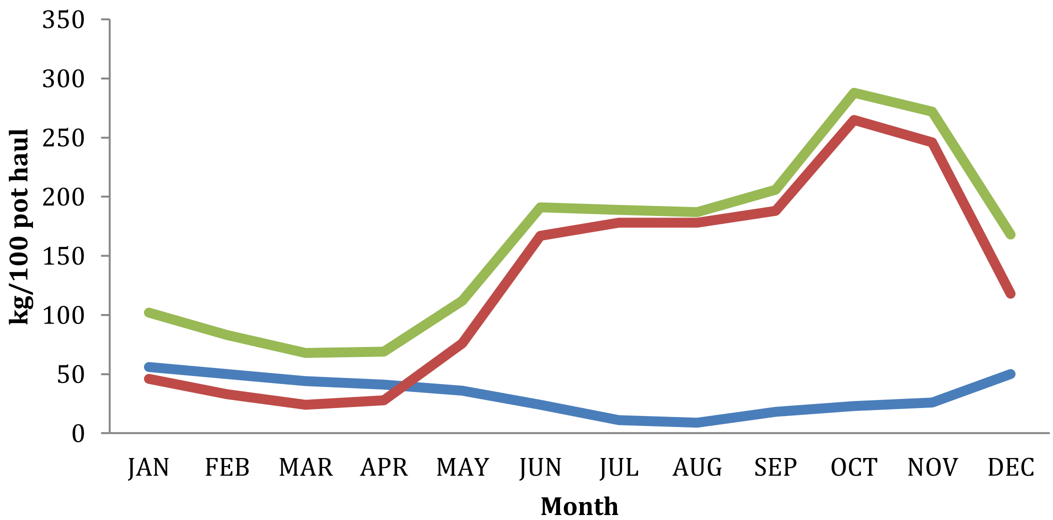


Figure 1.3. The catch of male (cocks), female (hens) and total Cancer pagurus as kg/100 pots hauled from 1971 to 1976 grouped by month. Source: (Brown and Bennett, 1980). Blue= Cocks, Red= Hens, Green= Total.

There is significant variation in the sex ratio landed throughout the year (See Figure 1.4.). Brown and Bennett (1980) found that the ratio of male to female crabs varied from 1:1 in March/April, to 96% females in August. This variation in temporal landing composition is strongly related to the female reproductive cycle. During the winter and spring months very few females are caught as they become largely inactive and buried in the seabed, in order to brood their eggs (Brown and Bennett, 1980). During this time they do not forage, and consequently their catchability is drastically reduced.

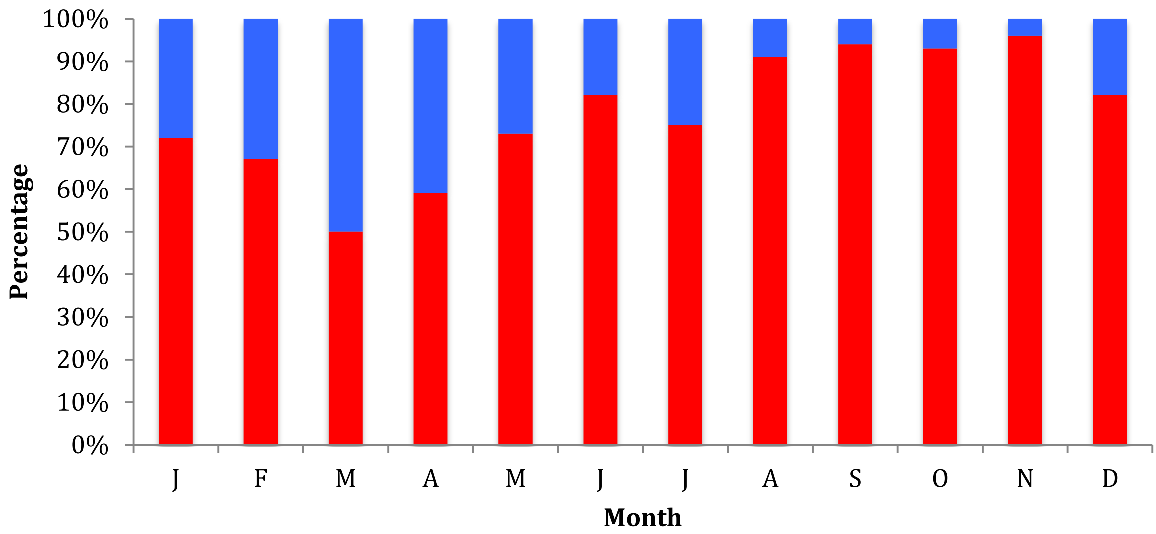


Figure 1.4. Mean monthly percentage of males and females of Cancer pagurus caught from one set area off Dartmouth between 1968 – 1975 (re-drawn from Brown and Bennett, 1980). Red: Females, Blue: Males.

The sex ratio of landed crabs also varies spatially. Brown and Bennett (1980) demonstrated that there was a higher proportion of female to male crabs in the western English Channel (Mounts Bay) compared to the eastern English Channel (Swanage) due to reproductive behaviour and the resulting migratory movements of females (Figure 1.5.). This phenomenon could be attributed to the depth and temperature gradient in the English Channel (Woll, 2006), with deeper seas in the west and shallower seas in the east (Coggan and Diesing, 2011).

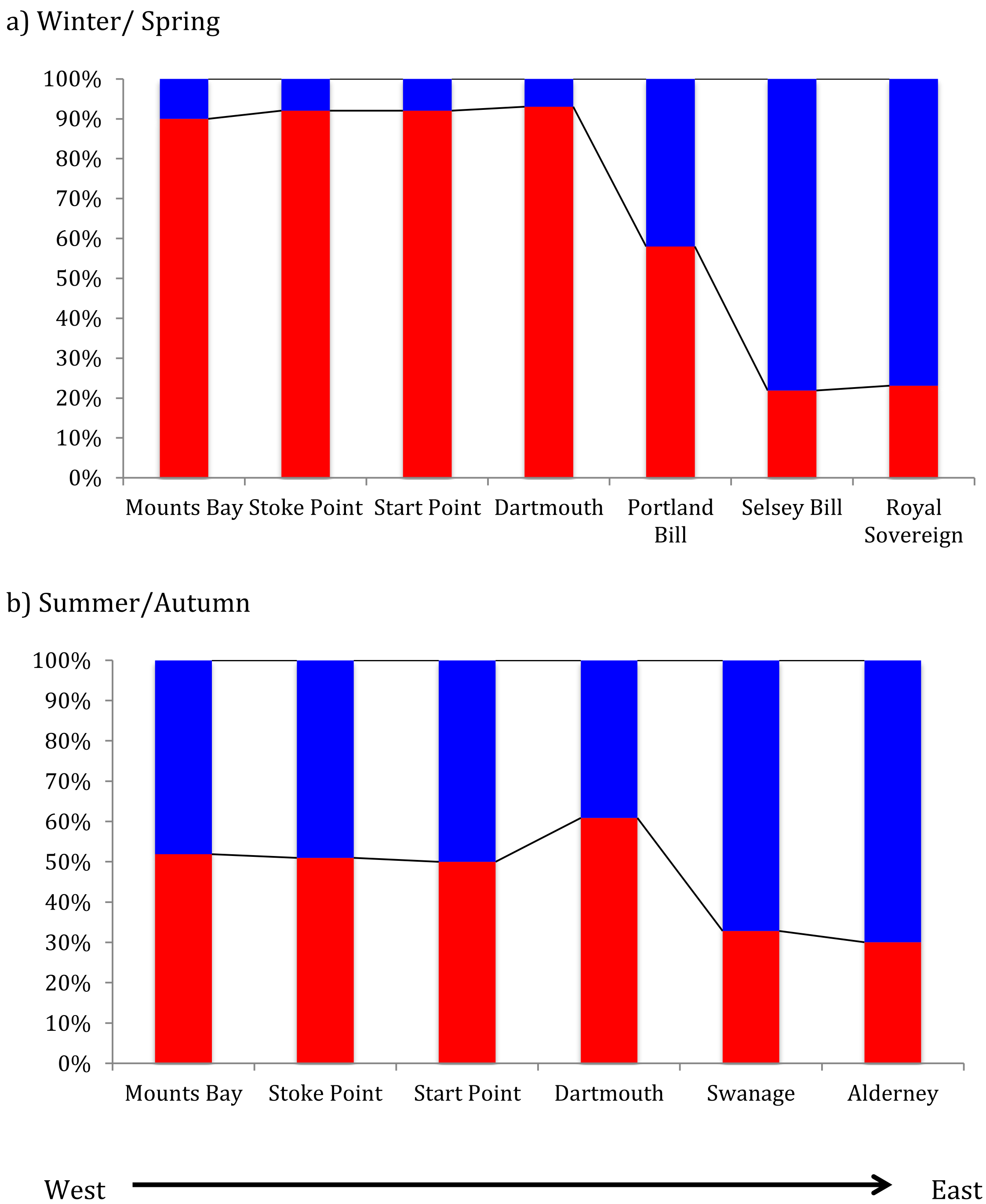


Figure 1.5. a) The sex ratio of male and female Cancer pagurus plotted from data collected from west to east along the English Channel, grouped between 1971 to 1976 for the months of December to May, b) The sex ratio of male and female Cancer pagurus plotted from data collected from west to east along the English Channel, grouped from 1971 to 1976 for the months of June to November. (Re-drawn from Brown and Bennett, 1980). Red: Females, Blue: Males.

Brown and Bennett (1980) found that the size composition of edible crabs (determined as carapace width (CW)) varied seasonally (Figure 1.6.). Males had the highest mean CW between February and March (175mm), and the lowest in July (141mm). The highest mean CW for females was October (175mm), and the lowest in March (155mm).

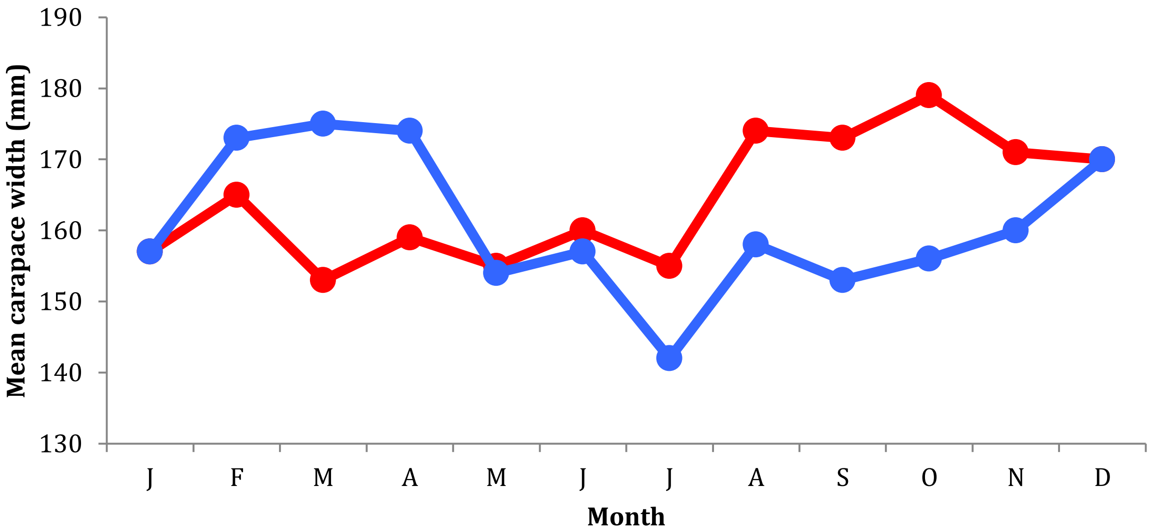


Figure 1.6. Mean monthly carapace widths for male and female Cancer pagurus sample from a set area off Dartmouth, Devon, 1968-1975. Red dot= Females, Blue dot= males. (Re-drawn from Brown and Bennett, 1980).

The authors explain the temporal change of mean carapace width by the moulting behaviour of the crabs. Once the previous integument has been shed crabs remain soft for 2-3 months, and are not landed again until they are hard-shelled. Therefore, if only landed catch is measured for size-frequency data, the moult increment or increase in CW will only be recorded 2-3 months after the moult has occurred.

Brown and Bennett (1980) recorded size frequency distributions and found that the mean CW increases with depth indicating an ontogenetic movement to deeper water. To further support this finding, Edwards (1979) elucidated that juvenile *Cancer pagurus* are found in rocky inshore waters. Geographically, they found that male and female crabs tended to have a lower mean carapace width in the eastern English Channel compared to a higher mean carapace width in the western English

Channel. It is likely that the CW of crabs is correlated to depth as the English Channel depth increases from east to west. A further explanation is that female crabs migrate from east to west over time, down the English Channel (Brown and Bennett, 1980, Hunter *et al.,* 2013), with an increase in size and age, there will tend to be larger females in the west than east.

Crabs increase in size by a process of shedding their exoskeleton called 'moulting' or ecdysis. The abundance of soft-shelled edible crabs in the catch fluctuates spatially and temporally (Edwards, 1979; Brown and Bennett, 1980) (Figure 1.7.). The exoskeleton of a post-moult crab does not return to its pre-moult rigidity for 2-3 months post-ecdysis (Williamson, 1904; Pearson 1908), during which time they remain largely sedentary; once they re-start their search for food their catchability increases.

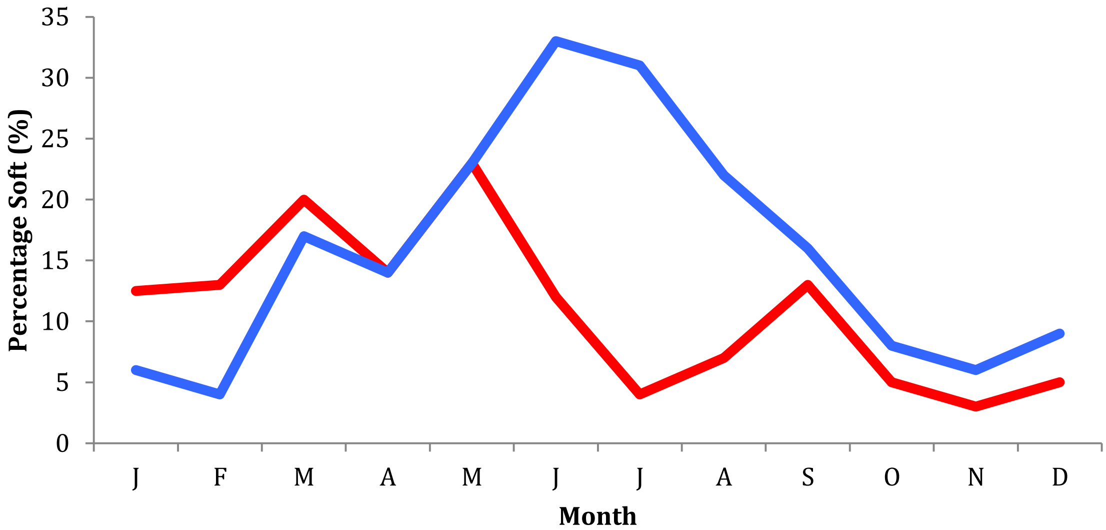


Figure 1.7. The mean proportion of soft male and female C. pagurus in the catch from various sites off south Devon grouped by month from 1968-1975. Red= Females, Blue= Males (Re-drawn from Brown and Bennett, 1979).

In the waters off south Devon, soft-shelled crabs occur in all months with the highest proportion caught in the spring (Brown and Bennett, 1980). The highest mean percentage of soft-shelled male crabs (30%) was recorded from May to August, indicating that this is their moulting period. There are two definitive moulting periods for female *Cancer pagurus* between March and May, with approximately 20% of the total catch composed of soft-shelled females, and then July and September with approximately 15%. Brown and Bennett (1980), Tully *et al.,* (2006), Tallack (2007a), Keltz and Bailey (2010) argue that the alternate temporal moulting pattern of male and female crabs is associated with the reproductive cycle of *Cancer pagurus*. Female edible crabs must be in a soft-shelled, recently moulted state to be able to copulate with a male. When female crabs are in this state they are vulnerable to predation and cannibalism and are often guarded by hard-shelled males waiting to copulate. For these reasons crabs have evolved a staggered moulting period for male and females (Edwards, 1979).

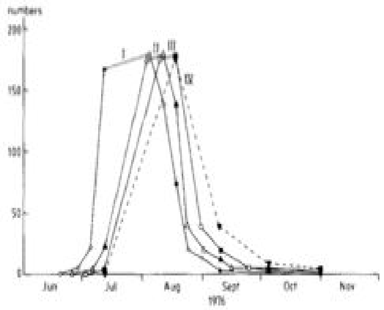
Once fertilised female crabs prepare to spawn their eggs. They create a small cavity or pit in the substrate, which enables the eggs to adhere to each other and to the female (Edwards, 1971). Females remain sedentary without feeding for between six to nine months from late autumn to the following spring (Edwards, 1979; Mill *et al.,* 2009) until their eggs are ready to hatch into larvae. CEFAS (MF1103, 2008) deployed DST tags showed inactivity of female crabs to last between 126 and 198 days (mean= 177± 24 days). It was found that the onset of inactivity began in late autumn and extended to spring/early summer, when females released their eggs. Due to this phase of inactivity and non-feeding very few berried females are caught during the spawning period (Mill *et al.,* 2009). Howard (1982) found 77% of all crabs observed at a SCUBA dive site in Lyme Bay were ovigerous females in May. Similarly, only 2% of the total catch by Lyme Bay fishing vessels contained ovigerous females during the same time period. Edwards (1979) observed 0.8% of berried crabs in total catches and Brown and Bennett (1980) found berried females comprised only 0.01% of the total catch. For these reasons, the direct estimation of the abundance of berried female edible crabs has remained largely inaccessible to fisheries dependent research, as their catchability during the spawning period is very low. In a spatial context, Brown and Bennett (1980), and Howard (1982,) found that mating usually occurs inshore and thereafter females move to deeper, sandy/muddy habitats to spawn their eggs.

Brown and Bennett's (1979) research gave a comprehensive overview of the life history of *Cancer pagurus* in the English Channel, using large samples sizes and a long-term study over 10 years. However, this research is over 35 years old, in which time the effort and landings of the fishery have increased and requires updating.

A summary of past work on the life history traits of *Cancer pagurus*

There is an abundance of past work on most aspects of *Cancer pagurus'* life history. In the following tables (1.2, 1.3 and 1.4) we concisely summarise the parameters useful to mechanics of the fishery from previous knowledge.

Table 1.2. A summary of the parameters of Cancer pagurus' life history useful to mechanics of the fishery.

	Methodology	Parameter/s	Comments	Reliablity of study	Author/s
Life History Trait					
Growth	N/A	Growth is accomplished by combining moult increment and moult frequency data for a population. An estimate of the annual increase in carapace length of male and female *C. pagurus* can be produced by assigning the age at 100mm for both sexes at '*t*' (approx. 3-5 years), then multiplying by the proportional moult increment and moult frequency at age at *t* + 1 year, *t* + 2 years and t + 3 etc.	One of the largest hurdles in the study of population dynamics is the accurate estimation of individual age. Defining age in crustaceans is particularly difficult, as they do not display continuous growth rendering age-length estimations useless. Further, they do not contain otoliths or any other structure, which can easily and quickly be used to identify ages of individuals *en masse*.	Small sample size of 330 crabs. To accumulate sufficient data to produce the growth curves, Bennett extended the study period by ±12 weeks around the one-year anniversary from the crabs release. In doing so, increasing the probability that some crabs could have moulted twice, within the one-year ± 12 week period, which could have produced erroneous results.	(Bennett, 1974b)
Fecundity	Investigated the size-fecundity relationship in female *Cancer pagurus* ranging from 129-212mm carapace width (N=55).	In*Teggs*=2.277 x lnCW +2.508. (*Teggs*= estimated number of eggs per brood, and lnCW= logarithm of crab carapace width).	Female *Cancer pagurus* conform to a positive size-fecundity relationship. eggs per brood to be estimated between 785,278 to 2,433,758. I Information detailing the size-fecundity relationship combined with the size frequency data of a population can estimate the eggs per recruit (Annala and Bycroft, 1987).		Tallack (2007)
Recruitment	Plotted daily production curves for the first four zoea stages from five surveys off the north-east of England, between June and October in 1976 (Fig. 2). The daily abundances of stage I zoea were summed over the entire hatching period of June-October to produce the seasonal production at 7.23 x 10^{12}.	Mean fecundity of 1.46 x 10^6 eggs per female (at a size of 152mm CW). Figure 2. 	Once a crab larvae hatches in an embryonic form as a prezoea it enters five zoea stages, and a megalopa stage before becoming a juvenile which settles to the seabed (Ingle, 1981). They found *Cancer pagurus* larvae to be prevalent from July to mid-October in the English Channel (Nichols et al. 1982).		From Edwards (1979)

Mortality					
Total Mortality Rate (Z)	Annual growth curves and size composition data to estimate Z	z= 0.45 for male *Cancer pagurus* and 0.4 for female *Cancer pagurus* in the south west of England.	The inability to age large crustaceans makes the estimation of mortality extremely difficult (Bennett, 1979). Several methodologies have been used to measure mortality rates these are: Length-Frequency data (Hancock, 1965; Annala, 1979), anniversary method (Conan, 1975; Caddy 1985) and tagging experiments (Bennett and Brown 1976, CEFAS (2008)).	These rates have been biased due to tag loss, non-reporting and migration into and out of the area.	Bennett and Brown (1976)
Fishing mortality (F)	Recapture rates from tagging experiements.	*F* to be between 0.2- 0.3.			Bennett and Brown (1976)
	Diver observations immedaitely after a trawl	25% catch effiecency of *Cancer pagurus* as a non-target species in scallop dredges.			Jenkins *et al.* (2001)
Natural mortality (M)		5% mortality rate of crab undergoing ecdysis			Edwards (1979)
		Mortality rate due to disease in edible crab remains unknown			Stentiford (2008)
	Recapture rates from tagging experiments	Typical *M* in the southwest area was between 0.2 and 0.3		These rates have been biased due to tag loss, non-reporting and migration into and out of the area.	Bennett and Brown (1976)

Interaction with fishery

Table 1.3. A summary of the parameters of Cancer pagurus' interaction with fishing gear pertinent to the fishery.

	Methodology	Parameter/s	Comments	Reliablity of study	Author/s
Crab interaction with fishery					
Gear-induced movement	Ultrasonic transmitters while crabs at liberty	The distance at which the crab began its search from the pot was 12-48m (mean= 28m).	A fundamental for fisheries stock assessment on a fishery where traps (pots) are set to catch fish is; over what area do the baited pots attract crabs.		Skajaa *et al.*, (1998)
		6/9 pot entries due to chemo-orientation. All pot localisations and crab activity occurred during the night and minimal movement was recorded during the day, leading to the conclusion that *Cancer pagurus* display a nocturnal activity pattern between 2200 and 0400 GMT+2			Skajaa *et al.*, (1998)
		Cancer pagurus consume five times more oxygen during the night in comparison to the day			Ansell (1973)
Soak Time	5 south Devon crab fishermen to kept daily logbooks on catch per unit effort (CPUE) and soak time of pots over 1 year in 1971.	CPUE was negatively correlated with soak time in males and females due to pot saturation	Soak time (or pot immersion time) is the length of time that pots are left on the seabed to catch fish		Bennett (1974a)

Pot Saturation			The effect of trap saturation should be taking into consideration when modelling the dynamics of a fishery, which uses pots or traps. As crabs enter a baited pot and are caught, their presence in the pot reduces future catch rates. Beverton and Holt (1957) defined trap saturation as 'the tendency for the fishing power of a unit of gear to be reduced as the catch increases'.		
	Two conditions: fished and non-fished. Under the fished condition all crabs were removed from pot every 2 hours for a 12-hour period, while in the non-fished condition, crabs were counted every 2 hours for a 12-hour period but were not removed from the pots. This was repeated for 3 sized pots: small, medium and large	The cumulative total of crab in the fished condition was at least 1.7 times higher than the non-fished condition. Irrespective of size, saturation still limited the amount of crab caught.	Investigated the phenomenon of trap saturation on a natural *Cancer productus* crab population and aimed to identify the optimal trap design and fishing strategy to maximize catch	*Cancer productus* not *pagurus*	Miller (1979)

Effect of abiotic factors on *Cancer pagurus* behaviour

Table 1.4. A summary of the effects of abiotic factors on Cancer pagurus' life history pertinent the south Devon fishery.

	Methodology	Parameter/s	Comments	Reliablity of study	Author/s
Effect of abiotic variables on crab catch					
Tide			It has been well documented that some marine species illustrate lunar or tidal rhythms and that these are usually linked to reproductive behaviours		(Korringa, 1947; Enright, 1975; Naylor, 1976).
			Terrestrial crab use tidal/lunar rhythms are used as a biological clock		Saigusa (1980)
			Green crab (*Carcinus maenas*) circatidal locomotor activity rhythm. highest locomotory activity in the green crab correlated to the time of high tide		Naylor, 1958
			Uca crenulata, the California fiddler crab, also has an endogenous rhythm that may be synchronized by tidal cues		Honegger, 1973
			Atlantic horseshoe crab (*Limulus polyphemus*) demonstrate that circatidal activity rhythms could be entrained and synchronised with artifical tidal cues		Chabot *et al.*, (2008)
		No significant effect of current direction on the direction of movement of *Cancer pagurus*			Skajaa *et al.*, (1998)
				No research has been carried out to explore the relationship of tidal rhythms with edible crab catch rates	
Bathymetry			Most research thus far only pertaining to the depths at which crabs were caught or observed.		
		Cancer pagurus occurred from the intertidal zone to depths of 100m			Brown and Bennett (1980)
		Positive relationship between mean carapace width of *Cancer pagurus* with increasing depth, suggesting an ontogenetic movement to deeper water.			
	Tagging with DST tags	Average depth range experience by crabs to be from ~18m to 80m			CEFAS (2008)
		Migrating crabs were not following depth contours as a means to navigate their migration routes.			
		Crabs released inshore off south Devon inhabited depths between ~45-90m			
		Average depth of brooding for crabs was 57 ± 23m			

Temperature			*Cancer pagurus* are poikilotherms . Accordingly, the temperature of seawater in which *Cancer pagurus* exists affects the organism's behaviour and locomotion.		(Aldrich, 1975)
			The yearly regularity of the rise in catch suggests it is related to the rise in temperature of the sea'		Edwards (1967)
		At 15.5 °C crabs ate 46% of the food supplied to them, but at 4.5 °C only 1% of the food was consumed. Also observed that at temperatures below 3.8 °C crabs that were usually active, became immobile and stopped feeding.		Labatory conditions	Edwards (1967)
			Postive corrleation between lobster catch rates and locomotion with sea bottom temperature		Drinkwater *et al.,* (2006), McLeese and Wilder (1958)
		At higher temperatures larger catches were taken as crustaceans moult (and hence grow) more frequently in warmer water.	Temperature also has a positive correlation with moulting frequency and thus growth		Koeller (1999)
		Study found that egg brooding by *Cancer pagurus* began at 13± 1.5°C. Thereafter, they became active again at 11 ± 2 °C.			CEFAS (2008)

Substratum			Substrate type is an important factor affecting the distribution of many crustaceans including amphipods, isopods and decapods (Cobb 1971). Further, investigators have found that the particle size and nature of the substrate were important factors in determining the selection of a habitat by many crustaceans (Crawford 1937, Dixon 1944, Teal 1958, Cobb 1971), and especially for spawning by ovigerious females (Bennett and Brown, 1983; Woll, 2003; Rebach, 1974)		
		The seabed off Devon, where large concentrations of female crabs are caught, is composed of sand or gravel with rocky outcrops inshore (Prattje, 1950; Lee and Ramster, 1976). The confinement of female crabs to burying in regions of sandy bottom indicates that substrate is an important determinant in which areas can be used as over-wintering and spawning grounds.			
Wind		Governs the amount of days fishing per year.	Wind speed determines sea state and ultimately whether a vessel can operate safely.		
			Many fishermen note that winds from a particular direction result in good catches, while winds blowing from the opposite direction drive catch down' due to the Ekman Effect.		Drinkwater *et al.* (2006)

Alternative tools for data collection: Fishers Local Ecological Knowledge

Fishers have a broad and detailed knowledge of fisheries stemming from on-going and extensive interactions with the environment in which they fish (Ruddle, 1994 from Zukowski *et al*., 2011); this is known as Fishers Local Ecological Knowledge (FLEK). Consequently, as well as using fishers to collect data, their wealth of knowledge of the resource they exploit and its environment should be incorporated into stock assessments and the design of management measures (Johnson and van Densen, 2007; Hind, 2014; Stephenson *et al*., 2016).

Fishers are often the first to perceive changes in fish stocks as these directly affect their income and livelihoods (Friesinger and Bernatchez, 2010). As a result, fisher's knowledge of the resource they prosecute is of value to fisheries management (Hill *et al*., 2010). By including fishers in the collection of data, design and implementation of management regulations, the measures are likely to be more effective. Wilson *et al*., (2006) stated, 'fisheries management cannot be effective if it is not considered legitimate by stakeholders'. As a result, there has been a surge to capture fisheries knowledge in a way, which is useful for fisheries management. As such, both methods to capture fisher's knowledge, and a framework to utilise it within fisheries management are required. In studies aiming to capture fisher's knowledge, methodologies such as, semi-structured interviews, questionnaires, focus-groups, map drawing, timeline drawing (Wilson *et al*., 2006), consensus analysis (Leite and Gasalla, 2013), telephone surveys, logbooks and fishers diaries (Pollock *et al*., 1994) and to fill gaps in ecological modelling data (Bevilacqua *et al.,* 2016; Deepananda *et al.,* 2016).

In recent years there has been an increase in the collection of, and value placed on, local ecological knowledge (LEK) and specifically, fisher's local ecological knowledge (FLEK) (Leite and Gasalla, 2013) but this knowledge has rarely been translated into a practical application for management (Gasalla and Tutui, 2006) with only a few examples in the literature (Chemilinsky, 1991; Mackinson and Nøttestad, 1998).

Many scientists criticise the reliability of LEK (Jentoft *et al.,* 1998, Mackinson and Van der Kooji, 2006) and as a result studies often do not translate LEK into management measures. To demonstrate the reliability of fishers local ecological knowledge, Zukowski *et al*., (2011) compared fisher's catch data to data collected by scientists on Murray crayfish (*Euastacus armatus*) to determine the reliability of fisher's knowledge, and if it could be incorporated into fisheries management. They concluded that the fisher's knowledge they captured correlated with scientific data and could be used as a reliable source of data. Further, Ebbers (1987) found that there were only small differences in the population structure of large-mouth bass (*Micropterus salmoides*) in Minnesota, USA when data from scientific electrofishing surveys, fishing tournaments and fisher's diaries were compared, again validating the use of FLEK in management.

An example of integrating fisher's local ecological knowledge into management was demonstrated by Leite and Gasalla (2013). They collected fisher's LEK about three topics in a small-scale mixed fishery in São Paulo, Brazil. Firstly, they wanted to determine the spatial and seasonal occurrence of mature and juvenile females in the mixed fishery (shrimp, croaker, squid, and jacks). Secondly, they set out to determine fishing grounds, and lastly to collect fisher's suggestions for local fisheries management. Leite and Gasalla (2013) carried out rounds of semi-structured interviews using the Delphi methodology (the Delphi method uses a 'group of experts who anonymously reply to questionnaires and subsequently receive feedback in the form of a statistical representation of the "group response," after which the process repeats itself. The goal is to reduce the range of responses and arrive at something closer to an expert consensus.' (Rand.org)), which included a consensus of opinions on all three topics above. As a result of Leite and Gasalla's (2013) research local essential fish habitats were defined, current closed seasons were reconsidered, and new regulations were proposed to avoid the bycatch of juveniles by larger vessels and the use of a larger mesh size.

Other 'alternative' data collection methods available to managers are tools such as smart phone apps, such as E-catch as being developed in the Lyme Bay Fisheries and Conservation Reserve by Blue Marine (http://www.lymebayreserve.co.uk), automatic data collection devices such as video capture of a Welsh *Cancer pagurus* fishery catch (Hold *et al.,* 2015).

The above research demonstrates that on the whole fishers LEK can be successfully and reliably translated into local management measures in small-scale fisheries with validation. Leite and Gasalla (2013) also found that as a by-product of carrying out LEK interviews communication between scientists and fishers improved, conflicts reduced, and community development and empowerment were increased. Consequently, increased compliance to the agreed management measures was observed.

Co-management and participatory research

The method of management where fisheries managers and stakeholders work together to manage a fishery is termed 'co-management'. Co-management has been successful in producing sustainable fisheries in numerous instances as demonstrated by Castilla and Fernandez (1998). Co-management often creates a sense of ownership and responsibility in fishers for the common resource they exploit, much more than imposed management (Haward and Wilson (1999), cited in Shotton (1999)). Ownership encourages fishers to look to the future for the long-term management of the fishery, to fish responsibly (Cochrane, 2000), and to move away from short-term exploitation. Further, community initiated agreements increase compliance among stakeholders (Sweeting and Polunin, 2005).

To successfully manage fish stocks it is imperative to realise that management measures, have to be understood, accepted and adhered to by fishers (Wilson *et al*., 2006). Therefore, when management measures are designed it is important to consider if they are fit for purpose to create sustainable stocks for the fish population in question and socio-economically viable for the fishers who exploit the population. Unfortunately, these socio-economical aspects of fisheries management have often been overlooked with efforts focused on the ecology of the exploited population. As such fishers often adapt their fishing techniques, strategies and adherence to management measures to insure they have a viable business, often leading to less successful stock management. Therefore, if managers work together with fishers the measures resulting from this co-operation are usually more effective at producing sustainable fisheries as a product of the measures being more readily accepted by the fishers (Sweeting and Polunin, 2005).

One example of successful co-management is the Canadian Sablefish Association (CSA). After the collapse of this fishery in 1977, the fishermen of the CSA requested Individual Vessel Quotas (IVQ) from the Canadian Department of Fisheries and Oceans (DFO). The CSA now self- funds and coordinates, observer and dockside monitoring programmes for the IVQ's with the sablefish fishery has recently gaining MSC certification for its sustainable practices. (From FAO ftp://ftp.fao.org/docrep/fao/010/a1497e/a1497e35.pdf)

A UK-based example of a participatory fisheries project was the Judgment and Knowledge in Fisheries Management Project (JAKFISH) (Pastoors *et al*., 2012). The project reports that the integration of fishers, scientists and policy makers requires an 'effective facilitation strategy' allowing communication between the three stakeholders, and that 'participatory research is built on trust and facilitates trust, both of which take time and continuity of engagement to develop' (JAKFISH Final Report, 2012).

Fisher directed stock assessments

The method of fisher-directed stock assessments (FDSA) is a progression from co-management towards self-management. Utilising a FDSA method means that there is no longer a balance in planning and decision-making power between fishers, scientist and managers, fishers now take the lead in these areas. For example, instructing scientists on what to research and identifying and implementing sustainable management measures to be overseen or enforced by fisheries managers.

The FDSA method uses fishers to self-collect data while they are carrying out their commercial activities. These data are used to assess the sustainability of the exploited stock and then, with assistance from scientists and managers, used to set their own future catch rates. Examples of fisher-directed stock assessments are relatively rare as the approach is a new concept in fisheries management but some are outlined below. The benefits of such an approach are that they build trust between fishers and managers and improve communication and scientific education of the fishers. Large data sets can be gathered from commercial vessels, in some cases producing Fully Documented Fisheries (FDF's) and as many fishers self-collect the data as part of their basic activities for their own records, the cost of data collection is low. Potential disadvantages are the extra time at sea collecting and recording data and its obvious financial implications, extra crew may have to be employed and there may be additional fuel costs. For fisher's local ecological knowledge to be incorporated into local assessments as highlighted by Dolder *et al.*, (2013) an effective validation mechanism needs to be in place, to control for bias.

In the IPA, fishers believed that as crab catches began in abundance in the western IPA that crabs were migrating eastwards, as this is how they saw catch quantities increase in the early spring. However research by CEFAS (MF1103, 2008) demonstrated overwhelmingly that crabs were reacting to the currents warming from the west and becoming active and consequently having an increased catchability in the west, before the waters warmed further east. This example indicates that whilst fishers observations were accurate (catches are larger, earlier in the west compared to the east) that their explanation for this phenomenon was not accurate and needed empirically investigating.

The Shetland Shellfish Management Organisation (SSMO) is an exceptional example of the self-management of a small-scale crab fishery. In 2000, the Scottish government devolved power to the organisation to self-regulate its own fishery within 6 nm of Shetland. The SSMO is a partnership organisation and it is ultimately administered by 8 directors representing the following backgrounds; a community councillor, a processor, a Shetland Fishermen's Association representative, and several license holders. The SSMO works closely with the local North Atlantic Fisheries College (NAFC) Marine Centre who undertakes the scientific aspects of the fishery's management. To quantify the success of the SSMO the fishery was granted MSC Accreditation in 2012, the only accredited fishery for *Cancer pagurus* in the world.

Modelling

The aim of this thesis is to provide data and context for an individual based model (IBM), which could be used to assess the sustainability of the south Devon crab fishery. A model is being created by Prof. Hart which, when complete, would enable fishers to input catch rates to set future quotas, thus in theory, creating a sustainable fishery. We are using onboard spatiotemporal catch and discard data along with environmental data and FLEK to develop and test the model. Throughout the data collection process, and model development we have worked collaboratively with fishermen from the south Devon crab fishery to integrate their FLEK and feedback into the model.

An IBM of the crab dynamics for the south Devon fishery will need to be developed and take into consideration local parameters on bathymetry, temperature, crab movement etc. The system to be modelled in this thesis is the female crab fishery in the Inshore Potting Agreement area and its immediate surroundings off south Devon, UK. The system includes the crabs, the fishers and the environment in which they operate. Data which was input into the IBM was taken from a number of sources; catch and discard data was sourced from onboard trips with fishermen and 10 years worth of fisher's diaries. Environmental data such as sea temperature was procured from external institutions and vital knowledge on crab life history parameters were taken from the literature. Professor Hart will develop and code the IBM using NetLogo software (Wilensky, 1999), with input from the lead author and south Devon crabbers.

To demonstrate suitability of IBM for this study, we considered previous work involving the modelling of fish and more specifically, crab behaviour using IBM's. Fish population models have been reviewed, in depth by DeAngelis *et al*., (1990); van Winkle *et al*., (1993) and Tyler and Rose, (1994) all cited by Grimm *et al*., (1999). All of these papers use Individual-based simulation modelling to track the attributes of individual fish through time and aggregate the outcomes of these interactions to generate emergent insights into population function (van Winkle *et al*., (1993). More specific to crab populations an IBM was developed by the South Carolina Blue Crab Regional Abundance Biotic Simulation Project (SCBCRABS) (clemson.edu/SCBCRABS) in 2007. This project focused on the Ashley River, South Carolina, USA and was created to 'predict population abundances of blue crabs (*Callinectes sapidus*) in South Carolina' as well as to 'determine how disturbances such as fishing pressure, hurricanes and droughts might influence these populations.'

Advantages of using an IBM to simulate the fishery are; that all individuals within the model are tracked across time and can also be tracked in space and are built from the bottom-up. In contrast top-down, differential models average characteristics across populations and attempt to simulate changes in these averages for the whole population, losing the emergence of individual interactions. Further, the IBM method 'provides a framework within which researchers conceptualise the natural processes, design their research, analyse results, and combine empirical studies and modelling in a synergistic manner' (van Winke, 1993), and they can incorporate any number of individual-level mechanisms (DeAngelis and Grimm 2014). Additionally, by using NetLogo to develop IBM's there is the ability to visualise the outputs of the modelling while it is running which is beneficial for the stakeholder to view rather than follow the complex mathematics of differential models.

There are however some disadvantages of modelling using an IBM approach. There is a trade-off between the level of complexity of the model to give a true reflection of the situation being modelled in reality, and the ability to gather accurate data in adequate detail, and then analyse what is emergent from the model. Other disadvantages outlined by Grimm *et al*., (1999) are that IBM's are more complex in structure than analytical models, they have to be implemented and run on computers with large processing capacity, and IBMs are more difficult to analyse, understand and communicate than traditional analytical models (Grimm *et al*., 1999). Hence Grimm *et al*., (2006) developed the ODD Protocol, a standardized method for communicating and describing IBM's. Despite these disadvantages, due to the many aforementioned advantages, ability to visualise the model, and flexibility of the IBM approach we will use this method to model the south Devon crab fishery.

The present south Devon crab fishery

The south Devon crab fishery is predominantly for edible crab (*Cancer pagurus*), however other species caught commercially are the European lobster (*Homarus gammarus*), European spider crab (*Maja squinado*), Dog Whelk (*Nucella lapillus*), Common whelk (*Buccinum undatum*) and dive-caught King scallops (*Pecten maximus*).

The fishery is contained within the boundaries of the Inshore Potting Agreement Area (IPA). The IPA currently covers an area of approximately 478.4 km^2 (Blyth *et al.,* 2002). This area extends from Bigbury Bay in the west (50 18.09 N, 004 04.30W) to Berry Head in the east (50 20 12.42N, 003 32.08W). The seaward boundary is the inshore 6 nm limit throughout its entirety. The IPA is composed of seasonally open and closed areas, with 349.7km^2 of sea used exclusively for static gear and the remaining 73.2km^2 rotated between static and mobile gear on a seasonal basis (Sweeting and Polunin, 2005) (See Figure 1.8.).

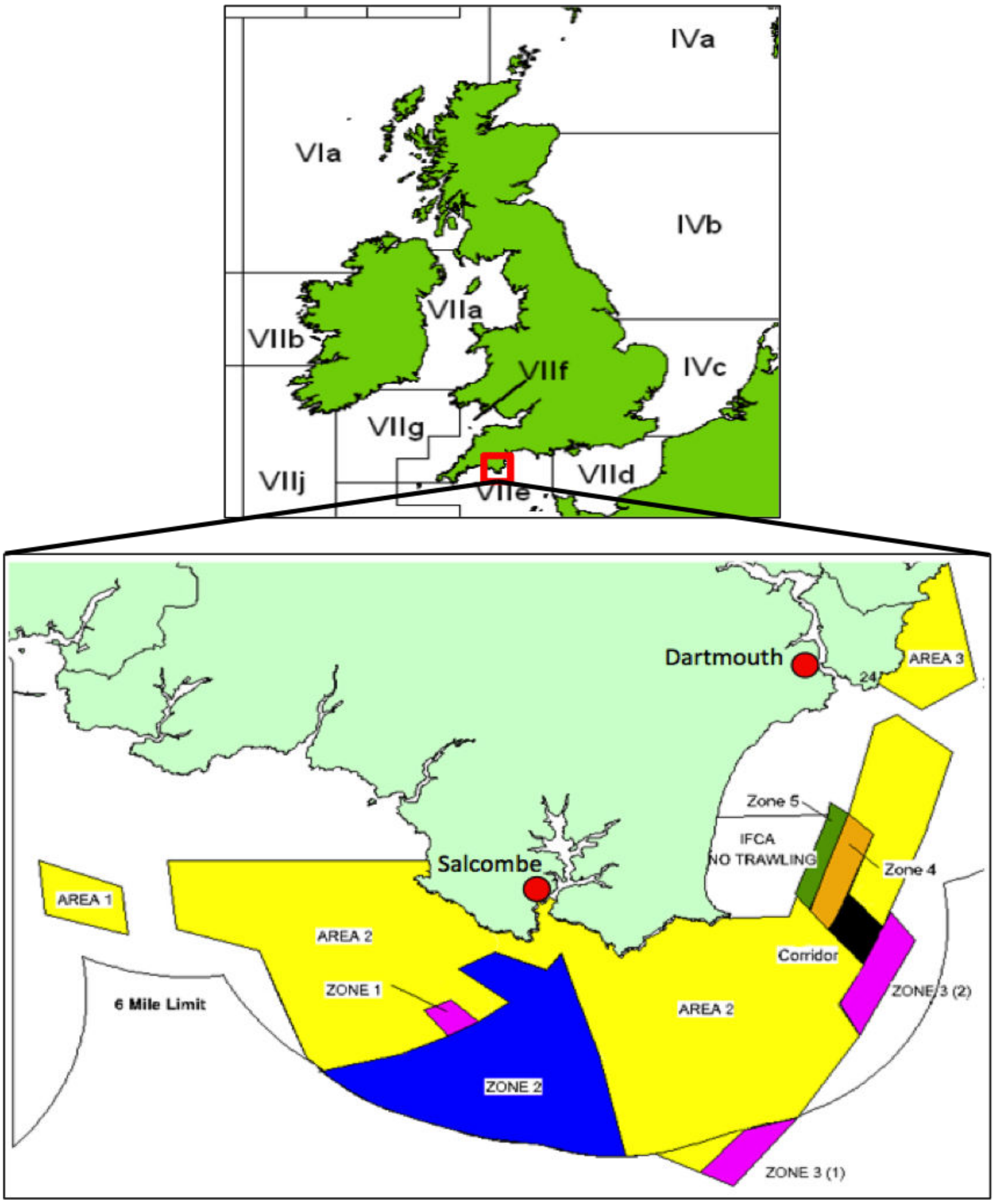


Figure 1.8. The location of the IPA in relation to the UK with ICES area VIIe. The Inshore Potting Agreement area as defined for 2013 (Trawling is permitted in Area 3 provided such vessels have an engine power of no more than 100kw and scallop dredging is permitted provided such vessels use no more than two tow bars, and that any tow bar used does not exceed 2.6 meters in total length and there are no more than three dredges attached to each tow bar.) Zone 1: Trawling 1st Jan – 31st March. Zone 2: Trawling 1st Jan – 1st June. Zone 3 (1): Trawling 1st Jan – 31st March. Zone 3 (2): Trawling 1st Jan – 31st March. Zone 4: Trawling 1st Feb – 31st August. Zone 5: Trawling all year. Corridor Trawling 1st Feb – 31st March. Areas 1, 2 and 3- Pots all year. Source: SDCSA (2013).

There is a long history of fishing activity in south Devon. The earliest documentation of fishing in south Devon can be found in the Domesday Book (Firestone, 1967) and many villages along the coast of south Devon were established as a result of the tradition of fishing from their beaches (Figure 1.9. and 1.10.). Early fishers stored gear here but lived inland and only moved permanently to the coast when opportunities to work on the land diminished (Fox 2001). Firestone (1967) established that fishing was carried out from the shore at Torcross, Beesands and Hallsands as long ago as 1890. Furthermore, the fishers that presently operate in Start Bay are at least third or fourth generation crab fishermen (Blyth *et al*., 2002). As a result, crab fishing has a long-standing tradition in this coastal region and is embedded in family and village histories (Fox, 2001) also Figure 1.9 and 1.10.

Figure 1.9. Beesands Beach in the early 1900's showing long lines, crab store pots and ray poles used to dry the fish. Source: www.facebook.com/groups/205638326210169

Figure 1.10. Fishermen at work in Beesands 1959.
Source: www.facebook.com/groups/205638326210169

The fishers of south Devon voluntarily established the IPA in 1978 (Blyth *et al*., 2002) to mitigate conflict between static and mobile gears and reduce the financial implications of gear loss, by implementing seasonally open and closed areas. However, only in 2002 was the IPA finally given a legal basis. Although the IPA was initially founded to reduce the number of crab pots being destroyed by trawlers and dredgers, it had significant unplanned conservation benefits (Kaiser *et al.,* 2000b; Blyth *et al.,* 2002; 2004; Blyth-Skyrme *et al.,* 2006; Kaiser *et al*., 2007).

An explanation for the IPA's continuing success over the past 38+ years is that it was designed and implemented by fishermen for fishermen using a bottom-up approach to management. Fishers took the initiative and developed a management plan that delivered their intended goal; the mitigation of gear loss. They then pressed the local IFCA over many years to legalise the framework that they had devised. The success of the IPA can be attributed to the fact that it was mutually beneficial for all parties involved (potters and trawlers) and each year a meeting is held with all stakeholders to discuss any necessary changes to the IPA's spatially and temporally open and closed areas. Demonstrating that the IPA has already successfully designed and implemented a bottom-up management regime (Hart, 1998) indicating they are a pioneering organisation.

In 2008, the 'south Devon Potting Effort Survey: 2008' indicated there were 38 vessels with a total of 75 crew members operating within the IPA boundary and fishing 13,304 pots (Clark, 2008) (See Table 1.5.).

Table 1.5. The number of vessels working, the number of pots being fished and the number of crew working in the IPA, and the number of under and over 10m vessels all categorised by home port.

Home Port	**Number of Vessels**	**Number of Pots**	**Number of Crew**	**Under 10m**	**Over 10m**
Brixham	1	293	2	1	0
Dartmouth	19	7405	41	13	6
Beesands	1	15	1	1	0
Salcombe	16	5551	29	12	4
Plymouth	1	40	2	1	0
Total	**38**	**13304**	**75**	**28**	**10**

The IPA is saturated with pots at a density of 27.8 pots per km^2 (13,304 pots/ 478.4km^2) (Clark, 2008). As such fishers have accrued hypothetical 'territories', although in law they do not own the right to fish a set area of sea. Nevertheless, fishers mutually respect each other's 'territories', and each time the pots are hauled they are put back in the same area so retaining that 'territory'. Territories in the form of pots are traded amongst existing fishers and as new shellfish licences are not available, new entrants must buy a licence, pots and consequent territories from fishers exiting the fishery or reducing their number of pots, in essence creating a one-in-one-out system.

Once caught the crabs are landed by the majority of fishers to a small number of local processing factories. This enables fishers to continually sell large volumes of crabs on a daily basis and to build a business. Smaller vessels and single-handed fishers tend to sell independently to local restaurants, fishmongers or food markets.

With a reported £18.9 million first sale value (MMO, 2011) resources should be directed to sustainably manage the fishery in the short and long term, as the activity supports the local economy and continues the heritage of the area. These socio-economic factors should be a consideration in the development of management regimes designed to maintain the sustainability of crab stocks, as neither the value of the fish or value of fishermen's skills and livelihoods can be treated as mutually exclusive.

There is no evidence to support or refute if the south Devon fishery, *per se,* is being fished sustainability as CEFAS' stock assessment only applies to the western English Channel stocks as whole. Regardless of the CEFAS assessment, the Marine Conservation Society (MCS) rates the fishery as '2', on a scale of 1 (excellent) to 5 (poor). Therefore, it would be beneficial for the sustainability of crab and the fishers themselves to create an inexpensive, reactive and localised model to facilitate an assessment of fishery's sustainability and market the crab as such.

Conclusion

This literature review summarises past research concerning the population dynamics of *Cancer pagurus*, the affect of the environmental variables such as bathymetry and temperature on *Cancer pagurus* catch rates, the current models employed in stock assessment, and how FLEK can be captured and incorporated into future fisheries management.

To date the most comprehensive edible crab population research off south Devon was a 10-year long CEFAS study by Brown and Bennett between 1967-1977. Although this long-term research programme produced much insightful knowledge on aspects of the fisheries such as CPUE, seasonal abundance of soft-shelled, undersized and berried crabs, and other spatio-temporal metrics, very little research has been carried out on this fishery since. In 2011, the south Devon crab fishery was worth an estimated £18.9 million per year at first sale value (MMO, 2011), therefore the sustainability of the fishery is of paramount importance to the local economy and jobs, let alone the local tradition of fishing. To this end, a study to assess and attempt to secure the sustainability of the fishery and fishermen is required.

The environment in which it exists affects the behaviour of any population and this review demonstrates that factors such as sea temperature affect the reproductive behaviour of female crabs (MF1103). As such, the model designed to recreate the population dynamics of *Cancer pagurus* cannot ignore these environmental variables. Currently, the sustainability of *Cancer pagurus* off the coast of south Devon is assessed as a western English Channel stock using Length Cohort Analysis which produces F_{MSY}. The level of uncertainty attributed to growth rates and rates of natural mortality within the LCA are high, and more research is required in these areas. The present fishery is judged to be sustainable by CEFAS as the crabs that are within the fishery are contained within the western Channel stock as whole. As the stock assessment, evaluates the entire western Channel stock, no research has been specifically undertaken to establish the sustainability of the south Devon crab fishery. The fishery is predominantly managed by the implementation of technical measures such as MLS, escape gaps and discarding practices, with no effort limits (other than overall vessel length) or quotas in place. This review highlights that fishers with their extensive, often daily, use of the resource can reliably collect data to be included in stock assessment. Further, fisher's invaluable knowledge of population dynamics and seasonality can be captured scientifically and translated into effective management measures (Leite and Gasalla, 2013; Bevilacqua *et al.,* 2016; Deepananda *et al.,* 2016).

Traditional stock assessment methodologies such as MSY have often failed to mitigate the over-exploitation of stocks, and therefore new methods for managing fisheries need to be explored. Fishers are able to collect an abundance of data and knowledge on specific areas of the sea and they can also help design management measures and thus increase compliance. In conclusion, the answer to a fisheries management system that leads to sustainable stocks is likely to in part, lie with the fishers themselves.

The above aims will be achieved by the following objectives of each chapter of this thesis:

1) Chapter 2 establishes and defines the methodology of working collaboratively with fishers in this case study and identifies the strengths and weaknesses of the study.

2) Chapter 3 presents fine-scale data on catch, landings and discards gathered onboard fishing vessels over most of a year and from fishers diaries.

3) Chapter 4 details the relationship between abiotic variables such as surface sea temperature, bathymetry and substrate type and catch within the IPA.

4) Chapter 5 reports the results of a questionnaire answered by a subset of fishers to gather their FLEK. The results of the questionnaire are then compared with what is known about the topics covered gathered from the scientific literature and data from Chapter 3 and 4.

5) Chapter 6 evaluates the empirical results of Chapter 3 and 4 as potential inputs to an Individual Based Model of the fishery that is being independently developed.

6) Chapter 7 provides a synthesis of the study and sets out a future plan to facilitate the incorporation of the IBM into management of the IPA.

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Chapter 2

Fishers and scientists in the same boat: A story of collaboration

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Abstract

The collaboration forming the basis of the UK *Cancer pagurus* case study builds on a relationship between scientists and fishers that was established in 1996. The emphasis of the case study was to develop awareness among fishers of the need to be more involved in the management of the resource on which their livelihoods depend. To engage fishers we have worked collaboratively towards the development of an Individual Based Model (IBM) of the south Devon crab fishery. The model replicates the dynamics of the fishery with crabs of varying size classes migrating into the exploited area and being removed from the area either as catch, natural mortality or by emigration. The interplay between these factors will then be used to determine the level of fishing effort the fishery can sustain. The ultimate aim is to enable fishers to collect their own catch data and input it into the model to establish sustainable levels of catch for the following year.

This chapter describes how fishers and scientists have collaborated during the case study. Initially fishers of the South Devon and Channel Shellfishermen's Association (SDCSA) were persuaded to collaborate by the Secretary of their association. While the crabbers were initially passive, a core group of the fishers became actively involved over the course of the project. We conclude with a discussion of the successes and shortfalls of the collaborative process and identify the key factors required to engage fishermen and scientists in the development of a bottom up management approach.

Introduction

Current EU fisheries management is heavily dependent on top-down control, which has led to the disconnection and alienation of small-scale fishers from policy and management decisions that directly impact their livelihoods (Wilson, 2006). It is more often than not the case that inshore fishers (whose activities are being regulated) are not directly involved in, or consulted during the process of data collection, negotiations or the subsequent legislation of management measures. Small-scale inshore fishers are greatly impacted by management measures, as they often do not have the opportunity to fish elsewhere. Here we demonstrate that through co-operation scientists and fishers have worked together to develop tools aimed at enabling fishers to become actively involved in the management of the crab stocks they exploit.

Based in Devon, UK, the South Devon and Channel Shellfishermen's Association (SDCSA) is a group of well-organised inshore crab fishermen. As such the fishers have provided an ideal platform from which to launch a fisher/scientist collaborative research project aimed at constructing a fishery-wide management tool. The SDCSA have already demonstrated their ability to voluntarily establish novel fisher-directed management tools, for instance, during the 1970s they established, and have continued to operate, a bottom up approach to utilising a system of seasonally open and closed trawling zones interspersed with potting only zones (Blyth *et al*., 2002) to mitigate gear loss. These zones are collectively called the Inshore Potting Agreement (IPA) (Figure 2.1.). The crab fishery is exploited by vessels based in Salcombe and Dartmouth, Devon, with these ports contributing 59% (£18.9 million) of the annual value of crab landings in the UK (MMO, 2012). This statistic highlights the financial value of the Devon crab fishery in terms of local socio-economics and the supply of crab to the market.

Despite what appears to be an intensive inshore fishery for crab off south Devon the most recent CEFAS stock assessment for crab in the Western English Channel (2014) concluded that fishing effort was 'moderate to low', with an exploitation level close to that producing Maximum Sustainable Yield (MSY) (CEFAS, 2014). Additionally, spawning stocks were rated as 'Good' and sufficient to sustain MSY.

In effect, the IPA created a fishery with a restricted spatial area, within which each vessel effectively fished its own 'territory'. These fixed 'territories' are useful from a scientific standpoint as they allow a time series of data to be collected per fixed area. For decades fishers of the SDCSA have supported government scientists, such as CEFAS, local managers such as Inshore Fisheries and Conservation Authority (IFCA) (formally Sea Fisheries Committee) and academics by supplying landing data upon request. However, fishers have not received feedback on the data they have provided, thus knowledge transfer has historically been in the direction of the scientist:

"In the past we have had people come down and ask for data not really giving much of an explanation what it was for, and didn't receive any feedback on the data. Which left fishers very suspicious and unwilling to help." (4th Generation Fisherman)

As such fishers have shown an interest in contributing to research, but have not had the opportunity to contribute their knowledge to the process of formulating management measures or work collaboratively on a project. The GAP2 method states that if a sustainable fishery is to be created then all stakeholders should be engaged at all stages in the set up of management measures. A collaborative approach between fishers and scientists is pertinent to this study as neither group alone has the expertise, knowledge or influence to enact the fishery-wide uptake of a management tool required to create a sustainable fishery.

As a result this study aims to create a management tool for the SDCSA fishers to use to generate a sustainable fishery for the future, implementing a collaborative approach to the process.

Current Management

At present CEFAS scientists produce regional stock assessments using fisheries dependent data taken from Monthly Shellfish Activity Returns (MSARs). The MSAR forms, completed by fishers capture the number of days at sea and the weight and sex of landed crab. The spatial scale at which the data is recorded is defined by the size of the ICES fishing areas; the IPA fishery covers just 0.8% (470 km^2) of ICES area VIIe, which encompasses a total of 56,378km^2 of sea (See Figure 2.1). However, the large spatial scale used for these retrospectively applied stock assessments (conducted every 3-4 years) does not take into account localised intensively fished areas within the western English Channel, such as the south Devon fishery, or localised environmental variables.

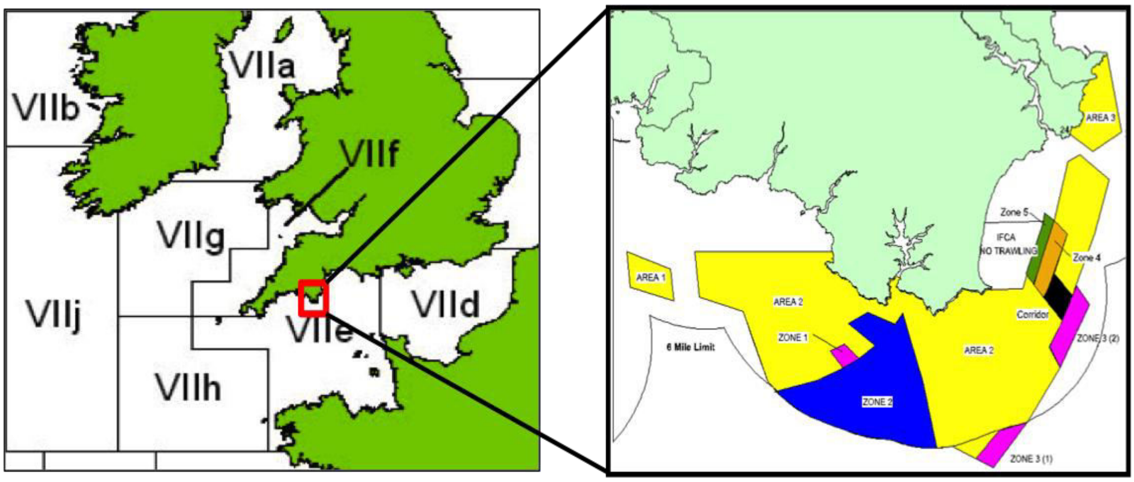

Figure 2.1. Left: ICES area VIIe at the western end of the English Channel. Right: The IPA with permanently closed areas to trawling marked in yellow and seasonally open and closed in green, orange, pink, black and blue.

In England, fisheries are governed by three levels of legislation: European Commission (EC), national e.g. MMO and DEFRA, and regional through the local IFCAs. The EC and national legislation demands that female edible crabs in UK waters are not landed below the Minimum Landing Size (MLS) across the carapace of 140mm and males not below 160mm. However, fishermen in the Devon and Severn IFCA have voluntarily set a 150mm MLS for female crabs. This high MLS can only be a positive contribution to ensuring that levels of crab remain satisfactory in the Western English Channel. A high MLS ensures that several spawning events have occurred before crabs are removed from the fishery (Warner, 1977). National legislation mandates management measures, which contribute to the current exploitation levels, i.e. the enforcement of discarding of both soft crabs, which are likely to have recently mated, and egg-bearing females, the further progeny of the population. Additionally, escape gaps must be fitted to all parlour pots to allow juvenile crabs to escape before pots are hauled. These measures are summarised in Table 2.1.

Table 2.1. Management measures and their limitations applicable to the Devon and Severn IFCA area.

Management Measure	Limitations
MLS (more stringent than rest of UK)	150mm for females (Voluntarily in D & S)
Maximum Vessel Length (within 6nm)	15.24m
Maximum Pot Limit	None
Use of edible crab as bait	Not allowed
Escape gaps in Parlour pots/ Creels	Yes
Towed gear restrictions	IPA and Mid Channel Blocks

CEFAS produce stock assessment reports using self-sampled MSAR's data and these stock assessments are then used to design local and national management measures to align fishing effort with MSY. The reports are then used by the IFCA to design and enforce management measures through the use of local by-laws and national legislation. Unfortunately, the IFCA is under resourced, with a budget of just £694,000 per year for 10 staff over an area of 3,306 km^2 (DSIFCA, 2016), and as such is not able to prosecute many transgressors. For example, since 2011, there have been 11 fines issued in the form of a Financial Administrative Penalty ranging between £250-3480 and four Simple Cautions (devonandsevernifca.gov.uk, 2016). All six transgressions, which have occurred during 2014, are still undergoing investigation (Mat Mander, D&S IFCA (Personal Communication)). These outcomes highlight the need for alternative management measures, which might be more successful than top-down enforcement in which fishers have no input.

Available Science

There are a number of shortcomings of the current CEFAS stock assessment methodology that led to a high level of uncertainty. Crab stocks in English waters are currently assessed by CEFAS, using the Length Cohort Analysis (LCA) method, which assumes that growth rates are constant across year classes. However, the discontinuous growth mechanism of crabs through moulting makes them notoriously difficult to age (Sheehy and Prior, 2008). The LCA method also assumes that 'the fishery is operating over the entire stock' (CEFAS, 2012) whereas the IPA covers just 0.8% of the stock assessment area (ICES Area VIIe), increasing the uncertainty in the stock status outputs, and impacting on the success of the corresponding management measures in a local context. Therefore, as crab fisheries are generally localised, there is a need for locality–specific stock assessments. Furthermore, the LCA methodology does not take into account the life history traits of crabs, such as migration. For example, female crabs in the English Channel make a contranatant migration from east to west down the English Channel, with no evidence of a reverse migration (Hunter *et al.*, 2013). The LCA method does not consider migration as a variable that could affect biomass. Due to the one-way migration of female crabs down the English Channel, stock assessments should consider that the biomass in any one area of the Channel is inextricably linked to the biomass of crabs further to the east.

The science underpinning all of the above management measures have tangible, perceivable benefits, for example, it is obvious that by landing egg-bearing females that potential progeny would be lost, and it is easy to see why crabs should reach sexual maturity and be given the chance to reproduce at least once before they become vulnerable to the gear. However, it is nearly impossible for fishers to comprehend the link between having a quota of crab to catch and perceiving this amount against the entire biomass of stock, especially when they do not have a perception of the stock as a whole. Furthermore, since CEFAS stock assessments only occur every four years, and are produced retrospectively, it is difficult for fishers to focus on the long-term goal of sustainability by reducing effort/landings to produce MSY. Consequently, this project aims to bring the long-term goals of sustainable fisheries to fishers' every day activities.

Due to the aforementioned uncertainties of the stock assessment process, lack of prosecutions against transgressors and the top-down implementation of management measures, fishermen lack both confidence, and engagement in the outcomes of stock assessments and consequent management measures that administer the stocks on which their livelihoods and local traditions depend.

In an attempt to redress these issues, this case study sets out to collaboratively engage and empower fishers to directly input their data and knowledge into the management of the resource they exploit. Whilst this study is unlikely to reduce illegal fishing by trawlers in the IPA, it will improve and update the current scientific knowledge of the fishery e.g. catch, landing and discard rates, as well as capturing fishers local knowledge of the resource. The study intends to improve upon CEFAS stock assessment by using localised data to develop an IBM model of the fishery, using vastly larger sample size than CEFAS and increase adherence to management measures by working collaboratively with fishers so they will appreciate that the data collected to form the model was collected within the IPA.

Description of the Case Study Process

Initial relationship

Collaboration between the scientists and fishermen of this case study began in 2008, as part of the GAP1 Project, although the relationship between scientists at the University of Leicester and SDCSA crab fishermen has been on going since 1996. Crab fishermen were initially approached to take undergraduate students from the University of Leicester, attending a field course on fisheries ecology at the Slapton Field Studies Centre to sea, to experience a day in the life of an inshore fisherman. As more was understood about the unique nature of the IPA, further studies were conducted (Hart 1998; Kaiser *et al*., 2000; Blythe *et al*., 2002, 2004, 2006, 2007). Scientists co-operated closely with local crab fishermen to better understand how the then voluntary IPA agreement between mobile and static gear fishers was maintained and what its conservation benefits were.

After Blythe's research during the early 2000s, contact was maintained with the Secretary of the SDCSA and ideas were developed for more scientific research within the IPA. The Secretary's motivation for further research was stimulated by his belief that the IPA was a great example of fisher-directed management and felt this should be broadcast to a wider audience. The fishery could also benefit economically if it could be demonstrated that crab was being exploited sustainably. This knowledge could be used to raise the market value of the product and the resource could continue to be exploited in the long term. These on-going connections meant that at the start of GAP2 the fisher-scientist partnership was primed to begin collaboration.

GAP1

In 2008, with the initiation of GAP1 preliminary data on the spatiotemporal distribution of crab catches, landings and discards within the IPA was collected. This enabled an assessment of the feasibility of collecting sufficient data to allow for the development of a novel bottom-up, fisher-directed stock assessment approach. The objective of GAP1 was to collect sufficient baseline data and further develop the collaborative relationship between stakeholders to allow for the future success of GAP2. This research provided the foundation for a close working relationship between scientists from the University of Leicester and fishermen of the IPA.

GAP2

The GAP2 project was initiated in 2011. Scientists used SDCSA monthly meetings as a platform to communicate both their ideas and a provisional plan for the project to local fishers. Fishers were asked if they would be willing to take a scientist onboard their vessels once per month for a 12-month period and additionally contribute to seminars, discussions and generally be involved in the project. The fishers did not show great enthusiasm for the proposed research but nonetheless agreed to take part. Their scepticism towards the research derived from previous encounters with scientists and management authorities as already outlined above.

Undertaking Project Work

In July 2011, fieldwork for the project began for a 12-month period. To select fishers whose catches would be a representative sample of the IPA, the area was divided into 8 areas (Figure 2.2.).

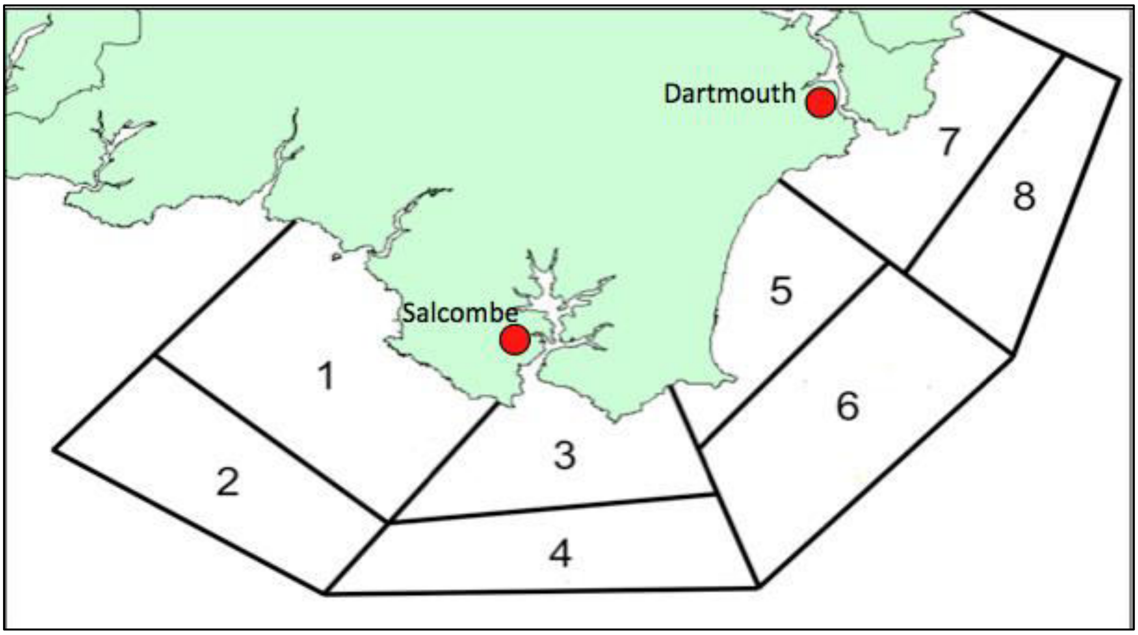

Figure 2.2. A map of the eight areas used to representatively sample the catches of the IPA. The IPA was split into four zones west to east and two zones, namely 0-3nm and 3-6nm.

Information on the spatial distribution of fisher's gear was obtained from Clark (2008). The secretary of the SDCSA provided fisher's contact information. A list of fishermen per area (approx. 3 to 4) was prepared and each fisherman contacted by phone at random. The aims and values of the project were explained to each fisherman individually and fishers were then asked if they would be willing to take part in the project. It was explained that if the fishers agreed they would need to commit to taking a scientist to sea, each month, for one year. Once one fisherman had been found for each area (n=8), no other fishermen who fished in that area were contacted. A summary of the roles undertaken by fishers and scientists for each task during the case study is outlined in Table 2.2.

Onboard data collection process

Weather permitting one trip per vessel per month was organised with each skipper. Once onboard, as each pot was hauled and emptied the number and sex of each individual crab and whether they were to be landed or discarded was recorded by the author. Discarded crabs were recorded as undersized (below MLS), soft-shelled or egg-bearing. In addition, by-catch such as whitefish, other crustaceans, molluscs etc. were documented.

Data were recorded directly on to a digital spreadsheet running on a tablet device. This allowed for the provision of instant, quantitative, catch information feedback to the skipper and crew, which consequently encouraged further discussions on the possible causalities of catch composition between fishers and scientists, which in turn assisted the participatory process.

Semi-Structured Interviews

During onboard trips it became apparent that the vast store of fishers' knowledge of the resource they exploited needed to be captured more coherently than through informal conversations whilst fishing. Therefore, semi-structured interviews were carried out with fishers in their own homes at a convenient time of their choice.

Substrate Surveys

In January 2014, a survey was mailed to all crab fishers operating within the IPA (n=46). The survey aimed to collect information regarding the substrate type within each fishers 'territory', leading to a comprehensive overview of the substrate within the IPA's. Only 11% of fishers replied to the survey with varying degrees of completeness. The poor response to the mailed survey highlights the importance of face-to-face contact with fishers in collecting fine scale, fishery wide data.

Table 2.2. A summary of the roles undertaken by fishers and scientists during the various tasks of the case study.

Case Study Tasks	Scientist Role	Fishers Role
Data Collection	To record landings and discards in space and time. Analyse results and feedback findings.	Take scientist to sea and announce reason for each discard.
Semi-Structured Interview	Provide questions and structure for interviews. Analyse results and feedback findings.	Convey wealth of knowledge regarding fishing and environmental factors to interviewer.
Substrate surveys	Create survey and distribute to fishers. Analyse results and feedback findings.	Completing survey and share knowledge.

Modelling	Developing framework and code model.	Review model and provide feedback to ensure the model reflected the reality of the fishery.

Exchange Visit

In 2012, members of the UK GAP2 case study took part in an exchange trip with members of the Norwegian GAP2 case study. Five Norwegian fishers visited Devon in October 2012 and in return five fishermen from south Devon visited the Norwegian cod (*Gadus morhua*) fishery in Steigen, during April 2013. The project's scientists took part in both exchanges. The visit to Steigen gave the Devon fishers the opportunity to learn about the fishing methods and management measures of the skrei cod fishery that takes place between the mainland of Norway and the Lofoten Islands in early spring. Other than the obvious benefits of learning about the Norwegian case study, this trip provided a platform for scientists and fishermen to informally socialise, integrate and learn together, which in turn built trust through this shared experience.

Results of a Collaborative Approach

As fishers and scientists spent time collecting data at sea, the interest and involvement of fishers in the study, improved over the length of the project. Crucial to the establishment of trust and increased engagement between fishers and scientists was the time at sea, and having one-to-one discussions on wide-ranging fishing related topics. The majority of knowledge transfer and mutual learning took place, at this time. Throughout the project, when fisher's knowledge of a given phenomenon clashed with that of current scientific understanding, the facts as they are known, were offered by scientists and discussed with fishers. Fishers also educated scientists in the same way with their understanding of the fishery and crab behaviour. These informal, mutual-learning events provided a neutral arena for knowledge exchange, thus closing the knowledge gaps of fishers and scientists and allowing for topics to be discussed in greater detail, leading to a deeper understanding from both parties.

As we learnt that fishers appreciated feedback we realised it was important to provide this on a variety of occasions. When scientists collected data onboard immediate feedback was given to fishers regarding the statistics of that day's fishing. Fishers would be shown metrics such as total catch, the percentage of male and female crabs per trip and pot, total discards and by-catch, demonstrating the usefulness of science to fisher's everyday activities. This led to a greater understanding of why fine-scale data collection was necessary to be able to create a model of the fishery and to discussions of all aspects of fisheries science. These discussions were aided by being onboard and therefore topics could be demonstrated or observed rather than merely being described in an interview on land.

Once all data collection trips had taken place, the data from each trip were analysed and emailed to the skipper of each relevant vessel, alongside graphs detailing the seasonal variations in catch composition. Landings and discard data were also presented to all fishermen who attended SDCSA meetings (n=8-15) to give a fishery-wide view of the temporal and spatial distribution of catches across the IPA. Throughout the project, when results from the project were presented to fishers, we encouraged them to say what they thought of the results and how environmental processes could explain the results and crab behaviour in their opinion. Consequently, fishermen commented on how useful it was to see the results of the data collection:

"Normally in other projects it [data] just disappears, we don't know where it's gone, or what it is being used for. This concerns fishermen as they do not know if it might be used against them in future for stock management or assessments without them knowing. With GAP2 we will be left with some tangible information at the end of the project which we can use ourselves to improve our fishery in the future and data that we know is reliable as we were involved in the collection of it throughout the whole process." - Fisherman 1a.

The continuity in communication between fishers and scientists then re-enforced the relationships that had been established during trips to sea. Fishers commented:

"With your [participatory research] approach you came to us [fishers] and explained exactly what you intended to do and what you would be using the information for and involved fishers from the very beginning, which inherently builds trust and participation. Also, the fact that you came aboard the boats and collected the data yourself on multiple occasions over a long period of time really aided the understanding of your project by fishermen. Once the data had been collected from the fishermen you didn't just disappear but kept returning to our meetings informing us of progress made, explaining other technical issues to us and helping in our monthly meetings with other fishing related issues. This whole process led to multiple strands of cohesion, producing a very strong bond between fishers and scientists." Fisher 5.

During fieldwork there was almost daily contact between fishers and scientists. Since June 2012 we have maintained regular contact with the crab fishermen by phone, email, social media and by attending monthly meetings of the SDCSA until March 2015.

Within the tight-knit fishing community of south Devon trust is paramount. When communicating with fishers, it is vital to remain neutral and not to discuss the catches of other vessels with competitors, as that would lead to trust being irreversibly lost. Trust was also maintained by promising anonymity of catch data and fishing grounds when showing data to people outside of the case study area. If trust is lost with just one member of the fishing community the repercussions of this could be felt throughout the community. It is also essential to follow up on promises made to fishers, no matter how small, be personable and helpful where possible in every aspect i.e. with data or information or simply helping onboard with processing the catch or the running of the boat.

GAP2 scientists demonstrated their commitment to the SDCSA fishers by completing monthly 500 mile round trips to attend SDCSA meetings. These meetings often discussed management issues outside the remit of GAP2 where the scientists could provide an alternative viewpoint, explain technical issues or help with interactions with other bodies. For example, the efforts of the UK Government following the Marine Strategy Framework Directive, to set up Marine Protected Areas (MPAs) and MCZ's has created problems for the crabbers. Scientists in the GAP2 partnership have been able to write letters to Natural England, and other bodies, to make a case for the preservation of the IPA as a stand-alone entity.

Fishers (n=~6) have also attended seminar evenings run by the GAP2 scientists to discuss how the IBM could be structured. Scientists and fishermen discussed in detail which environmental variables should be included in the model to make it realistic. Scientists described the mechanics of the model and explained how fishers might use the model once it was developed. However, fishers did not think that the model would be widely used to set catch levels in the IPA for the coming year, as they broadly believe the fishery is already sustainable. Instead, they were interested in the model as a tool to demonstrate the sustainability of the IPA to management authorities such as the IFCA, MMO, CEFAS and DEFRA. The existence of the model and its outputs might also help give fishers greater credibility when discussing management issues with these agencies and attaining some type of sustainability accreditation or eco-label for an increased market value of their product.

As time passed and trust developed the fishers became more forthcoming with ideas for how to collect environmental data, to capture their knowledge on the resource they exploit and to give ideas on how to automatically record their catch and discard data without the need for an onboard observer. The GAP2 Project has led to other opportunities for IPA fishers such as taking part in the Prince's Trust Fishing into the Future (FITF) project (of which one of the Devon crabbers is now Chairman) and increased the confidence of fishers to become involved in similar projects. Fishers have also been encouraged to attend the annual GAP2 meetings, with one attending the 2013 meeting and two at the 2014 meeting and three in 2015, (along with the local senior IFCA manager) which they would not have done voluntarily before the GAP2 Project. Therefore the project has empowered fishers to contribute their valuable input at such meetings.

Discussion

The disengagement of fishers from the management of the fishery they exploit often leads to misconceptions about stock assessments, which is compounded by poor explanation of the assessments when they are disseminated. Common misconceptions are that: fishers believe data were not collected directly from the fishery that they exploit, and therefore management measures are not relevant to their fishery; that all crabs should be counted to be able to do an accurate stock assessment; and that decades of previous exploitation indicates that the fishery must be sustainable in the long-term. Most frustrating for fishers is that they lack a well-established communication channel to engage with the government bodies that carry out the stock assessments and enforce the resulting management measures.

In an attempt to mitigate these problems this case study set out to bring together fishermen from south Devon and fisheries scientists from the University of Leicester to collect FLEK, fine scale spatiotemporal catch, discard and landings data. These data combined with knowledge from the scientific literature and FLEK was used to create a dynamic IBM of the inputs and outputs to the fishery (See Chapter 6). The case study has been successful in attaining this aim through collaboration between fishermen and scientists.

A collaborative approach to setting up a management tool was deployed in three parts:

- Fishermen took scientists to sea with the main aim of collecting data but also to allow face-to-face interactions, which led to the development of trust and mutual understanding, as described.

- Through semi-structured interviews of local fishers, scientists recorded fishers' knowledge of the resource and of the environment.
- Data feedback and discussions took place to contribute to the development of the IBM.

The key to the success of this project was the time spent onboard vessels building a rapport with fishers. The level of interaction between fishers and scientists within this project would not have been possible without the repeated sea trips together. The simple act of being onboard the vessels together led to irreplaceable insights for both parties regarding the realities of fishing and of fishery science, which could not be achieved by any other means.

Shortfalls

Although a core of local fishers have been involved in all aspects of the UK GAP2 Project, this core constituted only about 20% of the SDCSA members. The silent majority did not make an appearance at the monthly meetings and were not easily contactable. The SDCSA monthly meetings are the primary platform used to engage fishers with broader aspects of their business and with the GAP2 Project in particular. The meetings were open to all fishers within the IPA, as one has to be a member of the SDCSA to fish in the IPA. The core of fishers involved in the GAP2 project, were largely similar to the core of IPA users who regularly attended SDCSA meetings. No attempt was made by scientists to engage fishers who did not attend monthly SDCSA meetings or take scientists to sea in the project. Upon reflection this issue should have been tackled early in the project to increase engagement.

A further shortfall of the UK crab case study was that it was heavily scientist-led. As previously mentioned the ideas and aims of the project were initially suggested by scientists and passively agreed to by fishers, whereas in a true collaborative project both parties would have mutually derived the aims of the project.

The physical distance between the University of Leicester and the research site in south Devon, (240 miles) in some instances had a detrimental impact on the project. Fishers were frequently contacted by telephone, text or email instead of face-to-face, which would have been more beneficial. The distance also restrained scientists from attending meetings other than the monthly SDCSA meeting, such as MCZ consultations and IFCA meetings.

At the outset of the case study, effort should have been made by scientists to incorporate both fishers and local managers such as IFCA officers into the project. However, the latter were intentionally not engaged at the outset. Early on in the project during onboard data collection and general conversations with fishers it became obvious that a large proportion of fishers did not think of the local IFCA favourably. So as not to sacrifice the success of the case study at this early stage the scientists did not involve the IFCA in the project. In hindsight the IFCA should have been involved from the start. This has become evident as we saw that the Principal Environmental Officer of the Devon and Severn IFCA attended most monthly meetings and although there was always some antagonism between the IFCA representative and the fishers, there was considerable mutual understanding and trust was built over several years by their continuing attendance at meetings. Had we understood this earlier, with hindsight it would have removed our fears that association with the IFCA could have undermined the fishers trust in the scientists.

While the ultimate aim of the project has remained constant the objectives to achieve this aim have not been fixed. At the outset there were no time-dependent expectations outlined to fishermen. This reduced the perception of failures and as and when milestones were achieved they were perceived as successes, this built trust and a sense of achievement. Similarly there were no initial goals regarding numbers of fishermen to engage. Fishers were asked if they wanted to be involved and for those who decided to take part in the project, their motivation was purely intrinsic. This intrinsic motivation meant that fishers were only involved if they wanted to be due to their belief in the values of the project. Therefore, future engagement was gained 'organically', usually by word of mouth from already engaged fishermen. This led to a strong stable core of fishers involved in the project, in this sense the collaboration grew from the bottom up.

This case study was the first of their kind to collaborate in the manner set out above. To set up and execute research focused on creating sustainable fisheries whilst facilitating the involvement of stakeholders and use an Individual Based Model and to create detailed plans to implement the projects findings.

Future Work

The next step is to create legitimacy for the bottom up approach that we have been developing and integrate the approach into pre-existing the management system (see Chapter 6). This needs to be done with the current management agencies such as the MMO, the Devon and Severn IFCA and DEFRA. Without this, the approach we have taken will not be absorbed into the established management system and the interest of crab fishers in local management issues that has been developed through this project will dissipate after the GAP2 project finishes. Additionally, for future catch levels to be set, fishers will need to record their own data. The current method of stock assessment employed by CEFAS uses data reported by fishers to calculate landing volumes and fishing effort. Hence, in principle the credibility of self-collected data should not be challenged. Additionally, the IBM will be subject to a scientific peer review process, ensuring its credibility as a tool for use in managing the fishery.

Conclusion

The 'gap' between fishers and scientists has been reduced and there are now strong working relationships in place between these two parties. While this project was heavily scientist-led, it has bridged the gap between fishers and scientists through creating mutual exchange of data, opinions and ideas. Prior to this project, fishermen in the IPA had not been collaboratively involved in many research projects. Therefore, the GAP2 project bridged the gap between fishers who have been requested in the past to provide data but have had no further feedback or involvement with the research, and a truly collaborative project. The project has given fishers the skills and confidence to become involved in future projects and has highlighted the value of collaborative research to both scientists and fishers.

To this end, the attitudes of some of the fishers to collaborative research within the SDCSA have changed positively. Fishers feel empowered as they are 'listened to' and now have a communication channel through which they can 'have their say' and be heard by local managers. By giving fishers feedback from the data collection process, a positive feedback loop is created; the more information they receive, the more they want to know and the more they become involved in the research process.

The greatest future challenge is to translate the outcomes of this collaborative research into management measures that all fishers implement within the IPA and which operate within the context set by the Severn and Devon IFCA, MMO and the EU, after GAP2 has completed.

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Chapter 3

The spatial and temporal distribution of crab catches off south Devon, UK.

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Abstract

Fishermen and scientists have worked together with the aim to representatively sample high-resolution catch, landing and discard data from the south Devon crab fishery. We developed and demonstrated a methodology to enable a bottom-up approach to gather scientifically robust spatiotemporal data on an economically important and intensively exploited fishing ground, called the Inshore Potting Agreement area (IPA), Devon. Nine vessels participated in the study over a total period of 8 months. While the scientist was onboard fishers would empty their pots as usual and call out the sex of the landed crab and the sex and reason for discarding, as the catch was sorted. This information along with the GPS of each pot and other environmental variables were recorded onto a spreadsheet running on a tablet device. This method of recording data enabled instant feedback of catch statistics to fishers, which encouraged them to record further data. Time-series plots were created showing the seasonality of the catch, landings and discards, and contour maps were constructed to plot the spatial distribution of the catch, landings and discards over time.

Statistical analysis showed numerous significant differences in space and time for Catch per Unit Effort (CPUE), Landed per Unit Effort (LPUE) and Discards per Unit Effort (DPUE) delineating the seasonal and spatial pattern of crab catch distribution. There were significant differences between CPUE from the eastern and western areas of the IPA indicating, that over the summer months with more crabs caught in the east, congruent with the knowledge from Hunter *et al*., (2013) that females migrate from east to west down the English Channel. Further, we analysed CPUE, LPUE and DPUE for variation between inshore areas (0-3nm) and areas further out at 3-6nm, to elucidate if there was an ontogenetic movement of crabs in the IPA. Results showed that there were significant statistical differences for total small and female small crabs between 0-3nm and 3-6nm from shore. Indicating there is an ontogenetic movement offshore as in both cases the mean for small discards were significantly higher in the 0-3nm category compared to 3-6nm.

In conclusion, the study developed a method by which fine scale data could be collected onboard vessels to show the spatiotemporal variation of the catch and engage fishers in the approach.

Introduction

The English Channel is a major area of edible crab (*Cancer pagurus*) production in Europe (Hunter *et al.,* 2013). The ports of Salcombe and Dartmouth, in Devon, account for 59% (£18.9 million) of the total value of UK landings (MMO, 2012). In the past, the Devon crab fishery has been responsible for the highest catch per unit effort (CPUE) in Europe (Brown and Bennett, 1980). This highlights the importance of the fishery, in terms of local socio-economics and for the supply of crab to the food market and emphasises the need for the fishery to be managed sustainably now and in the future.

Despite this there has been little research detailing its catch rates since the 1980's. Bennett (1979), Brown and Bennett (1980), Bennett and Brown (1983), carried out extensive studies on the abundance and distribution of crab in the English Channel and more specifically the Devon crab fishery. They asked fishers to complete daily logbooks over 5 years (1971-76) to capture information on parameters such as the seasonal and spatial variation of: CPUE, LPUE (Landings per unit of effort) and DPUE (Discards per unit of effort), sex ratio, size distribution, and the moulting period of *Cancer pagurus*. However this data is over 30 years old and requires new investigation.

The present levels of exploitation for edible crabs are investigated by CEFAS stock assessments approximately every four years. In the western English Channel, the current CEFAS assessment in 2014, reported that fishing effort was 'moderate to low', with an exploitation level close to that producing Maximum Sustainable Yield (MSY) (CEFAS, 2014). Additionally, spawning stocks were rated as 'Good' and sufficient to sustain MSY. Notwithstanding this stock assessment, in recent years there has been a notable increase in UK crab landings from ~20,000 tonnes in 1994 to ~29,500 tonnes in 2012 (MMO, 2012). This rise in landings can be partly attributed to the provision of voluntary landing reports from the under 10m vessel fleet, operating in inshore waters since 2006. These vessels were not previously required to report catches and therefore an artificial rise in landings was observed. Modernisation of this fleet, along with the advent of large mobile vivier crabbers, the extension of the inshore fisheries to offshore grounds and an increase in the number of pots have all also been implicated as causes for increased landings (Bannister 2009). Nevertheless, an overall lack of data means that the degree to which commercial exploitation is affecting crab stocks is difficult to quantify. Consequently, Bannister (2009) recommended 'a precautionary approach to future crab fishing' and 'the setting of a management objectives to prevent any further increase in fishing mortality in UK crab fisheries'.

Current management

See 'Chapter 1- Current Management'

Establishment of the IPA

In the 1970's, Devon fishers demonstrated 'self motivation' to manage their own fishery by designing, implementing and adhering to their own solutions to localised fishing issues such as gear destruction. They created seasonally open and closed areas to mobile gear to mitigate static gear loss; they collectively called the areas the 'Inshore Potting Area Agreement' (IPA) (Blyth *et al.,* 2002). In 2002, the IPA was set in a legal framework by the IFCA, 30+ years after its instigation. Although the IPA was initially founded to reduce the number of crab pots being destroyed by trawlers and dredgers and the obvious consequent financial loss, it has had significant unplanned conservation benefits (Kaiser *et al.,* 2000b; Blyth *et al.,* 2002, 2004, Blyth-Skyrme *et al.,* 2006; Kaiser *et al*., 2007). Numerous areas of the IPA have not been trawled for 40+ years, and as such are on occasion intentionally and illegally trawled for large scallops (*Pecten maximus*), which can be found on the un-trawled beds. Since November 2014 there have only been 6 prosecutions by the IFCA for 3 vessels caught trawling in the closed areas of the IPA (See Table 3.1.), despite frequently reported infringements by crab fishers to their secretary at monthly meetings of the SDCSA (Personal Observation).

Table 3.1. A summary of the prosecutions of Devon and Severn IFCA investigations from November 2014 to the latest update September 2015 (source: devonandsevernifca.gov.uk/Bye_laws).

Offence Date	Offence	Location	Outcome/ Current Status
28/11/14-01/12/14	Using demersal towed gear in a closed area.	South of Start Point	Master and Owner fined a total of £18,740
15/12/14	Using demersal towed gear in a closed area.	South of Start Point	
08/02/15	Using demersal towed gear in a closed area.	Northeast of Start Point	Master and Owner fined total of £13,250
09/02/15	Using demersal towed gear in a closed area.	Northeast of Start Point	
16/03/15	Using demersal towed gear in a closed area.	South of Salcombe	
29/06/15	Using demersal towed gear in a closed area.	Start Bay	Written warning
22/07/15	Removing undersize edible crab otherwise in accordance with the potting permit	East of Start Point	£250 FAP accepted

The establishment of the IPA by the fishers demonstrates their willingness to try new management methods for the benefit of the fishery, the lack of prosecutions for illegal trawling by the authorities, and recent increase in landings indicate a new method for local management involving all stakeholders could be more successful than the current top-down regulations.

The present method used to collect data for CEFAS stock assessments, requires skippers of under 10m vessels to fill out paper forms called Monthly Shellfish Activity Returns (MSAR's). The form details the ICES area (i.e. location) in which the landings are taken, effort (number of pots), the weight and sex of each species and the number of days fishing. At the end of each month, fishers post this form to the MMO, DEFRA and CEFAS, where it is manually transferred to a digital copy, at a cost of over £50,000 per year (Personal Communication, Ewen Bell). CEFAS then use these data to create a stock assessment (in the case of this fishery) for the western English Channel. Once the assessment has been completed it is summarised on a two-page hand-out and a representative from CEFAS visits the concerned fisher's organisations to deliver the results. These results are written in the language of a fisheries scientist and therefore not easily understood by those not familiar with the concepts of fisheries science and as a consequence the detail and reasoning are largely ignored.

The low percentage of prosecutions compared to reported illegal trawling infringements and the low number of random spot-checks for technical measure infringements carried out by IFCA, combined with the technical language used to deliver stock assessment outcomes, leads to fishers feeling disenfranchised from their local stock assessments, bye-laws and, by extension, fisheries managers and their institutions.

While the aforementioned assessments indicate a healthy fishery in south Devon (as part of the western English Channel), the management of the fishery and engagement of the stakeholders should be improved in anticipation of increasing pressure on stocks, and possible amplified technical measures in the coming years. In preparation for this fishers and managers need to build solid relationships based on transparency and trust, where data, results and management decisions are tackled by a bottom-up approach with all stakeholders and managers fully engaged.

We executed the aims of this study by working on-board and in co-operation with fishers from the South Devon and Channel Shellfishermen's Association (SDCSA) as part of the GAP2 Project (see Chapter 2). A further aim was to demonstrate how this methodological blueprint could be integrated into local IFCA fisheries management and how a collaborative approach can lead to better data and knowledge flow between fishers and managers, which should ultimately lead to well-managed and more sustainable fisheries with engaged stakeholders (Chapter 7).

To give focus to the fine-scale data collection programme the fieldwork was designed to collect data to answer three questions and test two hypotheses about the distribution and abundance of crabs within the IPA. The following three questions and two hypotheses directed the investigation:

Three questions:

- How does CPUE vary spatiotemporally within the IPA?
- How do Landings per Unit Effort (LPUE) vary spatiotemporally within the IPA?
- How do Discards per Unit Effort (DPUE, small and soft) vary spatiotemporally within the IPA?

Two hypotheses:

- The highest CPUE of crab is found in the eastern sector of the IPA is due to female migration down the English Channel from the east.
- Lower DPUE of undersized crabs found in 3-6nm areas compared to 0-3nm areas due to ontogenetic movement of crab to deeper water.

Study Area

For detailed information on the IPA see Chapter 1- The present south Devon crab fishery.

Approximately, 35 vessels currently fish for crab the Devon and Severn IFCA, employing around 70 crew fishing over 13,000 pots (Clark, 2008) (See Table 3.2.).

Table 3.2. The number of vessels, their crew, and the number of pots being fished within the DSIFCA, categorised by home port.

Home Port	Number of Vessels	Number of Crew	Number of Pots
Dartmouth	19	41	7725
Salcombe	16	29	5551
Total	35	70	13276

Methods

Vessel Selection

We were able to engage nine vessels (approximately 25% of total fleet) to representatively sample the IPA for crab catch (Table 3.3.), eight of which participated in the full sampling period, and one of which collected data in July and August 2011 only. The IPA was divided into four sections from west to east (Bigbury Bay to Salcombe, Salcombe to Start Point, Start Point to Blackpool Sands, Blackpool Sands to Berry Head), and then split into 0-3nm and 3-6nm sections from the coast (Figure 3.2, henceforth areas 1-8). A vessel was then selected from each section by the following method.

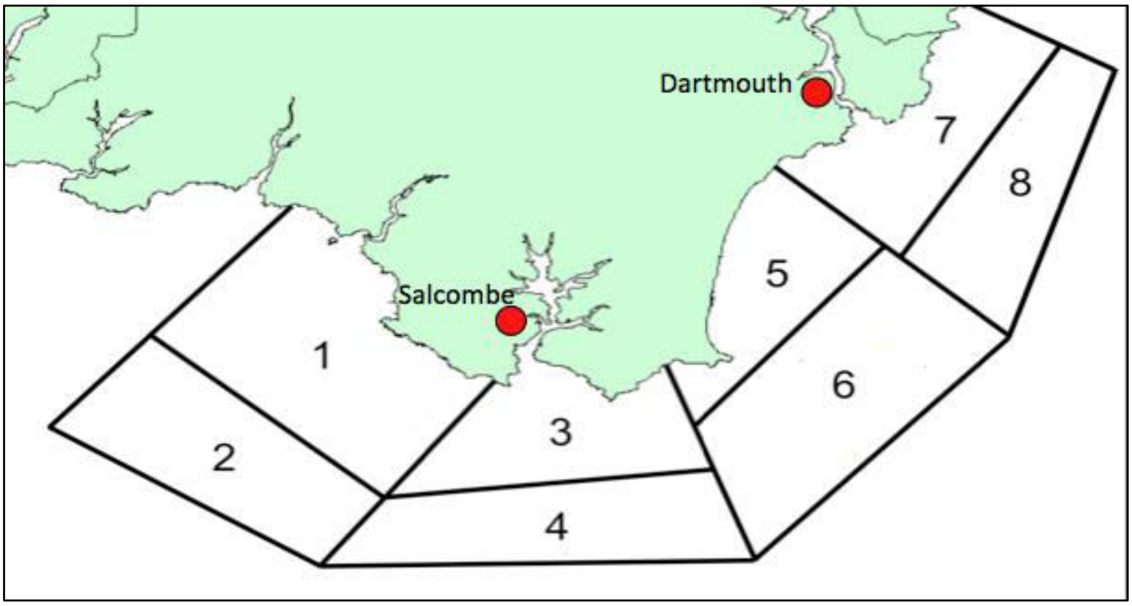

Figure 3.2. The IPA area divided into 8 areas for the purposes of data collection (1-8).

The secretary of the SDCSA supplied a list of vessels, which worked within the IPA and their corresponding 'territories' to the author. A vessel within each areas was selected from the list and the skipper telephoned at random and asked if they would like participate. If a skipper declined to participate (n= ~2), another skipper was selected within the same area. Reasons for declining to participate could have been: not enough space on deck, bad luck for a female to be onboard, fishers did not feel the benefit of the study to their vessel or simply did not want an external observer onboard. To maintain the confidentiality of fisher's sensitive catch data, we refer to the areas fished, rather than to individual vessels (See Figure 3.2. and Table. 3.3). Fishers were not paid for their participation in this study, but were reimbursed for their time once the GAP2 project had ended, which they did not expect, therefore participation was purely voluntary and not for financial reward.

Table 3.3. The vessel code and corresponding area of fishing of each vessel along with vessel length, number of crew, the mean number of pots fished and the home port.
** For reasons of confidentiality the length is rounded to nearest meter.

Vessel Code	Area Fished	Length (m) **	Under 10m or under 15m	No. of Crew	Mean number of pots	Home Port
1	1	8	<10m	2	258	Salcombe
1a	1	10	<10m	3	347	Salcombe
2	2	12	< 15m	2	376	Salcombe
3	3	8	<10m	2	201	Salcombe
4	4	15	< 15m	3/4	551	Salcombe
5	5	15	<15m	3	420	Dartmouth
6	6	14	< 15m	2	601	Dartmouth
7	7	9	<10m	2	362	Dartmouth
8	8	10	< 10m	1	52	Dartmouth

Five of the vessels participating in the study were under 10m with the other others under 15m. The factor, which varies most significantly between vessels, in the IPA and any static gear fishery is effort, in the study we refer to effort as determined by the number of pots fished. As the effort produced by each vessel varies we standardised the catch, landings and discard data by calculating catch per unit effort (CPUE) in this case catch per pot, Landings per unit effort (LPUE) and Discards per unit effort (DPUE).

Use of 'per unit effort' as a standardised measurement

CPUE is a quantitative method used to describe fisheries worldwide (Appleman, 2015) it is a measure of fisheries dependent catch, landings and discards. Throughout this study 'per unit effort' was used capture the variation of catch, landings and discard in time and space. Murray *et al.,* (2010) compared CPUE values for Green Shore crab (*Carcinus maenas*) with quantities counted during underwater visual surveys. They found CPUE not to be a good proxy for abundance as activity/feeding rates (and thus catchability) vary with sea temperature. Nonetheless, this study is not directly estimating abundance *per se*, but measuring the catch, landing and discard rates of the fishery to create a fisher-directed stock assessment of the IPA. Catch per unit effort is used to construct fisheries abundance indices on the assumption that CPUE is proportional to population abundance (Dunn et al., 2000) and has been used by fisheries scientists as an index of population abundance (Seber, 1982) for decades. Furthermore, alternative methods to gain estimates of crab abundance such as underwater visual surveys are costly, time consuming to review footage and also give no information such as sex, whether crabs were under or over MLS or their shell condition (soft/hard). Additionally, by using 'per unit effort' to measure catch rates we did not interrupt normal fishing activity and at the same time gained an insight into the daily activity of fishermen by being onboard.

Factors, which could effect the standardisation of 'per unit effort' measurements are soak time (or pot immersion time - the amount of time pots are on the benthos fishing) and pot size. Fishers in the IPA attempt to clear their pots every other day (48 hours) during most months apart from winter, when soak time is usually longer (3-5 days) due to the lower rates of crab catch and occurrence of bad weather limiting days at sea. Bennett and Lovewell (1974a) studied the effect of pot immersion time on CPUE and found that a two-day immersion time captured 88% of catch. Furthermore, crab CPUE per day is negatively related to soak time (Bennett, 1974a) due to pot saturation (the physical limiting of space for new crabs to enter the pot) due to the crabs already captured occupying space in the pot. Due to the high percentage of crabs caught within the standard interval between pot hauls we will not control for soak time during this thesis. The effect of pot size as a consequence of pot saturation could also affect CPUE. In the IPA fishery two types of pot are used Inkwell pot and Parlour pot (See Chapter 5). A calculation of an inkwell and parlour pot size gives the outcomes below in cubic meters.

Inkwell: Volume calculated using equation of a Conical Frustum=
$1/3 \times \pi \times 50 \times (17^2 + 17 \times 33.02 + 33.02^2) = 101612 cm^3 = 0.10 m^3$

Parlour: Volume calculated using equation of a half a cylindrical tank=
$(\pi \times 34^2 \times 65)/2 = 118029\ cm^3 = 0.12 m^3$

A mature male crab with the following dimensions: 20cm (carapace width) x 15cm (carapace length) x 10cm (height) gives a crude volume per crab of $0.003m^3$ indicating that hypothetically the volumetric difference between the two types of pots would be ($0.02m^3/0.003m^3$)= 6.66 crabs. However, the chance of a pot being totally saturated in this way is very uncommon. Therefore due to the small difference in possible highest CPUE between the two pot types we decided not to control for pot size in this study.

Onboard data recording

Fieldwork took place from July-November 2011, then again from April - June 2012. Days at sea during December to March were likely to be minimal due to poor weather conditions, so data recording did not take place over the winter period. To mitigate this data shortfall, a system was set up with a subset of participating fishers (n=5) to provide their LPUE over the winter. As will be discussed, this system was not entirely successful.

Weather permitting data collected occurred on each vessel once per month. Vessels were sampled at different times of each month to remove confounding variables associated with tidal state. During each sampling trip, we aimed to collect the following environmental data: weather (overcast, clear, rain, sunny etc.), sea state (Beaufort Scale), seabed substrate (as supplied by fishers knowledge and sonar), and seabed depth (from vessel sonar). As well as the GPS location of the first and last crab pot per string (from the vessel navigation system), the times at which the first and last pots were hauled per string, estimation of pot soak time, type of pot (inkwell or parlour), and the type of bait used.

The following procedure was then repeated as each pot was hauled and emptied by fishers: we recorded the number and sex of each individual crab and whether they were to be landed or discarded. Discarded crabs were recorded as undersized (below MLS), soft-shelled or egg bearing (henceforth referred to as small, soft and berried, respectively). If small crabs were also soft, for the purpose of this study, they were categorised as small. Other reasons for discarding were: both claws missing, and shell disease. All by-catch was documented to species level.

Data were recorded directly to a pre-formatted spreadsheet running on a tablet (iPad). In the case of very wet weather a printed version of the spreadsheet was drawn onto a dive board and transferred on to paper whilst each string of pots was being put back into the sea. The digital form allowed the provision of instant quantitative feedback on catch metrics, encouraging further feedback and discussion between fishers and scientists about possible causes of the catch patterns recorded, so aiding the fishers to develop a sense of participation in the study and engage in the fisheries science (See Chapter 2).

As soon as several months of data had been gathered and analysed, results were presented to fishers at SDCSA monthly meetings and this was repeated throughout the study. Fishers were encouraged to give feedback on the data, which had been collected onboard their vessels and to offer their insights into the findings. This feedback was recorded and integrated into the study at a later stage.

Missed Samples

We aimed to sample each vessel once per month, but on occasion, due to bad weather vessels could not leave the harbour. Consequently, not all areas were sampled each month. Other reasons for missed samples were; a fisher withdrawing from the study, and the observer not being able to contact a fisher to organise a sampling trip in a specific month (see Table 3.4.). As such there was a 3-month period encompassing July, August and September 2011 when data from 5 vessels (1a, 2, 4, 5 and 6) could be compared statistically. In all other months between 3- 7 vessels were sampled, however the areas sampled were not similar and could not be directly compared.

Table 3.4. The months in which, areas 1-8 (Figure 3.2) were surveyed. Grey: Onboard trips were not attempted due to the winter months or to vessel withdrawing from the study, or not yet being recruited (Area 3). Black: Fishers could not be contacted or bad weather meant a trip to sea was not possible. White: successful sampling occurred.

	Area								
	1	**1a**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
July 2011				Grey					Black
August	Black			Grey					
September				Grey				Grey	
October	Black	Black		Grey		Black	Black	Grey	
November	Black	Black		Grey			Black	Grey	
December	Grey	Grey	Grey	Grey	Grey	Grey	Grey	Grey	Grey
January 2012	Grey	Grey	Grey	Grey	Grey	Grey	Grey	Grey	Grey
February	Grey	Grey	Grey	Grey	Grey	Grey	Grey	Grey	Grey
March	Grey	Grey	Grey	Grey	Grey	Grey	Grey	Grey	Grey
April			Black			Black	Black	Grey	Black
May	Black	Black						Grey	
June		Black			Black		Black	Grey	Black

Data Analysis method and software

'Surfer 10' software was used to create contour maps of the CPUE, LPUE, and DPUE to display the monthly spatial distribution of crabs. The GPS of each pot with its catch, landings and discards were plotted separately for each month. The software interpolates between the real data points and estimates the catch for the areas in between. The colour scale was standardised for all plots, purple shades indicated 0-4 CPUE, LPUE and DPUE, through to red shades demonstrating the highest CPUE, LPUE and DPUE at 13-14.5 crabs per pot. The plots were superimposed onto Google Earth to give geographic reference therefore the background of the maps is blue indicating 'the sea' and not a colour representing a quantity of crab. The parameters used to create the contour maps can be found in Appendix A. The spatial distribution of crab catch expressed as the number of crabs per pot, from July 2011 to June 2012 (omitting December 2011- March 2012) are displayed in contour maps (Figure 3.10-3.13). Other software employed for statistical analysis was Microsoft Excel and JMP Statistical Software. To vastly extend the time series of landings data for the IPA we incorporated fisher's diaries data from 2003-2012 in to the study.

Fishers Diaries Data

Four vessels from Areas 1, 1a (the second vessel to give data in Area 1), 4 and 5 (Figure 3.2), kindly donated 10 years (2003-2012) worth of their self-collected diaries data for analysis. The diaries recorded landings of each sex, in kilograms per string of each fishing trip undertaken, which were then converted to kilograms landed per pot (KLPUE) by diving by the number of pots per string, and provided a much larger data set than onboard data (See '*Analysis of data extracted from fisher diaries*'). A disadvantage of using this self-collected data could be in accurate observations. However the fishers use their diaries to check that they have been paid correctly for their catch per trip by the processing factory. The factory weighs the crab before processing and pays the fisher accordingly. Therefore, one would expect the fisher's observations to be accurate within a few kilograms. Furthermore, at the time the landings were originally recorded the fishers would not have known that their diaries would have been used this study. A disadvantage of diaries data is that no discards are recorded. A table showing the completeness of fisher diaries from 2003- 2012 can be seen in Appendix C.

Results

Data gathered onboard

Catch, landings, and discards - overall results

In total, 58,238 crabs were caught during 42 sampling trips over an 8-month sampling period. There were 31,055 crabs landed with the remainder discarded. The total catch consisted of 16.6% males, and 83.4% females. The number of male crabs landed (1,767) was considerably less than females (29,288). The proportions of crabs discarded were as follows: small 62.3%, Soft 37.6%, and berried females just 0.1%. A full description of the number of crabs caught and landed is shown in Table 3.5.

Table 3.5. A summary of the number of crabs caught, landed and discarded during 42 sampling trips. The proportion of males and females in each category is detailed along with the reason for discarding.

<table>
<tr><td colspan="7">Caught</td></tr>
<tr><td colspan="7">58,238</td></tr>
<tr><td colspan="4">Male</td><td colspan="3">Female</td></tr>
<tr><td colspan="4">9,686 (16.6%)</td><td colspan="3">48,552 (83.4%)</td></tr>
<tr><td colspan="2">Landed</td><td colspan="5">Discarded</td></tr>
<tr><td colspan="2">31,055 (53%)</td><td colspan="5">27,183 (47%)</td></tr>
<tr><td>Male</td><td>Female</td><td colspan="2">Male</td><td colspan="3">Female</td></tr>
<tr><td>1,767 (5.7%)</td><td>29,288 (94.3%)</td><td colspan="2">7,919 (29.1%)</td><td colspan="3">19,264 (70.9%)</td></tr>
<tr><td colspan="2"></td><td colspan="5">Soft 10,225 (37.6%)</td></tr>
<tr><td colspan="2"></td><td colspan="5">Small 16,931 (62.4%)</td></tr>
<tr><td colspan="2"></td><td>Soft</td><td>Small</td><td>Soft</td><td>Small</td><td>Berried</td></tr>
<tr><td colspan="2"></td><td>2,008 (19.6%)</td><td>5,911 (34.9%)</td><td>8,217 (80.4%)</td><td>11,020 (65.1%)</td><td>27 (0.1%)</td></tr>
</table>

The mean number of crabs caught per pot (CPUE) over all sampling trips was 3.95 (±1.22 s.d.), the mean number of crabs landed per pot (LPUE) being 2.24 (±1.25 s.d.) and the mean number discarded crabs per pot (DPUE) was 1.72 (±0.74 s.d.). To elucidate the spatiotemporal patterns of the fishery the CPUE, LPUE and DPUE are subsequently analysed in terms of space, time and by individual sex.

Temporal variation of catch

Catch per Unit of Effort –both sexes combined

To gain an overall insight into the pattern of crab catch in the IPA we plotted the average CPUE per month from all vessels. The highest mean CPUE over all months from the data gathered at sea was in October 2011 (mean 4.41, ±1.77 s.d.), and lowest in April 2012 (mean 2.96, ±1.22 s.d.) (Figure 3.3.). The seasonal peak of CPUE was observed between August and October, declining steeply in November.

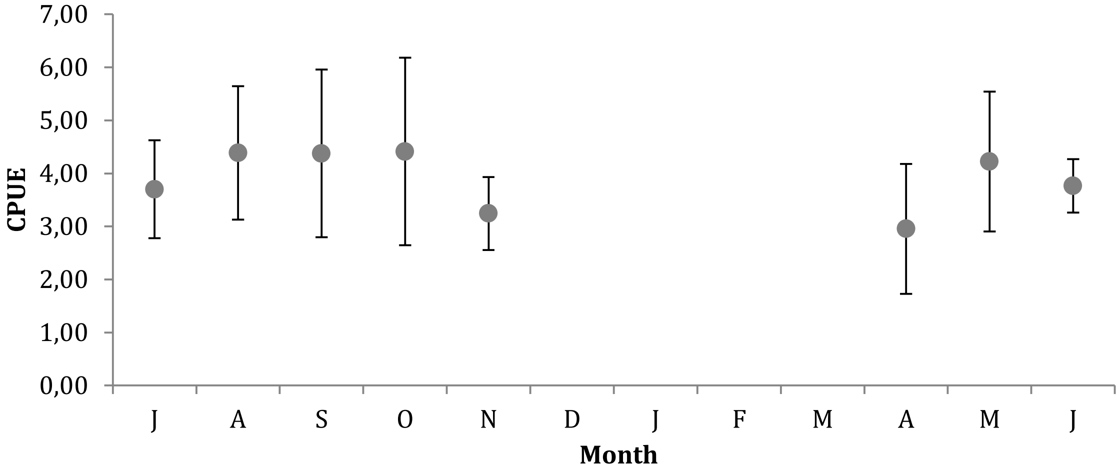

Figure 3.3. Mean ± standard deviation CPUE for all crabs caught from July 2011 to June 2012. Data was averaged by month from all vessels surveyed (n=9). Grey Dot= CPUE.

Landings and Discards per Unit Effort - both sexes combined

The average proportion of landings to discards were combined over all vessels to demonstrate how this changed over the season. It is pertinent to demonstrate the landings to discard ratio throughout the year to elucidate crabs annual life history events (such as discards due to moulting) and also to see when fishers can fish with most efficiency i.e. when landings are highest with lowest discards (and time spent sorting catch which is not profitable). The highest average LPUE occurred in October (3.33) equating to 76% of crabs caught being landed, and the lowest in April (1.97) with 33% of crabs being landed (Figure. 3.4).

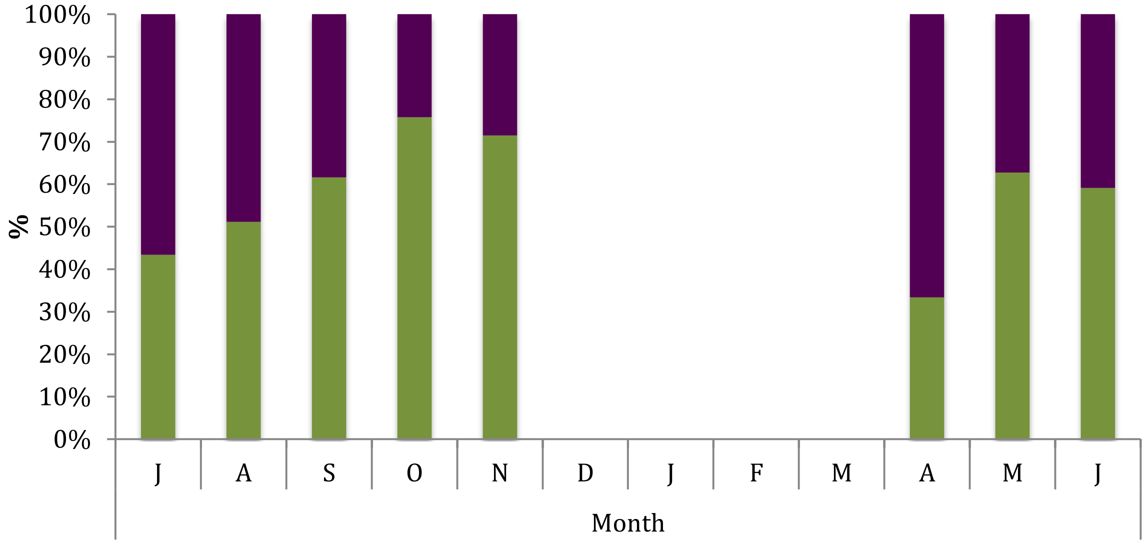

Figure 3.4. The mean landed and discarded crabs per unit effort from July 2011 to June 2012. Green= crab landed, Purple= crab discarded.

Crabs landed per unit of Effort - by Sex

A breakdown of the landings by sex revealed that female crabs were the predominant sex in all the months sampled (Figure 3.5.) indicating to fishers and managers that resources should be focused on females. There are two obvious peaks in the landings of female crabs. The first peak is observed in May with 2.41 crabs landed per pot (±1.26 s.d.) and a second peak in October with 3.30 LPUE (±1.73 s.d.). Curiously, as with CPUE, when the lowest LPUE of female crabs occurred in April the highest LPUE for male crabs was recorded at 0.31 (±0.09 s.d.). Further, as female LPUE troughs in June and July, the male LPUE increases from 0.08 in June to 0.12 in July (See Figure 3.17 for further analysis).

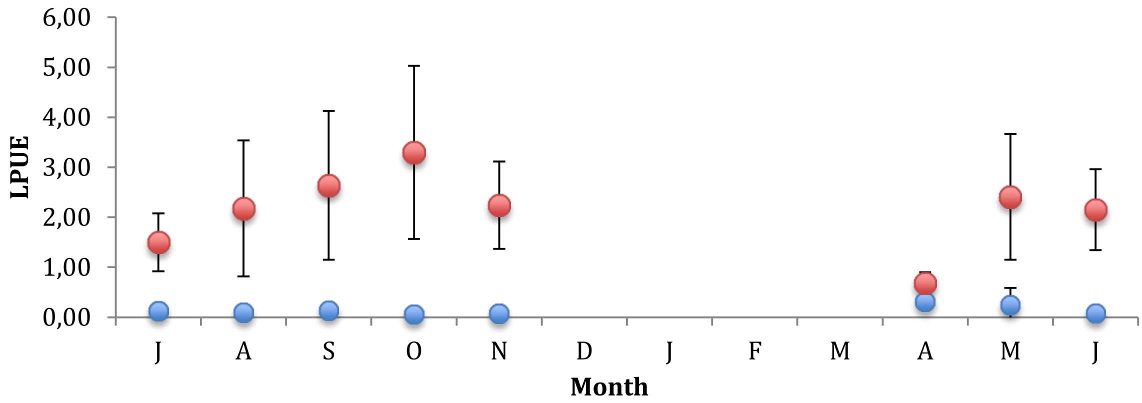

Figure 3.5. The LPUE for female and male crabs averaged per month ± standard deviation over all vessels. Blue dot= Male LPUE, Red dot= Female LPUE.

Discards per Unit Effort (DPUE)

It is critical to capture the annual pattern of discards as managers could use this information to reduce catch of discards in the future. This is useful for fishers to reduce time sorting their catch and by reducing the number of small and soft crabs caught in pots which are subjected to the physiological effects of being in a hauled pot with sudden pressure changes more may survive to produce progeny.

The reason for the discarding of crabs varied seasonally as shown in Figure 3.6. The most frequent reason for discarding was that crabs were small (<150mm carapace width, for females and <160mm for males). The second most frequent reason for discarding crabs was their shell being soft. Across all months only twenty-seven berried females were caught, with 14 of the berried crab attributed to one sampling trip in April 2011.

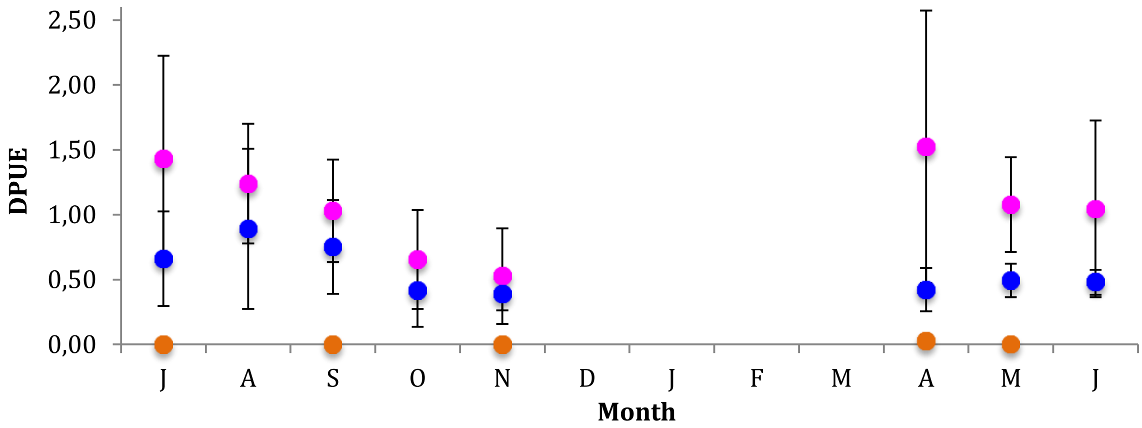

Figure 3.6. The mean ± standard deviation of soft and small crabs (males and female combined) and berried females discarded from July 2011 to June 2012. Pink dot= small crab DPUE, Dark Blue= Soft-shelled crab DPUE, Orange= berried crab DPUE.

Crab Discarded per unit of Effort - by Sex

The trend of female DPUE was very similar across April to June, and increased from July to its highest DPUE in August (Figure. 3.7) and then decreased month-on-month until November. The highest observed DPUE for male crabs occurred in April with an overall decreasing trend in male DPUE until October.

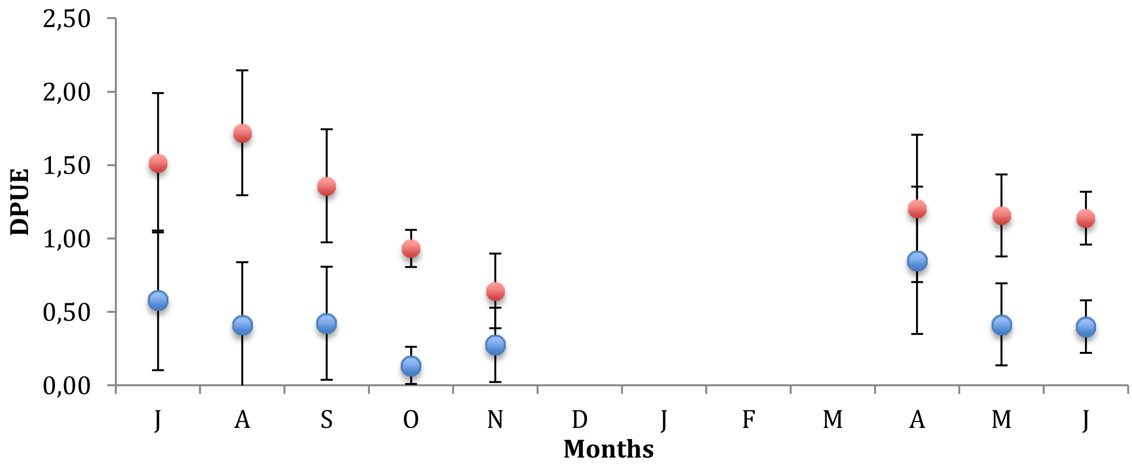

Figure 3.7. The DPUE of females and males from all areas ± standard deviation, July 2001 – June 2012. Blue dot= Male DPUE, Red dot= Females DPUE.

For crabs to mate the female must be recently moulted and as a result be in a soft-shelled state. Therefore by plotting the discards per month of soft crabs per sex we can infer their moulting period/s, local managers could then use this information to use measures to reduce the catch of soft discards in the future. Figure 3.8. shows that soft-shelled females were caught throughout the year with the a small peak in May and the highest rate seen in August. The highest rate of soft male crabs was detected in May and July, 1-2 months before the highest rate of female crabs.

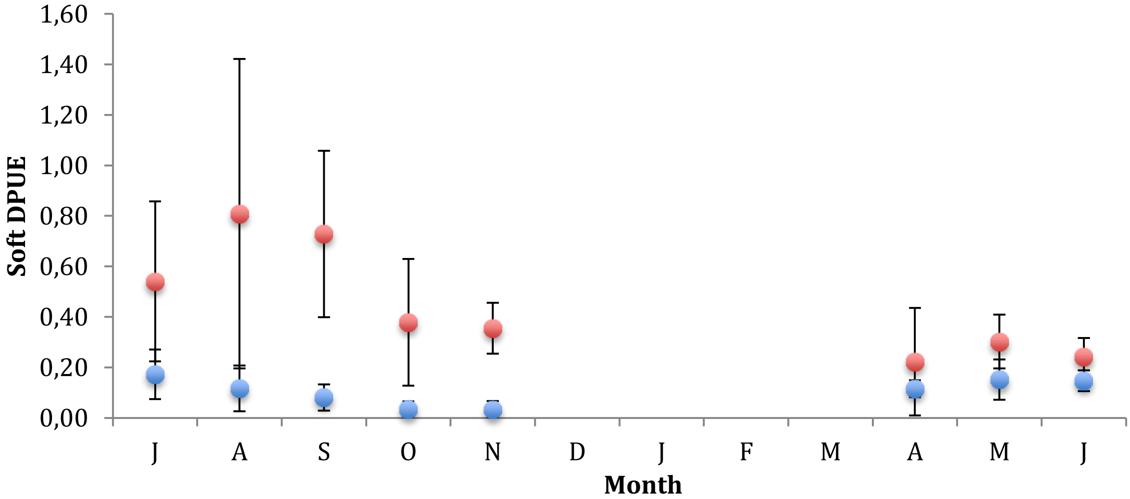

Figure 3.8. Discards per Unit Effort ± standard deviation of soft male and female from July 2011 to 2012. Blue dot= Male DPUE, Red dot= Females DPUE.

The number of small crabs (juveniles) caught can indicate the health of the fishery and as such their DPUE are outlined below. As with soft crabs, small crabs are caught and discarded in all months. (Figure 3.9.).

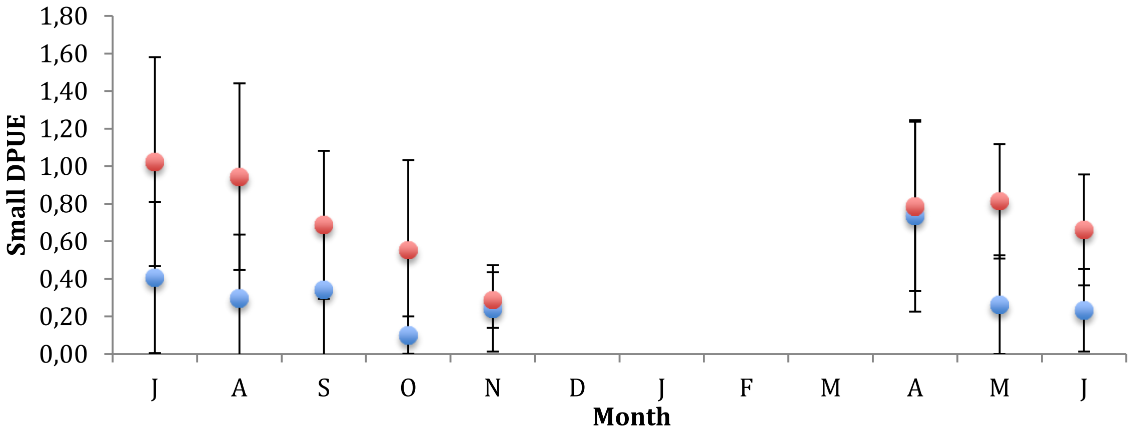

Figure 3.9. Small male and female DPUE ± standard deviation from July 2011 to 2012. Blue dot= Male DPUE, Red dot= Females DPUE.

Several one-way ANOVA's on the monthly means of: total LPUE, male and female LPUE, total discards, soft and small discards for each sex, from 5 vessels (1a, 2, 4, 5 and 6) over July, August and September were carried out to test for variation. None of the analysis of variance (ANOVA) results yielded statistically significant variation between months (See Table 3.6).

Table 3.6. A summary of the one-way ANOVA results for total discards, soft DPUE and Small DPUE testing for a significant statistical difference between July, August and September 2011 from 5 vessels (1a, 2, 4, 5 and 6).

	ANOVA
Landings	
Total	F(2,12)=0.83, p>0.05
Female	F(2,12)=0.34, p>0.05
Male	F(2,12)=0.45, p>0.05
Discards	
Total	F(2,12)=0.55, p>0.05
Female	F(2,12)=0.11, p>0.05
Male	F(2,12)=0.48, p>0.05
Soft	
Female	F(2,12)=1.81, p>0.05
Male	F(2,12)=4.45, p>0.05
Small	
Female	F(2,12)=0.89, p>0.05
Male	F(2,12)=0.18, p>0.05

The spatial distribution of crabs

Onboard Data

The spatial distribution of crabs in the IPA over time would be useful for managers to know where crab is being landed and discarded and in what number, perhaps when considering closed areas to protect juvenile (small) crabs or reduce physiological damage to recently mated female soft crabs by being hauled. To demonstrate the spatial distribution of crab contour maps were plotted in Surfer 10 software.

Onboard recording of spatial distribution of CPUE by Sex

Contour maps were plotted separately for number of male and female crabs caught per pot over the 8 months of sampling trips (Figure 3.10. and 3.11.). Throughout this chapter statistical comparisons were **only** made for catches in July, August and September as these were the only months in which data were successfully collected on the same vessels (See Table 3.4.).

Onboard recording of spatial distribution of male CPUE

Throughout July to September the highest number of male crabs were caught in Area 5 (Figure 3.10.). Within this area, July produced the highest catches with 13 male crabs per pot. The area of note during August and September was 1a with highs of 10 CPUE. By comparison other areas produced catches of 2- 5.5 male CPUE over the same time period (Figure 3.10.).

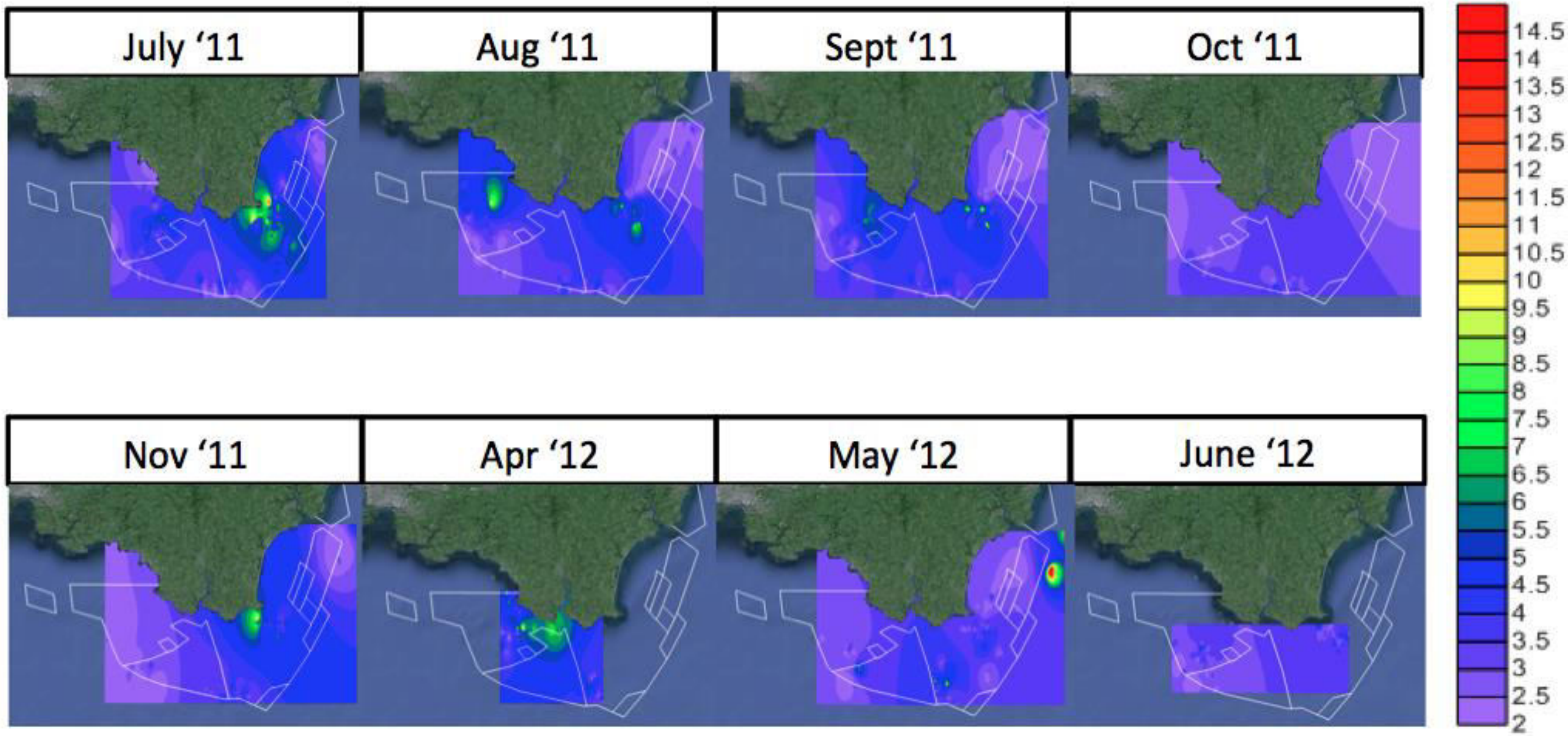

Figure 3.10. A contour map to show the spatial distribution of male crabs caught in the IPA. The colour key can be viewed on the right-hand side of the maps and indicates the estimated crabs per unit effort.

Onboard recording of spatial distribution of female CPUE

The females caught per pot over July, August and September are shown spatially in Figure 3.11. In July 2011 there were four areas around the IPA, in which over 14 female crabs per pot were caught: Areas 1, 2, 5 and 7. The area with the least amount of females CPUE was Area 1 in the west. During this month the eastern IPA seemed to display more female catches than the west (this hypothesis is tested below). In August, two areas contained female crab catches higher than 14 crabs: Area's 5 and 7, both inshore eastern areas. Areas containing 7-9 female crabs per pot were found predominately in the east in Areas 5, 7 and 8. In August there were small areas where catches were between 7-9 crabs, in the western Areas 1 and 4. The spatial distribution in September 2011 was very similar to August without a hotspot (14 crabs per pot) in Area 5 and with the distribution of 14 female crabs per pot being more inshore in Area 7.

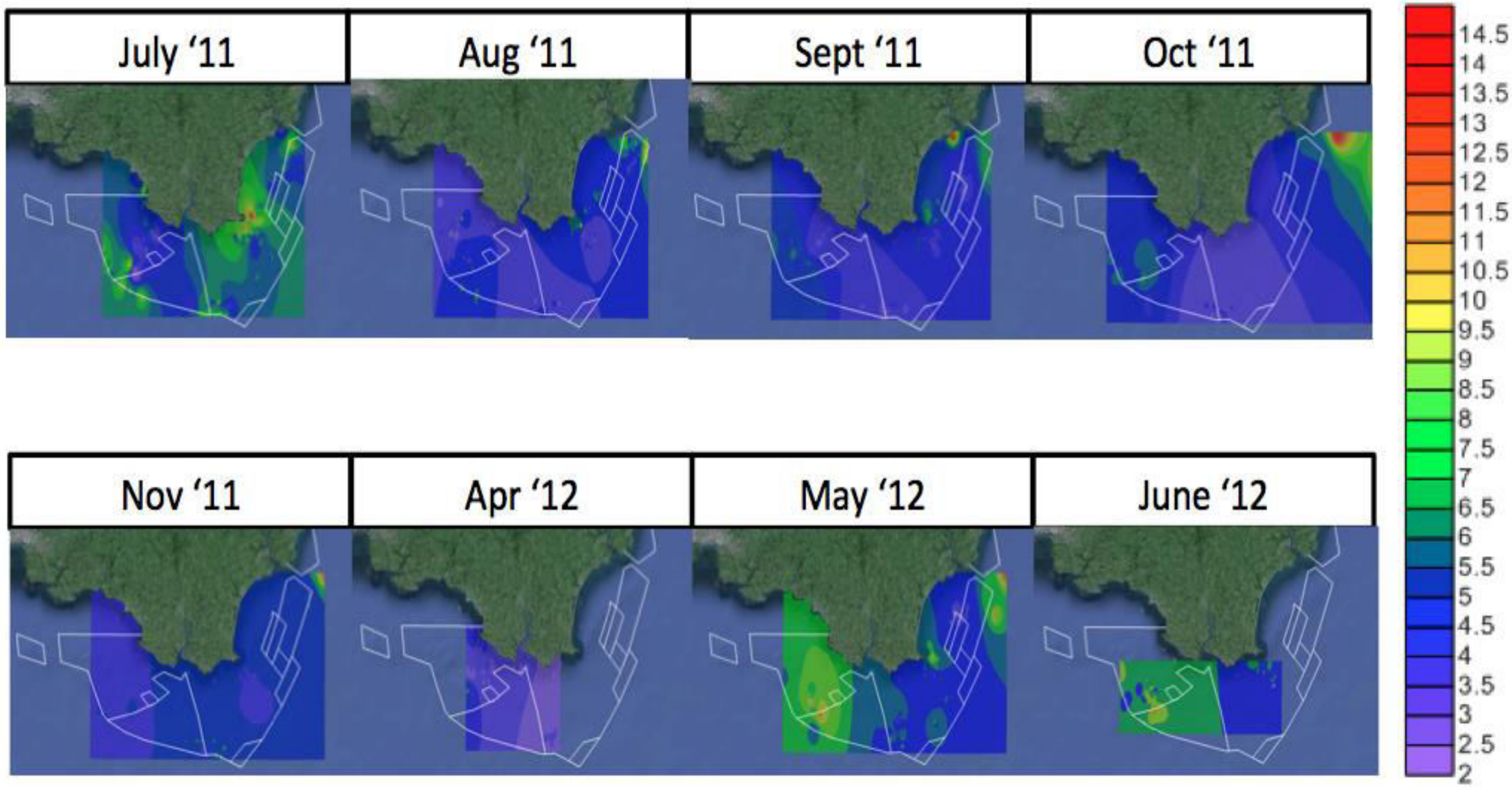

Figure 3.11. A contour map to show the spatial distribution of female crabs caught in the IPA.

Onboard recording of spatial distribution of Landings per Unit Effort

The spatial distribution of landed crabs is shown in Figure 3.12. In July 2011 most of the IPA areas only landed 2- 3.5 per pot. In August a hotspot in Area 8 existed, where over 14 crabs were landed per pot. The highest number of crabs retained was recorded in September with over 14 per pot in three hotspots in Areas 2, 5 and 8.

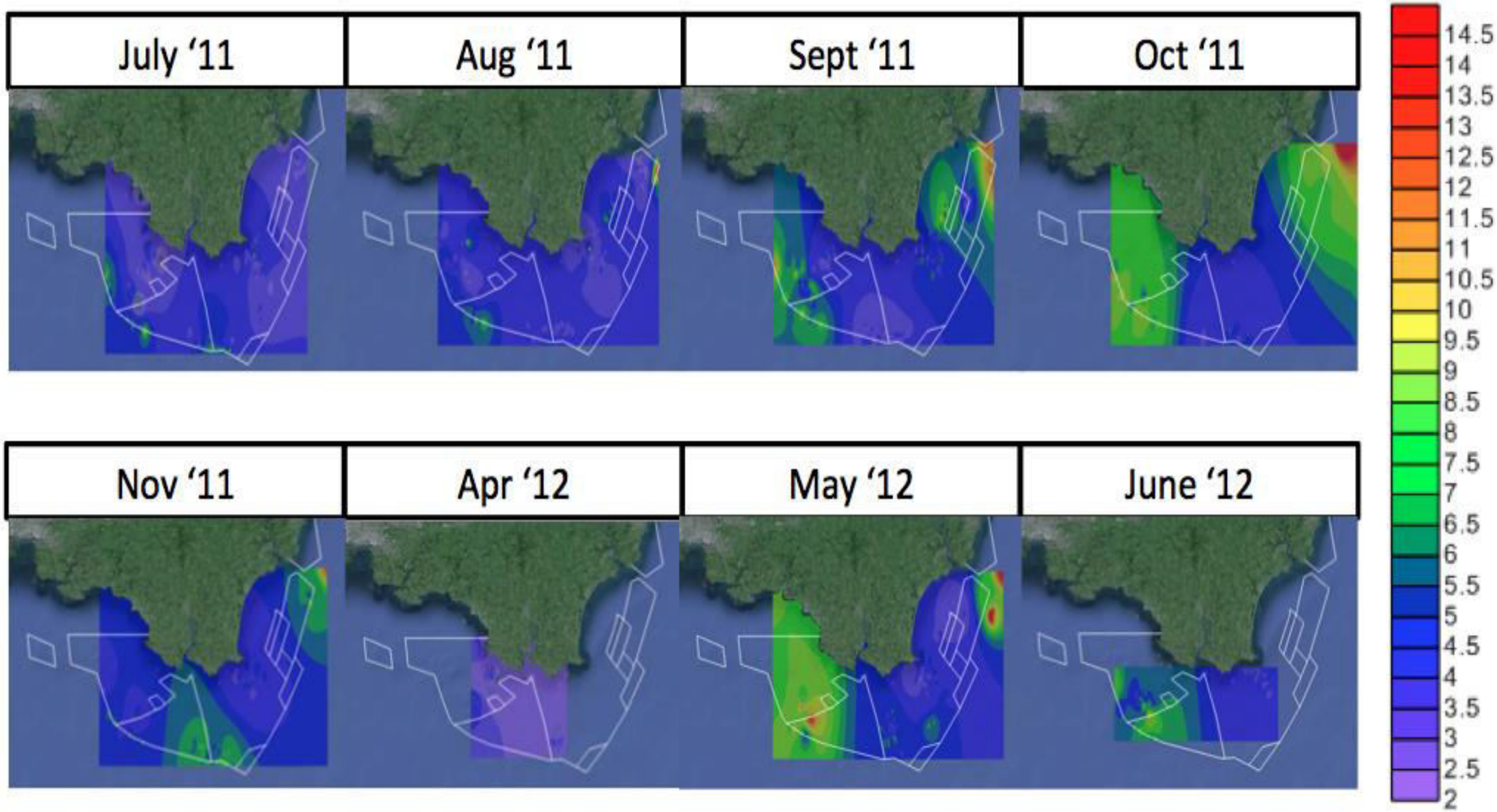

Figure 3.12. A contour map to show the spatial distribution of the crabs landed in the IPA.

Onboard recording of spatial distribution of discards

The highest number of crabs discarded per pot in July 2011, were found in Area 5 around Start Point (Figure 3.13), with other hotspots in July in Areas 1 and 7. In August there were two hotspots with over 14 crabs per pot in Areas 5 and 8. During September there were two hotspots of crab discarded in Areas 5 and 7 with the larger hotspot in Area 7.

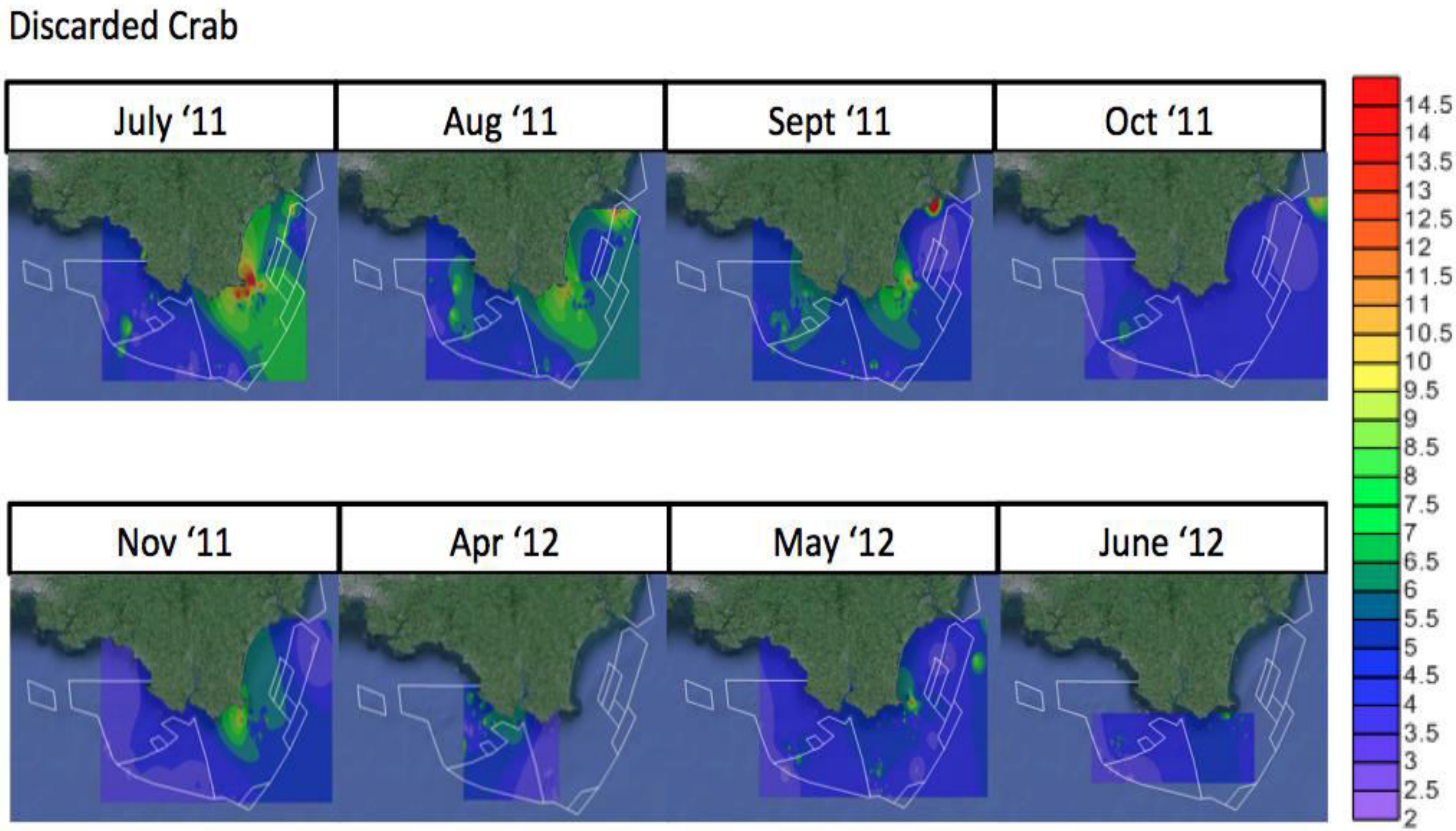

Figure 3.13. A contour map to show the spatial distribution of discarded crabs in the IPA.

Several one-way ANOVA's were performed on the monthly means of: female and male CPUE, and total LPUE, as well as total, female and male DPUE between areas (1a, 2, 4, 5 and 6) over July, August and September, which yielded the results as in Table 3.7.

Table 3.7. A summary of the one-way ANOVA results for: female and male CPUE, total LPUE, total, female and male discards testing for a significant statistical difference between areas 1a, 2, 4, 5 and 6 *in July-September. *In the table below the areas, which were significantly different from each other are listed under the Tukey HSD column e.g. 4 and 6 indicates areas 4 and 6 were significantly different from each other.*

	ANOVA	**Tukey HSD (Alpha 0.05)***
CPUE		
Female	F(4,10)=9.79, p<0.0017	4 and 6 1a and 6 1a and 2
Male	F(4,10)=3.40, p>0.05	
LPUE		
Total	F(4,10)=2.65, p>0.05	
DPUE		
Total	F(4,10)=2.98, p>0.05	
Female	F(4,10)=10.51, p<0.0013	4 and 6 4 and 5 1a and 6 1a and 5
Male	F(4,10)=4.82, p<0.02	2 and 5

ANOVA's were also applied to small and soft discards for both sexes with only small male crabs DPUE having a statistically significant result, $F(4,10)=5.78$, $p<0.0113$. A post hoc Tukey test showed that the small male DPUE between area pairs, 2 and 5, and 6 and 5 differed significantly at $p< 0.05$.

Ontogenetic movement of crab

We tested the hypothesis that there is an ontogenetic movement of crabs offshore. As carapace widths were not measured during this study we used small discards as a proxy for size. The test compared the small discards per unit effort for crabs of both sexes summed over all inshore areas from 0- 3nm (Area's 1a and 5) and all offshore areas 3- 6nm (Area's 2, 4 and 6). The same analysis was then performed for the DPUE of small males and small females separately. The ANOVA's for the data on total small and female small crabs revealed a statistically significant variation between the DPUE in areas close to (0-3nm) and far from (3-6nm) the shore. In both instances the mean DPUE's were significantly higher within 0-3nm than between 3-6nm. There was a non-significant result for small male discards (See Table 3.8).

Table 3.8. A summary of the one-way ANOVA results for total small DPUE, female small DPUE and male small DPUE testing for a significant statistical difference between inshore (0-3nm) and further off shore (3-6nm) areas of the IPA.

Category of DPUE	Distance from shoreline	n	Mean	Std. Dev	ANOVA
Total Small DPUE	0-3nm	17	1.39	0.68	F(1,40)=6.42,p<0.015
	3-6nm	25	0.93	0.51	
Female Small DPUE	0-3nm	17	0.96	0.52	F(1,40)=4.95, p<0.032
	3-6nm	25	0.65	0.38	
Male Small DPUE	0-3nm	17	0.43	0.40	F(1,40)=2.02, p>0.163
	3-6nm	25	0.27	0.29	

Catch distribution in the eastern and western IPA

To test the hypothesis that the 'highest CPUE of crab is found in the eastern sector of the IPA is due to female migration down the English Channel from the east' (as seen in Figure 3.11.) we tested for statistical variation between CPUE in the eastern and western IPA. We carried out a one-tailed t-test on the monthly means of total CPUE, female CPUE and separately, male CPUE data observed from 5 vessels in areas 1a, 2, 4, 5 and 6, over a 3-month period from July- September 2011. The areas were split into west or east categories depending on their location relative to the Start Point (the approximate midpoint of the IPA). Areas 1a, 2, and 4, were grouped in the west and Areas 5 and 6 in the east. The t-test for total CPUE and female CPUE data revealed a statistically significant variation between west and east (Table 3.9.). Separately male CPUE did not have a statistically significant difference between west and east group means. However the eastern IPA had higher group means in all three categories.

Table 3.9. A summary of the one-tailed test results for total, female and male CPUE testing for a significant statistical difference between east and west areas of the IPA.

CPUE Category	West/ East	n	Mean	Std. Dev	One-tailed t-test
Total CPUE	East	6	4.48	0.73	t(14)=2.93, p<0.0078
	West	9	3.42	0.63	
Female CPUE	East	6	3.69	0.90	t(14)=1.94, p<0.0406
	West	9	2.81	0.80	
Male CPUE	East	6	0.80	0.55	t(14)=0.69, p>0.256
	West	9	0.63	0.31	

Discard distribution in the eastern and western IPA

To further test for statistical variation in the distribution of discarded crabs between east and western areas, we carried out one-way ANOVA's on the monthly means of total small DPUE, female small DPUE and separately, male small DPUE (this also performed for soft discards) data observed from by 5 vessels in areas 1a, 2, 4, 5 and 6, from July- September 2011. The areas were split into west or east categories in the same way as '*Catch distribution in the eastern and western IPA*'. The ANOVA's which revealed a statistically significant variation between west and east areas were: total small DPUE, female small DPUE and total soft DPUE. The means for all three of the results had higher means in the east compared to the west (See Table 3.10.). Male small DPUE, and male and female soft DPUE did not produce a significant difference between west and east group means.

Table 3.10. A summary of the one-way ANOVA results for total small DPUE, female small DPUE and male small DPUE testing for a significant statistical difference between eastern and western areas of the IPA, over July-September 2011.

DPUE Category	West/ East	n	Mean	Std. Dev	ANOVA
Total Small DPUE	East	6	1.76	0.75	F(1,13)=10.97, p<0.006
	West	9	0.89	0.21	
Female Small DPUE	East	6	1.16	0.55	F(1,13)=10.58, p<0.006
	West	9	0.53	0.16	
Male Small DPUE	East	6	0.60	0.46	F(1,13)=1.66, p>0.221
	West	9	0.36	0.27	
Total Soft DPUE	East	6	0.92	0.17	F(1,13)=7.57, p<0.017
	West	9	0.63	0.21	

Analysis of data extracted from fisher diaries

A total 2,853 tonnes of crabs were landed during 5,170 days at sea (DAS) over 10 years. The total landed catch consisted of 9.9% (282 tonnes) of males, and a predominance of females at 90.1% (2571 tonnes), in a division similar to the data gathered onboard. The mean kilogrammes landed per pot (subsequently called 'KLPUE') across all areas and years were 0.64 (±0.51 s.d.), the mean male KLPUE was 0.13 (±0.09 s.d.) and female KLPUE was 1.14 (±0.66 s.d.).

Temporal variation in KLPUE

The daily KLPUE from each vessel showed a seasonal variation of landings (Figure 3.14). Each vessel in all years displayed KLPUE rates below 1.0 in the winter months. There was then a sharp increase in KLPUE during April or May when the landings rose to a peak, between May and July. A second peak of KLPUE was observed sometime between October and November, following on from a dip in KLPUE between July and August. KLPUE then drastically decreased from the highest KLPUE in November to the lowest KLPUE between December and April/May, at which time the seasonal landing cycle began again.

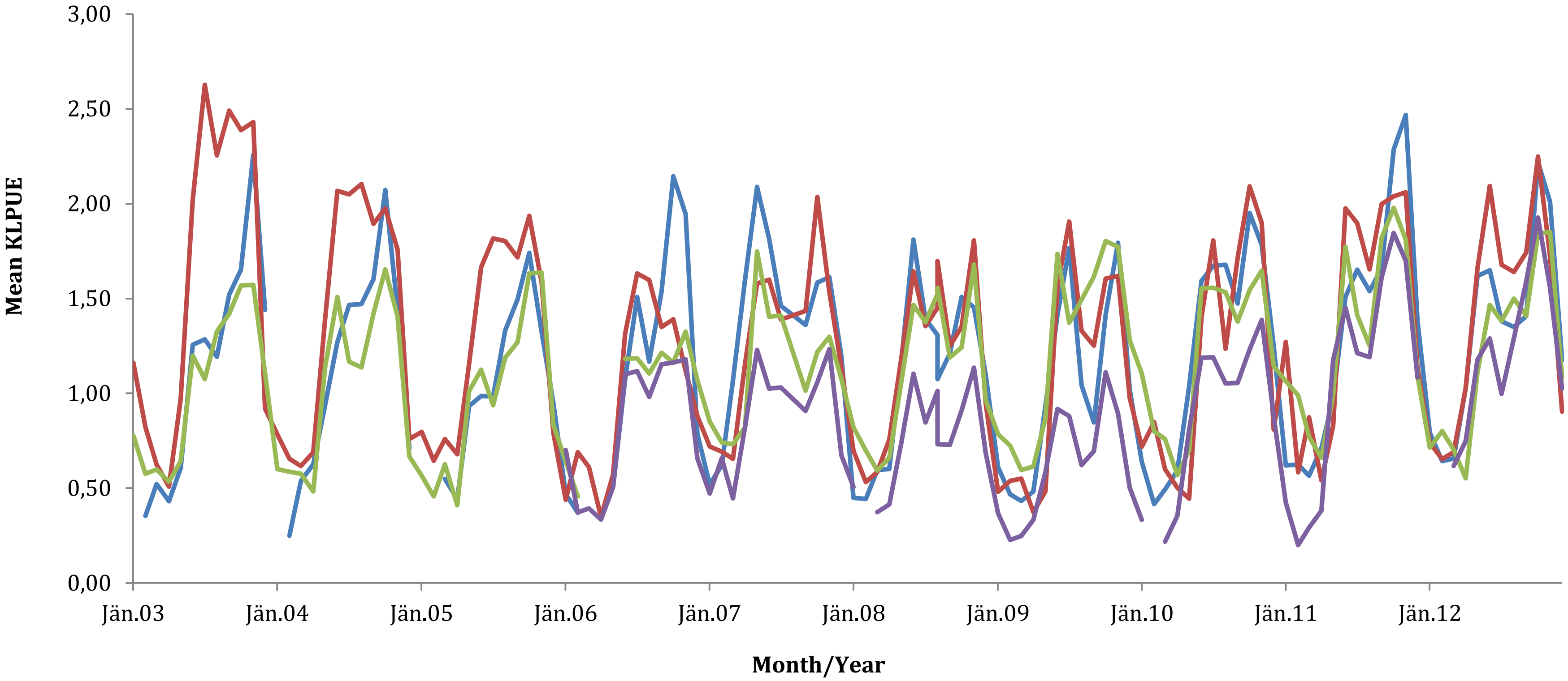

Figure 3.14. The mean daily KLPUE of each vessel (1, 1a, 4 and 5) between 2003- 12. Blue= Area 1, Red= Area 1a, Green= Area 4, Purple= Area 5.

A one-way ANOVA was performed on the monthly means of KLPUE derived from 4 vessels in areas (1, 1a, 4 and 5) over a 10-year period from 2003-12 (Figure 3.15.). This ANOVA showed significant variation between months, $F(11,419)=68.10$, $p<0.0001$. A post hoc Tukey test showed that KLPUE was statistically different between areas in 48 pairs of months at $p<0.05$ (for a full list of the significantly different months see Appendix B.).

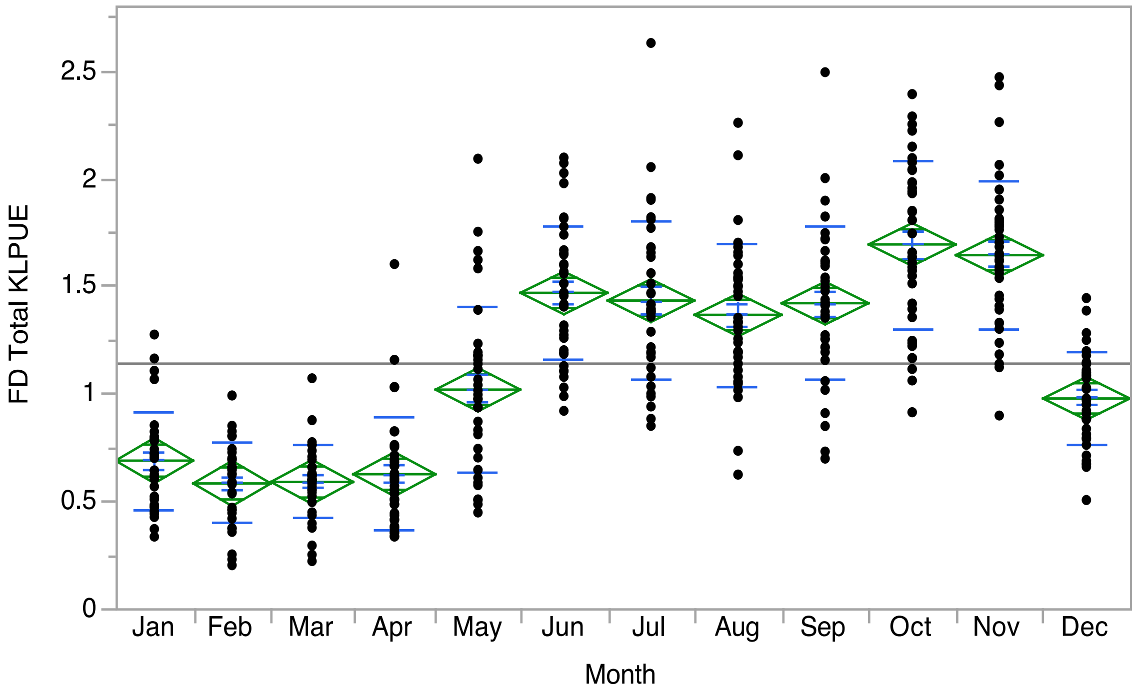

Figure 3.15. The mean total KLPUE plotted against month, showing the annual variation of landings from fisher's diaries (FD).

Temporal variation of KLPUE by sex - all areas combined

To demonstrate the seasonal variation in male and female KLPUE, the means of KLPUE per month from 2003-12 were plotted (Figure 3.16.). The graph shows that during the months of January to March the female KLPUE is at its lowest for the annual cycle, with between 0.24 and 0.27 KLPUE and highest for males KLPUE at 0.22 to 0.24. As the amount of female KLPUE begins to increase from March onwards and more steeply from April to June, during the same time period, the male KLPUE steadily decreases until it is at its lowest point of 0.07 in July. The male KLPUE then increased over the next 5 months to 0.15 kilograms landed per unit effort in December. In contrast the female KLPUE is reduced over August and September (1.16 KLPUE and 1.20 KLPUE respectively) with the highest KLPUE seen in October at 1.47 KLPUE. Female landings then drop slightly in November to 1.38 KLPUE and then steeply drop off in December to 0.76 KLPUE, producing the same pattern of landings as produced by the data collected onboard.

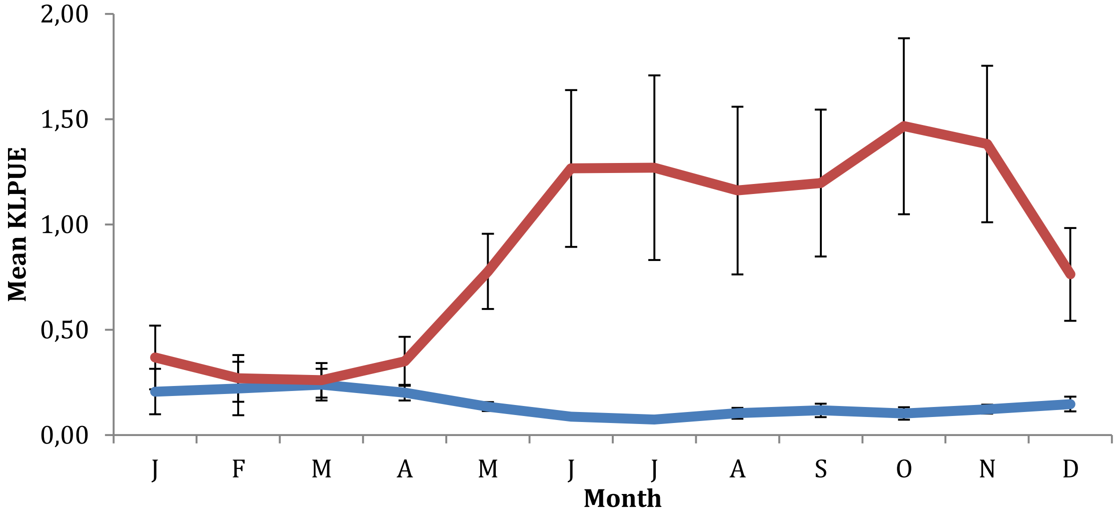

Figure 3.16. The mean monthly (± standard deviation) KLPUE of male and female crabs from 2003-12. Blue= Males, Red= Females.

A visual inspection of Figure 3.16. indicated a possible negative relationship between male and female KLPUE, which was also detected by Brown and Bennett (1980). To evaluate the relationship we plotted male LPUE against female LPUE for each area (1, 1a 4 and 5), we used average the landings per month over 10 years (Figure 3.17.). The correlations demonstrate a significant, negative correlation between male and female LPUE for Areas 1, 4 and 5, and weak non-significant negative correlation for Area 1a.

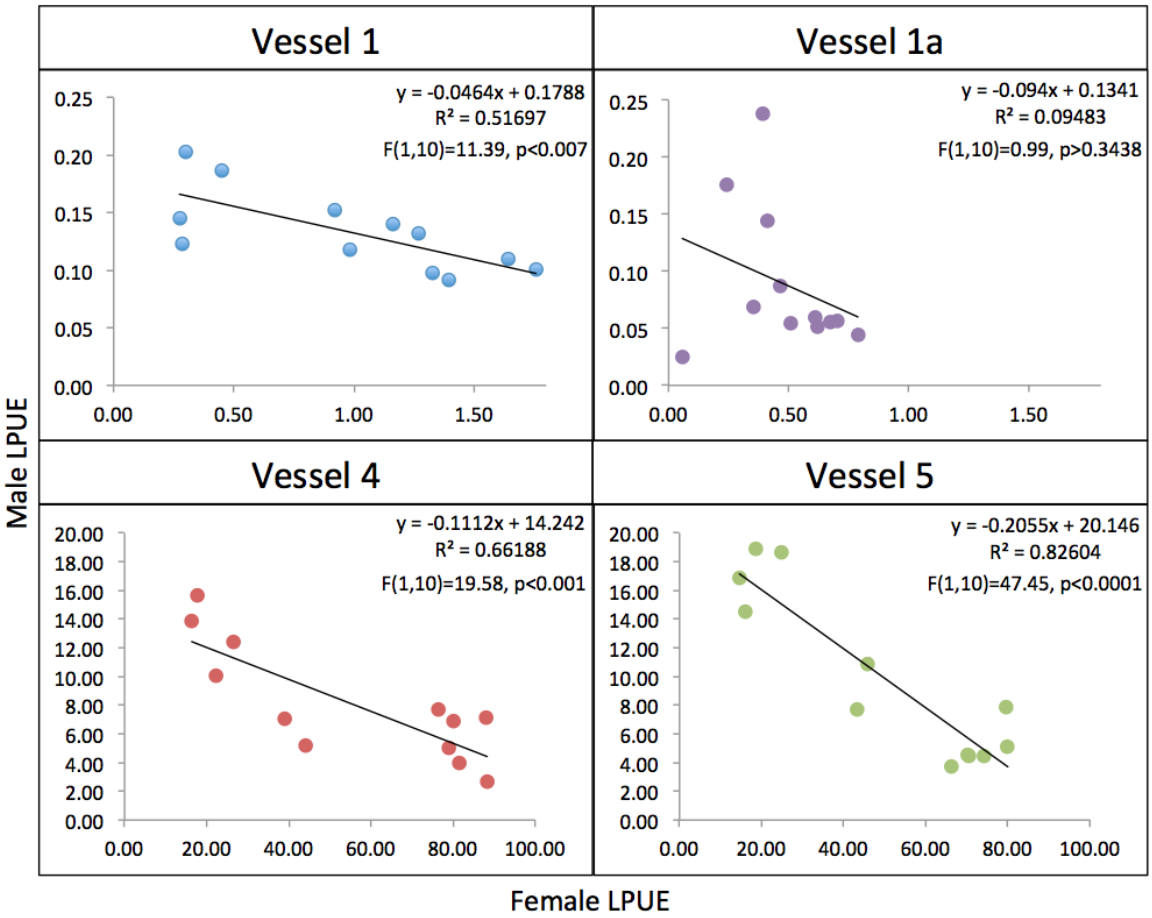

Figure 3.17. The relationships between female and male KLPUE for vessels 1, 1a, 4 and 5.

Temporal variation of female KLPUE

A one-way ANOVA was performed on the monthly means of female KLPUE yielded significant variation between months, $F(11,419)=110.30$, $p<0.001$. A post hoc Tukey test showed that the female KLPUE, differed significantly in 48 pairs of months (e.g. August and October, May and October. For a full list see Appendix B at $p<0.05$) (See Figure 3.18.). The pattern to these significant differences is largely that the winter months KLPUE, are significantly different from the summer months.

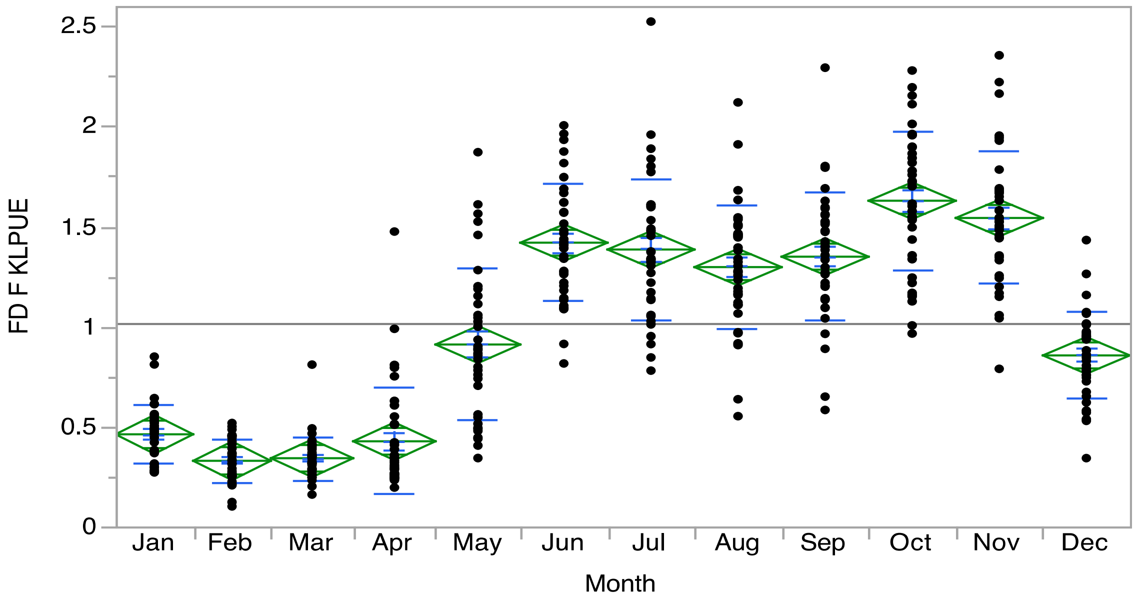

Figure 3.18. The mean female (F) KLPUE plotted against month, showing the annual variation of landings from fisher's diaries (FD). Grey horizontal line= overall mean.

Temporal variation of male KLPUE

An ANOVA on male KLPUE data yielded significant variation between months, F(11,419)=7.11, p<0.0001. A post hoc Tukey test showed that the male KLPUE differed significantly in 15 pairs of months (e.g. December and July, March and July. For a full list see Appendix B.) at p<0.05.

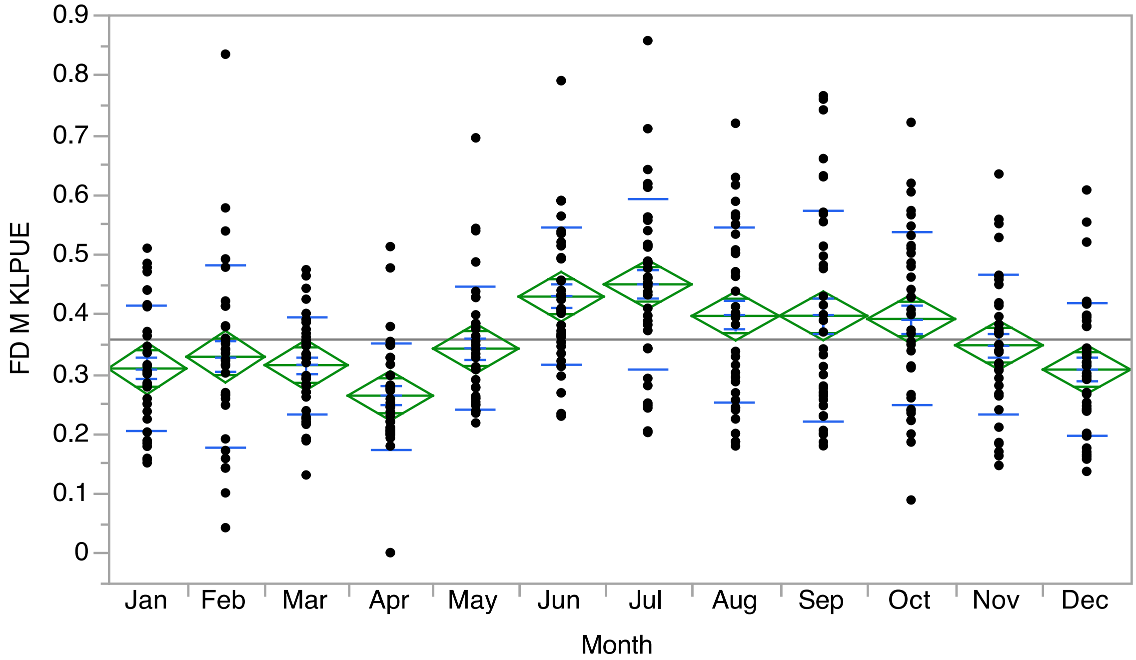

Figure 3.19. The mean male (M) KLPUE plotted against month, showing the annual variation of landings from 2003-12.

Spatial distribution of KLPUE by area for the two sexes

To detect if there were differences between areas in KLPUE over an annual cycle the mean KLPUE per month was plotted for each area (Figure 3.20.). All areas fitted the pattern of KLPUE as described above under '*Temporal variation KLPUE by Sex*'.

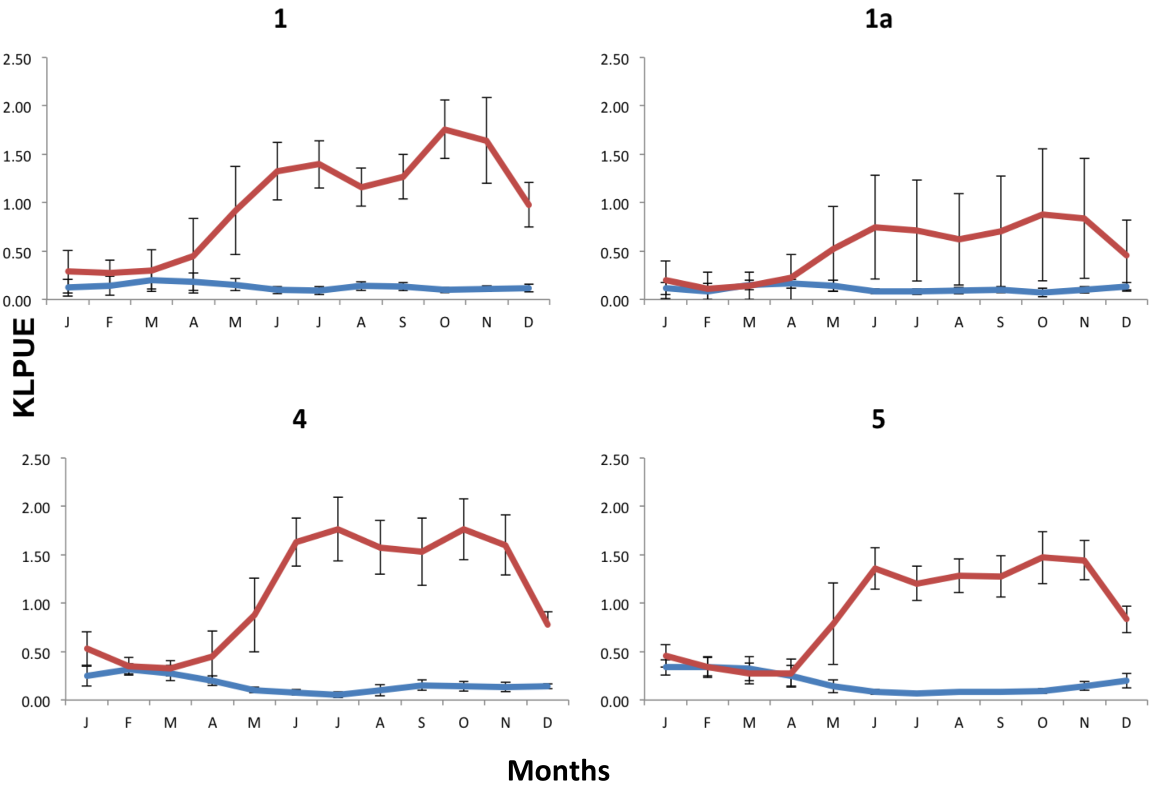

Figure 3.20. The KLPUE of male and female crabs from four areas 1, 1a, 4 and 5. Red= Females, Blue= Males.

To analyse how KLPUE varied with location several ANOVAs were performed on the four areas (1, 1a, 4 and 5) to see if there were significant differences between Areas (Table 3.11.). Each area contributed a mean landing per month averaged over ten years. As every vessel did not fish every month, 428 monthly means were tested of a possible 480. If a significant difference was detected then the post-hoc Tukey HSD test was carried out to see specifically which pairs were significantly different from each other.

Table 3.11. A summary of the one-way ANOVA results for total KLPUE, female KLPUE and male KLPUE testing for a significant difference between areas of the IPA. If ANOVA's were significantly different then a Tukey test was performed.

Test	F -Value	Tukey HSD (Alpha 0.05) *
Total KLPUE	F(3,427)=10.86, p<0.0001	1a and 4 1a and 1 1a and 5
Female KLPUE	F(3,427)=6.01, p<0.0005	1a and 4 1a and 1
Male KLPUE	F(3,427)=16.04, p<0.0001	1 and 5 1a and 5 4 and 5

Ontogenetic movement of crabs with fisheries diaries data

To test if there was ontogenetic movement of landed crab a one-way ANOVA was performed on the monthly means of total, female and male KLPUE on data from fisher's diaries in the same areas as above. Areas 1, 1a were in the 0-3nm region and area's 4 and 5 in the 3-6nm region. We would expect to see higher landing rates further from the shore as there would be less small crabs discarded further from the shore as they should be larger in size and therefore over MLS and not classed as small. The ANOVA's for total KLPUE and male KLPUE data yielded a significant variation between the mean catches from the two zones. The ANOVA for female KLPUE data yielded no significant variation between 0-3nm and 3-6nm (see Table 3.12.).

Table 3.12. A summary of the one-way ANOVA results for total KLPUE, female KLPUE and male KLPUE testing for a significant statistical difference between inside areas (0-3nm) and outside areas (3-6nm) of the IPA.

KLPUE	Distance from shoreline	n	Mean	Std. Dev.	ANOVA
Total KLPUE	0-3nm	194	1.06	0.50	F(1,429)=8.74, p<0.0033
	3-6nm	237	1.20	0.50	
Female KLPUE	0-3nm	194	0.97	0.53	F(1,429)=1.97, p>0.1616
	3-6nm	237	1.04	0.57	
Male KLPUE	0-3nm	194	0.34	0.13	F(1,429)=7.60, p<0.0061
	3-6nm	237	0.37	0.14	

Movement of crabs from east to west with fisheries diaries data

To test the hypothesis that 'Due to the migration of female crabs down the English Channel (from the east), the highest CPUE in the eastern IPA will be higher than the highest CPUE from the western IPA'. We tested the above hypothesis in terms of landings in the form of total KLPUE from fisher's diaries. Total KLPUE regardless of sex was analysed first followed by separate analyses for males and females. The areas were assigned to the west or east as in the section on the '*Catch distribution in the eastern and western IPA*'.

Table 3.13. A summary of the one-way ANOVA results for total, female and male KLPUE testing for a significant statistical difference between eastern and western areas of the IPA, over July-September 2011.

	East/ West	n	Mean	Std. Dev.	ANOVA
Total KLPUE	East	117	1.13	0.40	$F(1,429)=0.05$, $p>0.8151$
	West	314	1.14	0.54	
Female KLPUE	East	117	0.97	0.49	$F(1,429)=1.00$, $p>0.3180$
	West	314	1.03	0.57	
Male KLPUE	East	117	0.43	0.16	$F(1,429)=46.54$, $p<0.0001$
	West	314	0.33	0.12	

Discussion

This study set out to develop and demonstrate a methodology to collaboratively gather scientifically high resolution, spatiotemporal data of crab catch, landings and discards. This aim was set to address the lack of fine scale data on *Cancer pagurus* in the English Channel, and to provide a cheap and relatively quick method to facilitate catch, landings and discards data to be collected by fishers or an observer employed by fishers which would viably assess the dynamics of the fishery.

Below we discuss the results of the three questions and two hypotheses in terms of the dynamics of the fishery. This will be interpreted first in terms of the temporal and spatial variation in CPUE, LPUE and DPUE and in Chapter 4 the effect of abiotic factors such as sea temperature, bathymetry and substrate on catch, landings and discards will be discussed. Finally, we conclude our findings with a month-by-month account of the dynamics of the fishery.

CPUE

The first question that this chapter aimed to address was 'How does CPUE vary spatiotemporally within the IPA?'. Brown and Bennett (1983) described the catch structure of the Devon crab fishery but only recorded landings data. Results from this study therefore revealed details of the spatiotemporally variation of landings and discards within the IPA for the first time.

Temporal variation of CPUE

CPUE increased month-on-month from July-October 2011, then reduced in November to a rate below July's CPUE. Data was not collected through the winter and began again in April when the lowest catches of the year were recorded. CPUE then increased in May and June to a value of CPUE similar to that recorded for July 2011. This pattern of results is similar to Brown and Bennett's (1979) records of LPUE. The highest CPUE's were observed during October as the moulting cycle of the species and migration movements increase catchability at this time (Warner, 1977; Brown and Bennett, 1979). According to CEFAS (2011) during October female crabs exhibit their highest mean migration speeds in a westward migration so causing high immigration rates into the fishery and increasing catchability.

Catch rates from the unsampled months of December to March were likely to be similar to the CPUE recorded in April. Support for this conclusion comes from the data extracted from fisher diaries (Figure 3.18). During these winter and spring months female crabs are most likely to be buried in soft substrate to brood their eggs from November (Edwards, 1979) to the following summer, during which time they do not feed (Edwards, 1979; Brown and Bennett, 1980; CEFAS MF1103, 2008). This trait severely reduces the catchability of female crabs, which is reflected in the low CPUE recorded in April in the onboard data and throughout the winter in the fisher's diary data.

The life history traits of crabs explain the temporal variation of CPUE for males and females. During all months of the year female crabs are the predominant sex in the catch (or landings as in Brown and Bennett, 1979). Between July and November there was an overall increase in the proportion of female crabs caught, from 81.2%

in July to 95.6% females in October. Within this time frame the ovaries of females are developing and they are moving west (Hunter *et al.* 2013). It is not inconceivable that during this time, high levels of energy are required for migration and ovarian development. Therefore, females need to feed heavily to satisfy their energy demands, and as a consequence their catchability is increased. Conversely, the energy demands of males might be much less than females, as they do not migrate (Hunter *et al.,* 2013). The result is that males do not have to feed so often and thus their catchability is less compared to females.

Despite the above biological explanation for the variation of LPUE over time there were no significant differences between the mean monthly total, female or male CPUE from 5 vessels over the 3 months when data was directly comparable, in July, August and September. This non-significant result is likely due to the time of year from which data was analysed. To rectify this, data should have been collected over all months of the year, with repeated trips per month, per vessel for robust statistical analysis. At the time, it was judged that the likelihood was low of achieving nine trips per month during the winter months. This judgement was inspired by the knowledge that fishers often have to cancel trips because of poor weather. We distributed forms for fishers to fill out their landings data over the winter months, however only two vessels partly completed these forms and therefore we were not able to integrate them into this study. A repeat survey would be best advised to persist with winter sampling to achieve as many trips as possible throughout the whole year, perhaps with multiple observers or suitable automatic data recording technology (see Chapter 7).

Spatial variation of CPUE

Hunter *et al.,* (2013) showed that female crabs migrate west down the English Channel and therefore will enter the IPA from the east. On account of these facts, this study hypothesised that 'the highest CPUE of *Cancer pagurus* would be found in the eastern IPA, compared to the west, due to females migrating east down the English Channel'. This study showed that the mean monthly total CPUE and female CPUE in the east of the IPA were significantly higher than in the west. Therefore we can accept the alternative hypothesis that there is a significant difference between total CPUE and also female CPUE in the east and west of the IPA. This phenomenon is likely due to the movement of females from east to west during their migration.

Analysis of male mean monthly CPUE's revealed that there were no significant differences between areas of male CPUE over 3 months (July, August and September) from 5 vessels. However, there were significant differences between the monthly means of areas: 4 and 6, 1a and 6, and 1a and 2 for female CPUE with areas 6 and 2, having the higher means, respectively. The differences between areas are likely to be attributed to location-specific environmental variables such as substrate, bathymetry or prey abundance, with area's 2 and 6 containing a more 'favourable' environment (see Chapter 4).

In conclusion, the total, female and male CPUE data recorded during this study revealed a similar pattern of seasonal variation to the LPUE of Brown and Bennett (1979), who collected their data in the same fishery. The CPUE results we present serve as baseline of data spread across the IPA in time and space.

Landings per Unit Effort

We set out to study 'How does the LPUE vary spatiotemporally within the IPA?'. Below we discuss the variation of LPUE in time and space as shown by the data collected onboard and from the data extracted from the fisher's diaries.

Temporal variation of LPUE

Data collected onboard

The month-on-month increase in crab landings from July-October 2011 can be explained in terms of crab reproductive behaviour. Female *Cancer pagurus* have to be in a soft-shelled state to mate with males (Warner, 1977), who describes how females become soft-shelled between March and May and then again in September. Once they have moulted and so become soft-shelled and then mated, the exoskeleton begins to harden over several months through calcification. The hardening of the exoskeleton increases the female's catchability as they no longer have to hide to avoid predators and are free to seek food. Also at this time, fishers can legally land the crabs, which a few months before would have been discarded. Therefore there is an increase in LPUE when a large proportion of the population are approximately 3 months post-moult. According to Warner (1977) the male moulting period is between May and July and typically the soft state persists for ~3 months. This period explains the reduced LPUE for male crabs between August and October in Figure's 3.5 and 3.16. This study and that of Brown and Bennett (1979) demonstrates that during October there are low abundances of soft-shelled male and female crab in the catch and LPUE is increased. Nevertheless, there were no significant differences between the female or male monthly means landed by vessels over a 3 months period (July-September). As mentioned above, an explanation for this non-significant result is the time of year, which was analysed. As Figures 3.18 and 3.19. show from fisher's diaries data, there is little variation in the KLPUE of females and males over this time period and had data been recorded over all months from all vessels, it is likely from the standard deviations on Figure 3.18. and 3.19. respectively, that there would have been statistically significant differences between the monthly means if the winter months were included in the analysis.

The negative relationship demonstrated between female and male KLPUE (Figure 3.17.) could be explained by behaviour linked to reproduction. The months in which males have their highest KLPUE (January to May) in this study and that of LPUE in Brown and Bennett (1979) correspond to the months in which female crabs are immobile and not feeding. An explanation for the increased LPUE of male crabs in these months could be due to reduced competition for food and space from females.

Fisher Diaries data

Fisher's diaries data enabled a more complete view of the fishery dynamics, and provided important data on the winter months missing from the dataset gathered onboard.

The daily total KLPUE showed seasonal variation of landings (Figure 3.14.). Analysis revealed that there was a significant difference between 48 pairs of months between mean monthly total KLPUE and female KLPUE, and for males 15 pairs of months. The significant month pairs are largely the winter months compared to the summer months. During the winter months the catch is insignificant and catches only get going once surface sea temperature rises above a certain minimum approximately 9-11°C in spring (See Chapter 4). This indicates that the KLPUE is significantly affected by time of year through the effects of temperature. Many animal species have been shown to respond in various ways to changing photoperiod (Kenagy 1981, Silverin et al. 1993, Gwinner 1996, Watari & Arai 1997, Last & Olive 2004) (from Murray *et al.* 2010) and therefore this abiotic factor could effect crab catchability and catch seasonality. For example the increase of Norway lobster (*Nephrops norvegicus*) catch during the months of spring and summer are due to of greater light intensity (Aguzzi *et al.* 2004). Nevertheless, Murray *et al.* (2010) detailed that further research was required to 'establish whether feeding activity and metabolism are linked to photoperiod or light intensity'. However *Cancer pagurus* are known to be nocturnal feeders (Ansell, 1973; Skajaa, 1998; Heraghty, 2013) and therefore catchability is unlikely to be effected by day length/ light intensity and more likely sea temperature (Chapter 4).

These results indicate that more data were needed during the winter of onboard data collection as with a larger sample the fisher diaries data shows a high number of significantly different pairs between summer and winter months.

The pattern of monthly variation in KLPUE of both sexes can be explained by the same life history events as the variation in LPUE recorded by the onboard data. The results for KLPUE from this study are very similar to Brown and Bennett (1979). We converted Brown and Bennett's (1979) data from kg/100 pots hauled into kilograms per pot so the units were directly comparable and plotted them in Figure 3.21.

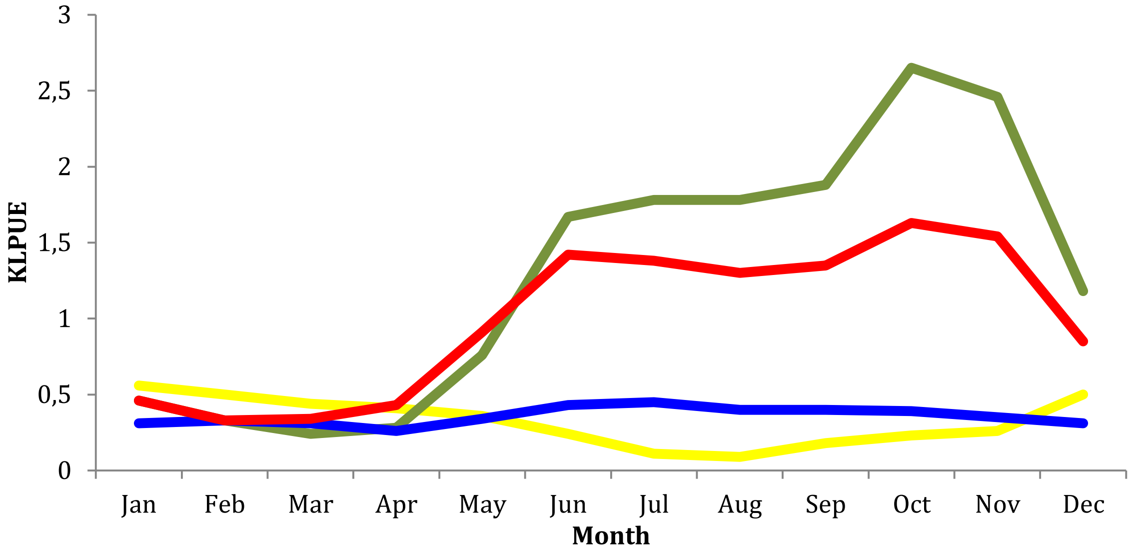

*Figure 3.21. A graphical representation of the male and female KLPUE from Brown and Bennett's (1979) study in the 1970's and the current study in 2011-12. Green= Females 1970s, Yellow= Males 1970s, Red= Females 2000's, Blue=Females 2000s. **= MLS in 1970's was 115mm.*

The general pattern of female KLPUE from this study (in 2011-12) and the Brown and Bennett (1979) (1970's) study is similar, with higher female KLPUE recorded from the 1970's from June to December, and from May to November for males. It is important to note that the MLS during the Brown and Bennett (1979) study was 115mm, compared to the 140mm and 160mm for female and males, respectively, in this study. This difference in MLS could account for the higher KLPUE in the 1970's compared to this study. In the 1970's a higher proportion of the whole population was available to the fishery because crabs could be landed at a lower MLS. Two further explanations are that there is now a smaller population of females, or that there are now more pots fished, therefore due to the increased effort, there is a dilution of the kilograms landed per pot.

Spatial variation of landings per unit effort

Onboard

There was no significant difference between the total LPUE monthly means between 5 areas over the months of July, August and September. This non-significant result is again likely to be due to the small sample size (n=15) and the time of year (July-September) from which data were available. Interestingly, the mean for female LPUE for Areas 2 and 6, were much higher than the other area means, implying that females had a preference for these areas over the summer. An explanation for this occurrence could be favourable mating grounds, substrate, food availability, or bathymetry (See Bathymetry and Substrate in Chapter 4).

Fishers Diaries

KLPUE, analysed as a total and split by sex, did show significant differences between areas. There were significant differences between areas when total KLPUE was analysed. These significant results indicate that an environmental variable within this area was affecting the total, female and male KLPUE and, by association, the distribution of 'land-able' crabs within the IPA. These location specific environmental variables could be: the existence of a special area where mating is more common, substrate, food availability or bathymetry.

We also used the longer data series from the fisher diaries to re-test the hypothesis, that 'as a result of the migration of female crabs down the English Channel (from the east), the group mean for CPUE in the eastern IPA, will be higher than group mean for the western half of the IPA'. The analysis indicated that there were no significant differences between eastern and western areas of the IPA, over all months for total KLPUE or female KLPUE. However, there was a significant difference between areas of the mean male KLPUE, with the east having a higher mean monthly KLPUE than the west. This phenomenon could relate to a location specific variable such as substrate influencing the landings of male crabs. Area's 5 and 6 contributed data to the 'eastern' category, the substrate in both of these areas is rock. Chapter 4 shows that male crabs have a preference for rock compared to other substrate types. This outcome could be a result of there being only one of the four vessels supplying data from the eastern sector and a small sample size. Further, there may have been no significant difference between means of east and west female KLPUE as the migrating females may be categorised as discards as they are small crabs and/or in a soft-shelled condition ready to mate. This will be discussed in the DPUE section below.

Discards per unit effort

We asked the question: 'How does DPUE vary spatiotemporally within the IPA?' Below we discuss the variation of onboard DPUE in terms of time and space.

Temporal variation of DPUE

Soft-shelled crabs are prevalent in all months, as crabs do not always moult annually there is only ever a reduction of crabs available to be landed rather than a cessation in landings due to the moulting cycle. We elucidated two peaks of female soft DPUE and one peak of male soft DPUE in May- July. The female peaks occur in May and then a higher peak in August-September. The two peaks of female soft DPUE can be explained biologically by the reproductive behaviour of females. The female crab has to be in a soft-shelled state to successfully mate with the male, which is hard-shelled (Edwards, 1966a). Therefore, females have aligned their peak moulting times to coincide with the time when the highest proportion of males is in a hard-shelled condition. This increases the female's chances of mating with a male when she is in a suitable condition to receive his sperm and he has the correct shell rigidity to guard and mate her.

After both sexes have moulted it takes approximately 3 months before crab shells return to their pre-moult rigidity (Warner, 1977). This time period would explain the distribution of soft-shelled crabs (females and males) discarded within the IPA. This trait not only increases the discarded crabs in the population but also reduces the abundance of crabs available to be landed, as soft-shelled crabs tend to hide from predation in rock crevasses. The increase in crab abundance and catchability is two-fold once they become hard-shelled and this is reflected in LPUE. The only significant ANOVA was for male soft DPUE in July and September. This result has captured peak soft males in July and a decrease in the abundance of soft males in the population over the next two months, resulting in a significant difference between mean soft DPUE for July and September.

Small crabs were prevalent in all months, as crabs age their moulting frequency is reduced (Bennett, 1974), therefore it would be expected that a higher proportion of small crabs will be soft compared to mature crabs. During the data collection for this study, if a crab was small, its shell state was not recorded. It is likely that small, soft crabs will be in a state of torpor so reducing their catchability. This phenomenon is seen in this study over the autumn and some winter months by a reduction in their discards.

It should be noted that small males measuring slightly over the MLS are often categorised and landed as females. Historically, this practice has been estimated to be less than 5% of total landings (Brown and Bennett, 1979). Interviews with current crab fishers (see Chapter 5) established that this practice continues as standard, because of the relatively small proportion of crabs classified in this way, we have not corrected for this in the current study.

Spatial variation of Discards per unit Effort

There were no significant differences in the mean total DPUE between areas over the months of July, August and September. However there were significant differences for mean female DPUE between areas: 4 and 6, 4 and 5, 1a and 6, and 1a and 5 with areas 5 and 6 having the higher means, in all pairings. With regard to male DPUE the only areas to produce statistically significantly difference areas were 2 and 5 with Area 5 having the higher mean. All iterations of sex and discard type (soft and small) were analysed and the only significantly differences between the means of areas were: 2 and 5 and 6 and 5 when means of small males were tested, with Area 5 having the higher mean. These results highlight that area 5 produces a high frequency of discards compared to other vessels. There could be several explanations for this phenomenon; firstly, there could be subjective differences between vessels regarding the categorisation of crabs as discards. Fisher's subjective judgement of whether to land or discard crabs, which are marginally over the MLS or soft, could differ between vessels. Secondly, there could be an environmental variable within Area 5, which produces higher mean discards over the months of July-September. This variable could be substrate. When entering the IPA from the east the first rock, which is encountered, is in Area 5 (See Chapter 4 '*Substrate*'). During the period analysed (July to September) the highest soft DPUE were mostly females and the rate of soft males began to reduce after their peak in July. As soft-shelled crabs prefer to hide from predators in rock crevasses, and males can only mate with soft females, it is not inconceivable that the high number of DPUE in Areas 5 may be because it is a mating area.

To further assess the spatial distribution of discarded crabs we tested if there was an ontogenetic movement of crab into deeper water with age as indexed by size. As carapace width was not recorded we compared the mean DPUE of small crabs between areas at 0-3nm and 3-6nm from the shoreline. These analyses revealed significantly differences between the group means of 0-3nm and 3-6nm in total small and female small DPUE. In both cases the mean for small crabs was higher in the 0-3nm regions than 3-6nm. This demonstrates that more female small crabs are found closer to the shore. This result was expected as Edwards (1966) and Brown and Bennett (1979) found an ontogenetic movement of crab with size (and inferred age). We would have expected to also see significant results for small males between 0-3nm and 3-6nm. An explanation of why a difference was not detected between the sexes could be the relatively small sample size of small male DPUE leading to large standard deviations. Alternatively, as male crabs moult less frequently than females, with larger moult increments these results could be explained by the time period, of the sampling programme (July-September). This could simply reflect a time in the life history of males when there is a reduced catchability due to moulting behaviours such as hiding from predators and not feeding. To rectify this issue more repeats per area per month are required.

Additionally, as females enter the IPA from the east Hunter *et al.,* (2013) we analysed the means of total, female and male small discards for variation between east and west sections. The mean total small, and female small discards were significantly different between areas with the east having the higher mean. This indicates that either the environmental conditions in the east are more favourable for small females or are boosted by immigrants entering the IPA from the east due to migration.

Criticisms and suggested improvements of the study

The 9 vessels sampled during this study were chosen to representatively cover the fishing grounds of the IPA in time and space. As a result the experimental design should have allowed for generalisations about patterns of spatiotemporal variation of average catch, landings, and discard rates throughout the IPA to be made. However, there are several shortcomings of the methodology.

The study set out to sample 8 vessels per month for one-year, totalling 96 trips. However, due to bad weather preventing inshore vessels from fishing, vessels leaving and entering the study, and data collection not taking place from December 2011-March 2012, only 42 trips (43%) were achieved, impacting on the sample size for statistical analysis. It is important to note for future sampling that on days of good weather, most vessels will go to sea, but as there was only one observer collecting data, the observer could only be on one vessel at any one time. The inability to sample more than one vessel concurrently highlights the need for an automated data collection system to be used by fishers each time they fish, which feeds real time data into a sustainability model (Chapter 7). An incentive for fishers to gather their own fine-scale data could derive from sampling in real time, which would show fishers the areas that have higher rates of LPUE (See Chapter 6), which would be useful to value 'territories' when fishers sell them. These data are of course invaluable to assess the sustainability of the fishery, to enable fishers to fish most economically and focus on times of the year with highest LPUE/lowest DPUE, as in this fishery stakeholders do not have the opportunity to significantly move their fishing grounds.

Further, a study such as this cannot rely on just one years worth of data to understand the fishery's dynamics. To rectify this and to extend the time span over which CPUE, LPUE and DPUE rates were captured we extracted KLPUE from fishers diaries from ~2003-2012. While this was a time consuming exercise it vastly increased the sample size for analysis, making it easier to identify variability in catch patterns. Nevertheless, the data from fisher diaries did not capture information on discards, the GPS of pots or any other environmental data, which with an onboard observer could be recorded in detail. Therefore, to increase the sample size of onboard data, at least 3 trips per month, per vessel would be preferable with an observer or an automated method of data collection.

An issue, which could have increased variability in results during data collection, was categorisation of the catch. As fishers hauled and sorted their catch the landings, discards (including the reason for discarding) and sex for each individual crab was recorded. Fishers sort their catch rapidly, and therefore it is likely that on occasion incorrect categorisations were recorded. To mitigate this, the same observer recorded all categorisations, and where possible the fishers told the observer the reason for discarding each crab as it was returned to the sea. As the categorisation of crab as soft-shelled is subjective, there could be some between-vessel variation when recording this reason for discarding.

Almost all of the useful environmental variables such as weather and sea state were recorded during onboard trips. It would have been pertinent to sample a subset of the catch of each trip for carapace width. This was not undertaken as fishers do not like the landed catch to be handled once caught as crabs can shed their chelipeds or indeed die, when stressed.

The use of contour maps (Figure 3.10 to 3.13) to map the monthly abundance of crab throughout the IPA from a sample of fishing grounds might have introduced variation into the results. Surfer 10 Software employs the Inverse Distance to Power (IDP) gridding method to interpolate values for grid notes without a real data value. Therefore all values calculated by the IDP method could be erroneous as they are purely calculated by value from neighbouring nodes and do not take into consideration any environmental factors such as substrate, bathymetry, and sea temperature. To rectify this issue, in addition to interpolated contour maps, catch, landings and discard data could be re-mapped using graduated symbol maps in ArcGIS using only the real data.

A final criticism of this study concerns the homogeneity of the fishing gear used during this study. Some variation of the results in this study could be attributed to the differences in effectiveness of the parlour pots and inkwell pots to catch crabs. This potential difference is investigated in Chapter 5. Additionally, fishing strategies could affect gear effectiveness for instance: the vessel that fishes Area 6 specifically targets sand gullies and moves pots daily to replace gear back in these sand gullies. To mitigate these fishery dependent variables we suggest fisheries independent data could be collected via costly visual underwater surveys.

Aside from data collection during this study, fishers realised the importance of taking part in research and communicated this to other fishers who did not participate. This vital word of mouth communication and first-hand experience of working closely with scientists will inevitably help to recruit a larger sample of vessels for future research.

Future research

The data collected during this study will be used to inform fishers and local authorities on spatiotemporal variation of crabs in the IPA. It will also be used as input to an Individual Based Model (IBM) of the fishery (Chapter 6). The IBM will attempt to recreate the dynamics of the south Devon crab fishery within the IPA boundaries. The results of this study will be used to set the parameters for the model recreating the dynamic inputs (growth and immigration) and outputs rates (catch, mortality and emigration) and environmental conditions. Local fishermen will then be able to utilise a version of the model to test the effect of varying environmental variables such as sea temperature and fishing factors such as number of pots on catch, with additional work on the model, the eventual hope to carry out fisher-directed stock assessment and set individual vessel quota's for the next season. This approach works towards creating a sustainable fishery for the future, using a bottom-up methodology. This model would then hopefully be integrated into local management and demonstrate to fishers and managers alike the usefulness of the relatively inexpensive, quick and scientifically robust, onboard data collection method.

Conclusion

The above results extend the knowledge of catch, landings and discards data initially recorded by Brown and Bennett (1979) within the IPA in light of increased potting effort in recent years (Bannister, 2009) and at present exhibits the most comprehensive annual series of *Cancer pagurus* catch, landings and discards data in the UK. The data collected by Brown and Bennett (1979) was grouped by month over a 10-year period and was not analysed on a spatial scale other than ‘off south Devon’. In contrast this study presents catch, landings and discard per pot data along with the reasons for discarding and the proportions of males and female with precise GPS co-ordinates.

We demonstrate that it is possible to produce robust data working co-operatively with fishers, without whom data collection would not have been possible on such a fine scale. To provide a synthesis of the temporal dynamics of the fishery in we have developed a timeline of female and male behaviours over a ‘typical’ annual cycle (Figure 3.22 and 3.23.). Landings data was taken from fisheries diaries (KLPUE) as this provides a long-term data set compared to onboard data, and discard data is plotted from onboard data.

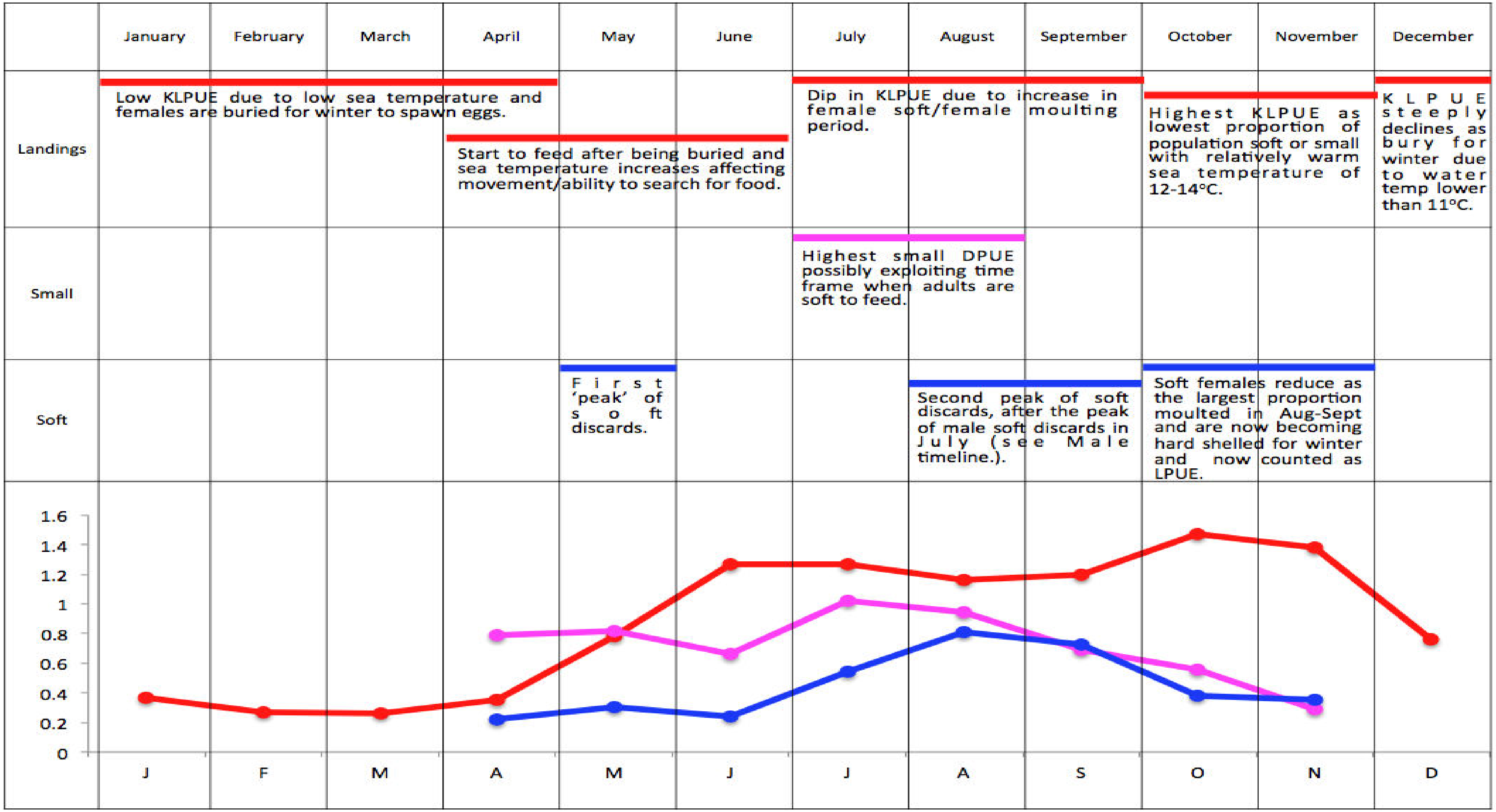

Figure 3.22. Month-by-month summary of temporal dynamics of the fishery female crabs. Red= female KLPUE (landings from fisheries diaries), Pink= female small discards per unit effort, Dark blue= female soft discards per unit effort.

The causes for the landing and discard rates seen above are explained in detail in throughout the discussion, however by displaying the pattern of landings and discards in one plot per sex, we can see that fishers should maximise their fishing efforts in June and then September to November as highest KLPUE for lowest discards occur in these months. Additionally, fishers within the IPA should also aim to align closed areas of the IPA to trawlers with the months of highest landings and the converse for open areas with lowest crab landings.

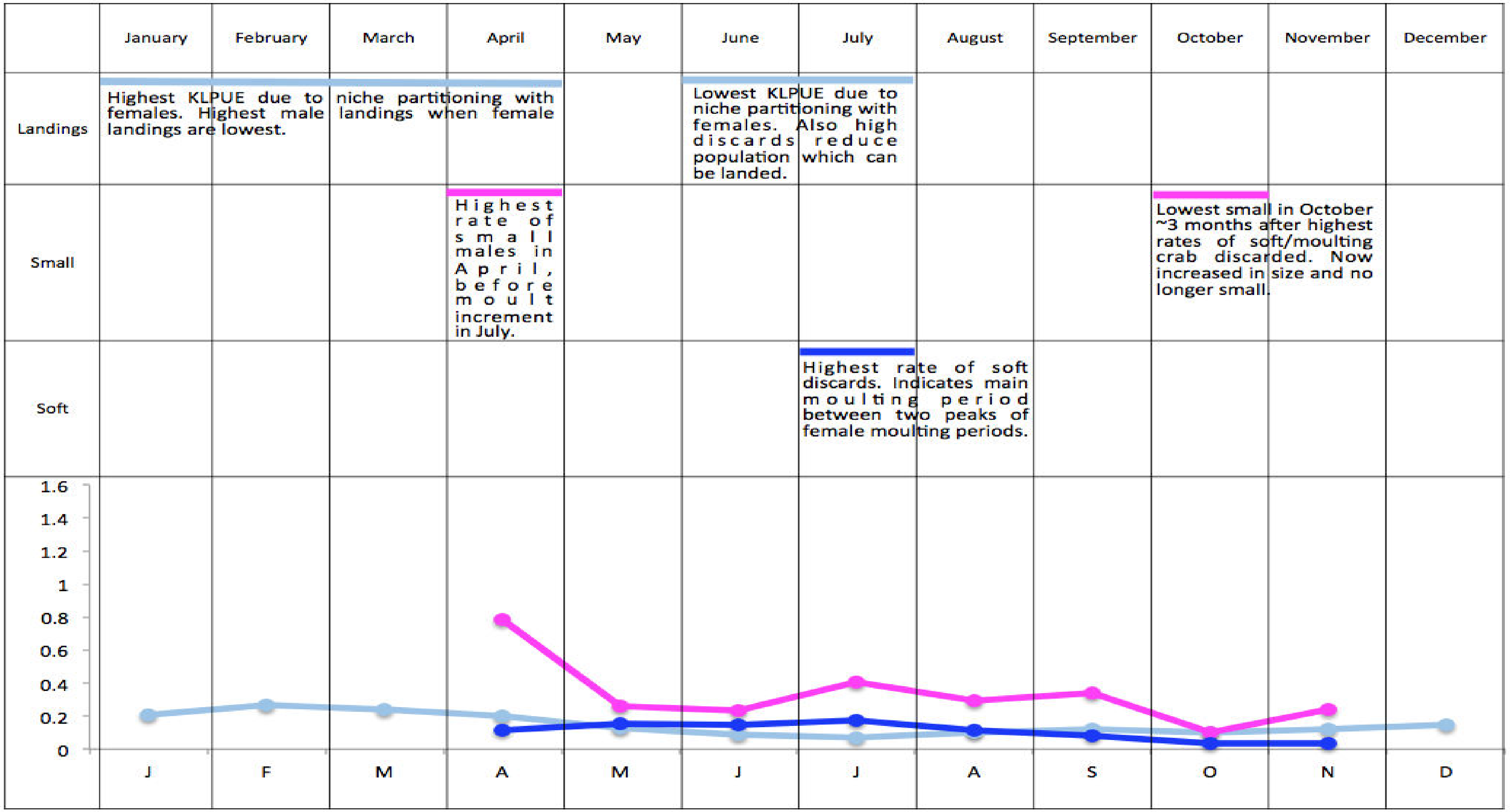

Figure 3.23. Month-by-month summary of temporal dynamics of the fishery male crabs. Light Blue= male KLPUE (landings from fisheries diaries), Pink= male small discards per unit effort, Dark blue= male soft discards per unit effort.

Local IFCA managers could use the high-resolution data contained within this Chapter (and Chapter 4) to stratify their carapace width sampling programme (for stock assessment) around the annual pattern of *Cancer pagurus* landings and discards. They currently sample approximately 3000 crabs for the western English Channel (WEC) crab stock assessment (CEFAS, 2014) however the data in this study estimates there to be upwards of 2,000,000 crabs in the IPA fishery, therefore the IFCA sample only equates to 0.15% of crabs in the IPA let alone the WEC. For further suggestions of how the local IFCA could stratify their sampling strategy in light of crab size correlations with depth and sex preferences for substrate see Chapter 7.

Furthermore, the detailed nature of this study enabled some comparisons to be made with research by Brown and Bennett (1979) and to make comment on how landings have changed since the 1970's. However, improvements are required in terms of sample size, recording of carapace widths and data must be collected throughout all months of the year in future studies.

This study and the highly detailed data gathered within the IPA will be an invaluable tool for scientist, fisheries authorities and fishers alike in the coming years of changes to the management of the IPA fishery and other comparable fisheries.

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Appendix A

Table 3.14. Parameters used to map onboard crab catch, landings and discard data using Surfer 10 Software.

Parameters	
Gridding Method	Inverse Distance to Power
Power	2
Smoothing	0
Anisotropy: Ratio	1
Anisotropy: Angle	0
Number of sectors to search	4
Maximum number of data to use from all sectors	n
Maximum number of data to use from each sectors	n
Minimum number of data in all sectors	8
Blank node if more than this many sectors are empty	3

Appendix B

List of month pairs with statistically significantly different from each other for one-way ANOVA's performed using monthly means of total LPUE from fisher diaries.

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

List of month pairs with statistically significantly different from each other for one-way ANOVA's performed using monthly means of female LPUE from fisher diaries.

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

List of month pairs with statistically significantly different from each other for one-way ANOVA's performed using monthly means of male LPUE from fisher diaries.

Nov/Jul	Feb/Jul	Jan/Jul	Apr/Jul	Mar/Jun
May/Jul	Mar/Jul	Dec/Jul	Feb/Jun	Jan/Jun

Appendix C

The number of Days At Sea (DAS) achieved by vessels from areas 1, 1a, 4 and 5 contributing fishers diaries data from 2003- 2012.

Area 1												
DAS	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	MEAN	S.D
January	0	0	0	3	6	5	4	8	6	8	4	3.16
February	1	1	0	2	2	4	6	1	1	7	2.5	2.37
March	6	6	7	0	7	4	8	4	8	8	5.8	2.53
April	8	8	14	5	14	14	6	10	11	9	9.9	3.31
May	15	19	13	11	15	19	11	15	11	19	14.8	3.33
June	15	15	17	18	18	16	21	19	12	11	16.2	3.08
July	16	17	16	17	14	14	11	18	17	14	15.4	2.12
August	19	15	18	16	17	10	14	13	16	13	15.1	2.69
September	19	11	14	13	17	14	17	15	13	13	14.6	2.41
October	14	10	13	9	21	7	13	12	12	13	12.4	3.72
November	7	18	12	6	15	10	2	10	10	11	10.1	4.51
December	9	11	10	10	4	10	9	7	7	5	8.2	2.35
TOTALS	129	131	134	110	150	127	122	132	124	131	129	10.12

Area 1a												
DAS	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	MEAN	S.D
January	0	0	0	7	6	5	7	8	8	0	4.1	3.63
February	0	0	0	2	2	0	1	0	1	0	0.6	0.84
March	0	0	0	2	13	9	14	6	11	12	6.7	5.79
April	0	0	0	16	20	15	15	13	16	12	10.7	7.67
May	0	0	0	16	15	21	14	17	16	22	12.1	8.71
June	0	0	0	23	18	18	21	21	19	16	13.6	9.58
July	0	0	0	21	16	16	17	20	21	21	13.2	9.32
August	0	0	0	8	22	15	20	17	19	17	11.8	8.94
September	0	0	0	16	19	15	15	17	16	17	11.5	8.02
October	0	0	0	13	18	14	19	14	14	18	11	7.86
November	0	0	0	10	16	13	4	16	15	15	8.9	7.11
December	0	0	0	10	6	12	12	11	8	7	6.6	4.97
TOTALS	0	0	0	144	171	153	159	160	164	157	110.8	76.77

Area 4												
DAS	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	MEAN	S.D
January	6	6	2	2	4	4	4	6	5	11	5	2.58
February	4	6	1	2	4	6	6	3	5	9	4.6	2.32
March	11	12	6	2	9	10	4	3	5	6	6.8	3.49
April	10	10	4	8	13	5	8	5	8	11	8.2	2.90
May	23	20	19	18	17	21	21	19	18	24	20	2.26
June	24	19	19	22	22	23	22	23	20	19	21.3	1.89
July	25	27	21	21	23	19	17	27	22	22	22.4	3.24
August	23	21	19	17	24	17	19	24	23	18	20.5	2.84
September	24	18	20	19	19	16	16	20	21	20	19.3	2.36
October	15	15	16	17	24	18	18	17	18	15	17.3	2.67
November	16	23	17	12	20	18	7	17	15	18	16.3	4.37
December	16	12	12	14	13	14	15	14	10	8	12.8	2.39
TOTALS	197	189	156	154	192	171	157	178	170	181	174.5	15.56

Area 5												
DAS	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	MEAN	S.D
January	6	5	4	4	4	6	6	7	6	7	5.5	1.18
February	4	4	3	3	4	4	7	4	6	8	4.7	1.70
March	5	2	5	0	7	5	6	5	7	12	5.4	3.17
April	3	3	4	0	5	3	3	3	4	4	3.2	1.32
May	10	12	10	0	11	10	9	9	8	11	9	3.37
June	12	12	11	14	12	14	14	13	11	9	12.2	1.62
July	12	11	11	15	14	12	12	13	14	11	12.5	1.43
August	11	11	12	13	13	11	15	13	12	12	12.3	1.25
September	13	11	12	11	11	11	8	12	11	11	11.1	1.29
October	10	7	10	13	12	10	12	10	12	10	10.6	1.71
November	9	11	12	8	12	9	6	10	9	10	9.6	1.84
December	7	7	7	8	5	7	6	8	6	5	6.6	1.07
TOTALS	102	96	101	89	110	102	104	107	106	110	102.7	6.45

Chapter 4

Environmental causes of spatiotemporal variation of crab in the Inshore Potting Area, Devon

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Abstract

To elucidate the causes of seasonal and spatial patterns of *Cancer pagurus* landings and discards rates, we investigated the effect of three environmental factors; sea temperature, depth and substrate within the Inshore Potting Area, Devon. Analysis showed that female landings are positively affected by sea temperature and male landings have a weak negative correlation. Landings from fisher's diaries showed a positive relationship with depth for males and females. Additionally, female DPUE had negative relationship with depth and there was no relationship between male DPUE and depth. Three types of substrate were fished on within the IPA; Rock, Rock and Muddy Sand and Muddy Sand. We concluded that female catch, landings and discards are (mostly) significantly related with muddy sand, whereas male catches, landings and discard are linked to rock.

The knowledge gained during this study will be used to inform fishers of the abiotic factors, which drive the landings and discard rates they observe. The information will also inform management and be used to set environmental parameters for an individual based model recreating the dynamics of the fishery.

Introduction

In an attempt to determine the environmental drivers of the variation observed in CPUE, LPUE and DPUE in time and over space, we used onboard and fisher diaries data as described in Chapter 3 to explore the relationship between temperature, bathymetry and substrate.

Water Temperature

Cancer pagurus and all crustaceans are poikilotherms (Aldrich, 1975: Woll, 2006), accordingly the temperature of seawater in which the species exists affects its behaviour. Ambient sea temperature affects the locomotion and hence the catchability of the species (Edwards, 1967). Sea temperature can also act as an environmental cue for *Cancer pagurus* to elicit certain behaviours such as egg brooding in females and pit digging in both species. Edwards (1967) stated, 'the yearly regularity of the rise in catch (of *Cancer pagurus*) suggests it is related to the rise in temperature of the sea'. He conducted laboratory based feeding experiments at varying temperatures. He discovered that crab held at 15.5 ^{o}C ate 46% of the food supplied to them, but at 4.5 ^{o}C only 1% of the food was consumed. Edwards also observed that at temperatures below 3.8 ^{o}C crabs that were usually active, became immobile and stopped feeding. Furthermore, the effect of temperature on activity in Atlantic rock crabs (*Cancer irroratus*) was observed by Jeffries (1966). He compared the walking activity at temperatures of 6 ^{o}C, 14 ^{o}C, 22 ^{o}C, and 28 ^{o}C. The mean percentage activity was highest (80%) at 14 ^{o}C and decreased as follows: 22 ^{o}C (65%), 6 ^{o}C (50%) and 28 ^{o}C (5%).

More recently, Drinkwater *et al.,* (2006) found a positive correlation between the mean temperature change during the 24 hours before traps were hauled and the average catch of lobsters per trap haul. They found that increasing bottom temperatures led to increased catch rates. These increased catch rates were attributed to increased activity with increased temperatures. Further, McLeese and Wilder (1958) found that lobster catch rates increased with a rising sea temperature in experiments. They took walking rate as an indicator of lobster activity and found that activity was temperature dependent. Moreover, Morgan (1974) (From Drinkwater et al., (2006)) found that monthly catchability coefficients were correlated positively with water temperature and salinity. Koeller (1999) found that in years of higher temperatures, larger catches were evident. This is because crustaceans moult (and hence grow) more frequently in warm water and thus crab would reach MLS more quickly than if they grew at a slower rate in colder water. As crabs would attain MLS more quickly, fishermen could land more crabs above MLS at a younger age giving the impression of high catch rates. Rebach (1974) also experimentally tested the effect of temperature on the locomotory activity of Hermit crabs (*Pagurus bernhardus*). They found that activity gradually decreased as the temperature of beakers containing the crabs was cooled. All hermit crabs retreated into their shell and ceased activity at a mean temperature of 3.2 ± 1.1 degrees. However, hermit crabs continued to elucidate a righting response until 2.0 ± 1.2 degrees. It is hypothesised that as environmental temperatures decrease hermit crabs move into deeper water and bury themselves in regions of sandy bottom. Overwintering in this manner might decrease the predation of hermit crabs by benthic organisms while the crabs are in a state of torpor (Rebach, 1974).

Bathymetry

The current literature focused on the effect of depth on *Cancer pagurus* is rather limited, with most research thus far only pertaining to the depths at which crabs were caught or observed. Brown and Bennett (1980) stated that *Cancer pagurus* occurred from the intertidal zone to depths of 100m and that there is a positive relationship between mean carapace width of *Cancer pagurus* with increasing depth, suggesting an ontogenic movement to deeper water. More recently CEFAS (2008) recorded the depth profiles of individual *Cancer pagurus* using DST tags, throughout their time at liberty (See Fig. 4.1). Crabs released in the eastern Channel migrating west experienced the largest range of depths Figure 4.1, shows the average monthly depth range experience by crabs to be from ~18m to 80m.

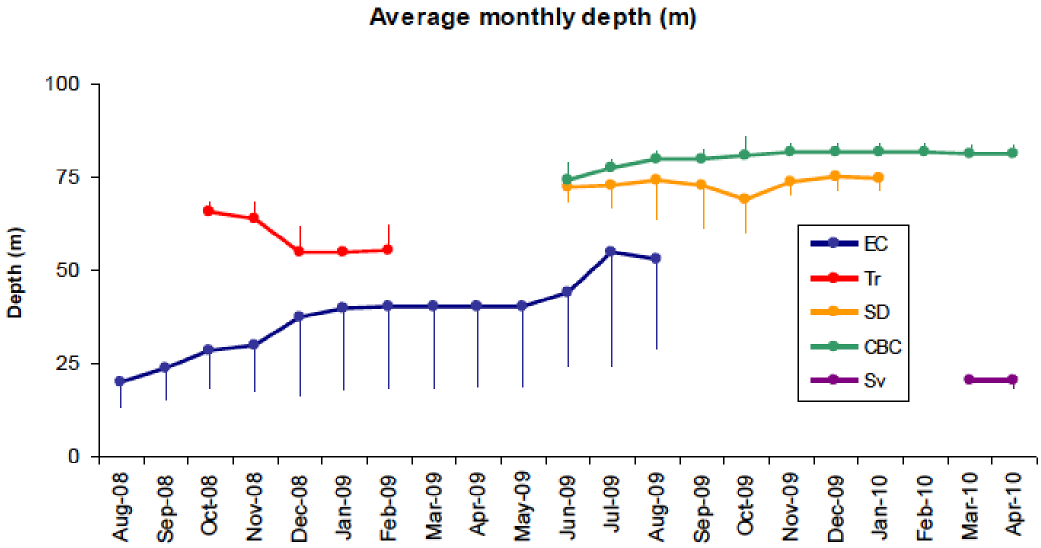

Figure 4.1. The average monthly depth experienced by DST tagged male and female Cancer pagurus. Release sites: EC= eastern Channel; Tr= Trevose; SD= south Devon; CBC= Channel Block C (Offshore in south Devon); Sv= Sovereign Shoals.

The depths encountered are reflected in the bathymetry of the English Channel as denoted by Coggan and Diesing (2011) with a depth gradient from east to west (Figure 4.2).

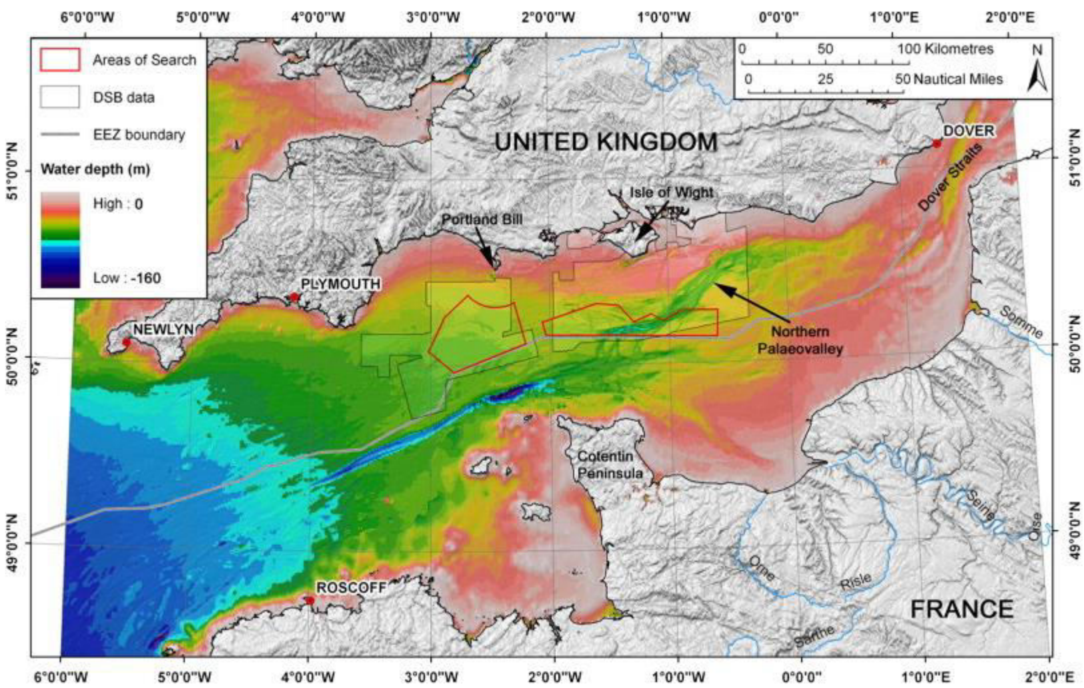

Figure 4.2 The depth contours of the English Channel (from Coggan and Diesing, 2011). Grey and Light pink denote shallow depths through to dark blue of depths ~160m.

Therefore as expected CEFAS (2008) found from DST tagged crabs (n=3) that eastern Channel crab migrating to the west experiences high depth variability. Importantly, CEFAS (2008) did not discover that migrating crabs were following depth contours as a means to navigate their migration routes.

Substrate

The nature of the substrate is a factor that affects the distribution of many crustaceans including amphipods, isopods and decapods (Cobb, 1971). Investigators have found that the particle size and nature of the substrate were important factors in determining the selection of a habitat by many crustaceans (Crawford 1937, Dixon 1944, Teal 1958, Cobb, 1971), especially for spawning by ovigerous females (Bennett and Brown, 1983; Woll, 2003; Rebach, 1974).

The seabed off Devon, where large concentrations of female are caught, is composed of sand or gravel with rocky outcrops inshore (Prattje, 1950; Lee and Ramster, 1976). The confinement of female crabs to burying in regions of sandy bottom indicates that substrate is an important determinant in which areas can be used as wintering grounds. For instance, Rebach (1974) found that Hermit crabs were not able to dig a proper depression in gravel to bury themselves, they were able to dig a depression in mud and sand but only continued to be buried long-term in sand. He concluded that as sea temperature decreases Hermit crabs seek a sandy bottom and bury themselves to decrease the probability of predation. The research of Rebach (1974) demonstrates the complex interaction of the behaviour of crab with environment factors such as temperature and substratum.

To give focus to this research we asked, 'are bathymetry, sea temperature and substrate correlated with catch (CPUE), landings (LPUE) and discards (DPUE)?'.

Methods and Study Area

The methods and study area for this study are as described in Chapter 3 '*Methods*'.

Sea Surface Temperature

Local Sea Surface Temperatures (SST) were acquired from the Plymouth Marine Laboratory (PML). *Cancer pagurus* are a bottom dwelling species and idealistically a bottom temperature data set would have been used in this study. These types of long-term and location specific temperature readings were not historically recorded and therefore could not be used, therefore SST data was used. Holme (1961) researched the variation between SST and bottom temperatures in the English Channel. His research concluded that 'in winter, complete vertical mixing occurs, so that the surface and bottom temperatures for February are identical.' For the remainder of the year and especially the summer months 'a thermocline is set up in the western half of the Channel', however due to 'strong tides and shallow waters, the vertical temperature gradient is small (Matthews, 1911; Dietrich, 1950, From Holme, 1961)' thus supporting the use of the SST data set for bottom dwelling crabs.

The SST (in ^{o}C) from Plymouth Marine Laboratory was recorded at 50°15.0'N, 4°13.0'W, approximately 3.65nm south of Rame Head, Plymouth, a few miles west of the IPA. A range of 1 to 8 recordings of SST were taken per month, these were then averaged to produce a monthly mean per year (e.g. Jan 2003, Feb 2003 etc.). The corresponding daily KLPUE data from 4 vessels (see Chapter 3- *Fishers Diaries Data*) was also averaged per month, for each sex. The fishers diaries data was donated by 4 vessels (1, 1a, 4 and 5) and was used to examine the relationship between temperature and female KLPUE and separately, male KLPUE. The data gathered onboard was not useful for this analysis, as it did not extend over a long enough time period.

Bathymetry

Data collected onboard fishing vessels by the author and from fishers diaries were analysed with bathymetry data from the Salcombe Approach Admiralty Chart (2005), to assess the effect of depth on CPUE, LPUE and DPUE. The bathymetry contours of the IPA are shown in Figure 4.3.

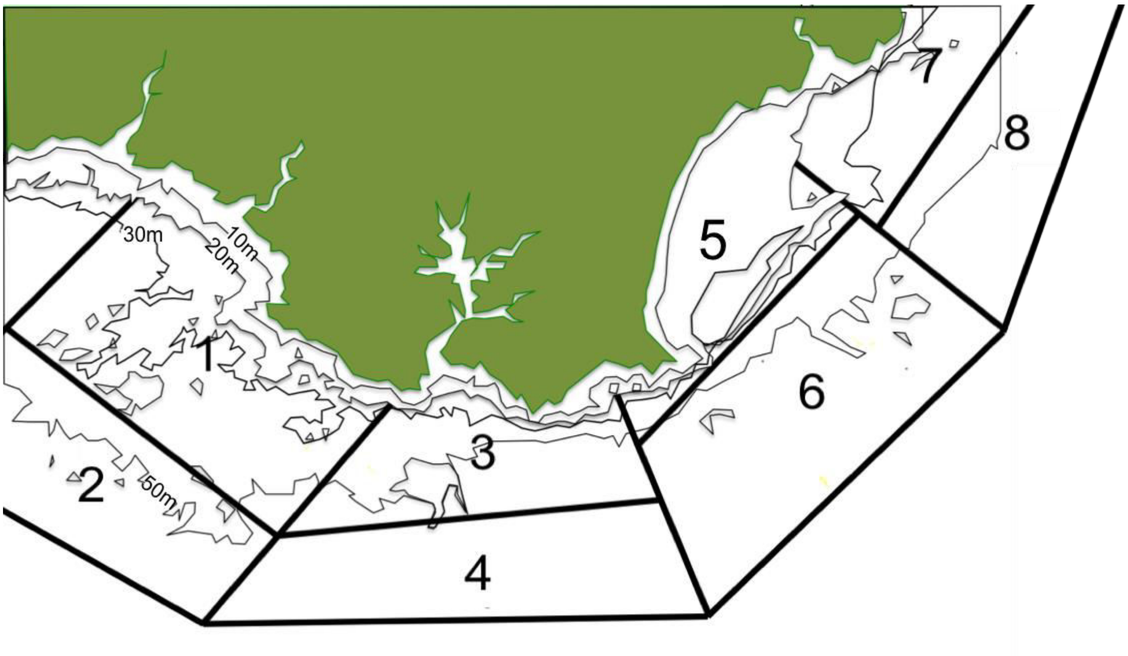

Figure 4.3. The depth contours of the IPA (10, 20, 30 and 50m lines) overlaid with the eight IPA areas sampled in this survey.

During onboard data collection, the depth of each string of pots was recorded as the first pot was hauled. To obtain the depths at which landings were taken for the fisher diaries data depths were taken from the Salcombe Approach Admiralty Chart (2005) at the point where the strings had been set. For analysis each depth was grouped into the following depth ranges: 0-10m, 11-20m, 21-30m, 31-40m, 41-50m, 51-60m, 61-70m and 71-80m.

Substrate

To investigate the relationship between catch, landings, discards and substrate type we used substrate data from EMODnet (emodnetseabedhabitat.eu, 2016) to map the substrate type over the IPA and fishing Areas 1-8 (See Figure 4.4.).

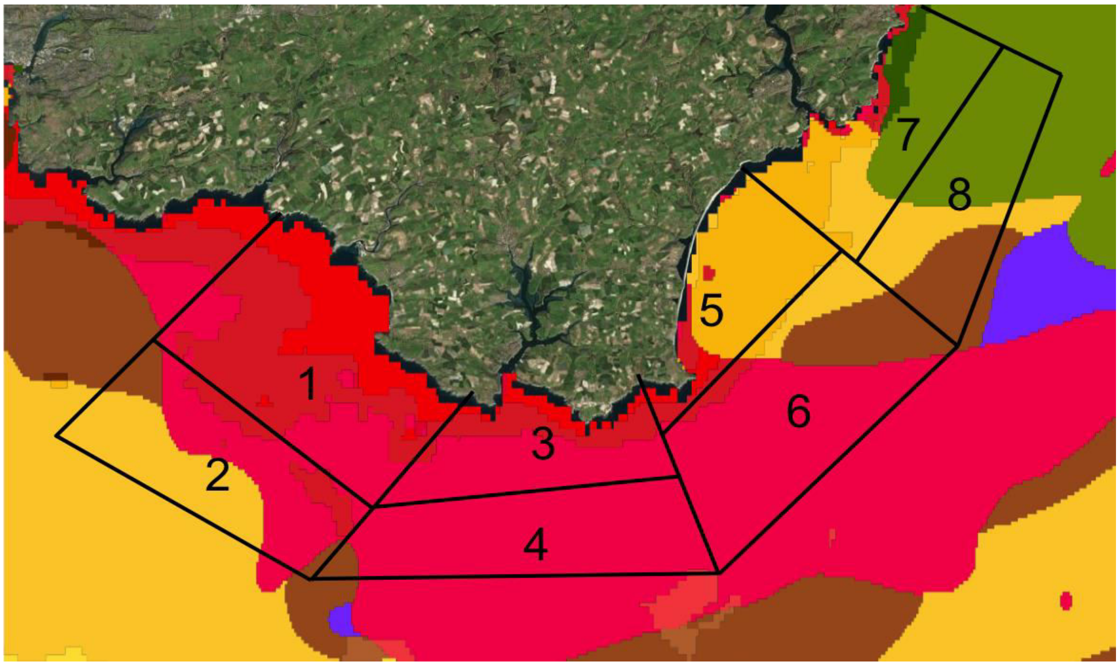

Figure 4.4. Substrate type from EMODnet mapped onto Google Earth with areas 1-8 superimposed. There are three types of rock (Pink: moderate energy circalittoral rock, Red: high energy infralittoral rock and Reddish brown: moderate energy infralittoral rock), which we class as 'rock'. There are two types of muddy sand (Dark Yellow: Infralittoral fine or muddy sand, Yellow: Circalittoral fine or muddy sand) classed as 'Muddy sand'. Lastly, there are two categorises of sediments (Brown: Circalittoral coarse sediment and Purple: Circalittoral mixed sediment) classed as sediments.

Due to matters of confidentiality we have summarised the specific type of substrate on which each vessel fishes, within each area in Table 4.1. so as not to aid the identification of a vessel by the substrate type it fishes upon.

Table 4.1. The area in which each vessel fished with the corresponding substrate type.

Vessel	Area	Substrate
1	1	Rock
2	1a	Rock
3	2	Rock and Muddy Sand
4	3	Rock
5	4	Rock
6	5	Rock
7	6	Rock
8	7	Muddy Sand
9	8	Muddy Sand

In the analysis of catch, landings and discards with substrate type, we were only able to use data collected onboard vessels by the author, all fisher's diaries data was collected on 'rock' and therefore there were no different substrate types to compare. The fishing grounds of the vessel, which fished in Area 2, were comprised of two types of substrate rock and muddy sand. Therefore three substrate types are compared throughout this study; Rock, Rock and Muddy Sand and Muddy Sand.

Results

Effect of temperature on female KLPUE

To elucidate the effect of SST on female landings the mean monthly female KLPUE from fisher's diaries were plotted against the mean monthly SST over a 10-year period from January 2003 to December 2012 (Figure 4.5.). A visual inspection of the plot indicates a positive relationship between temperature and female KLPUE.

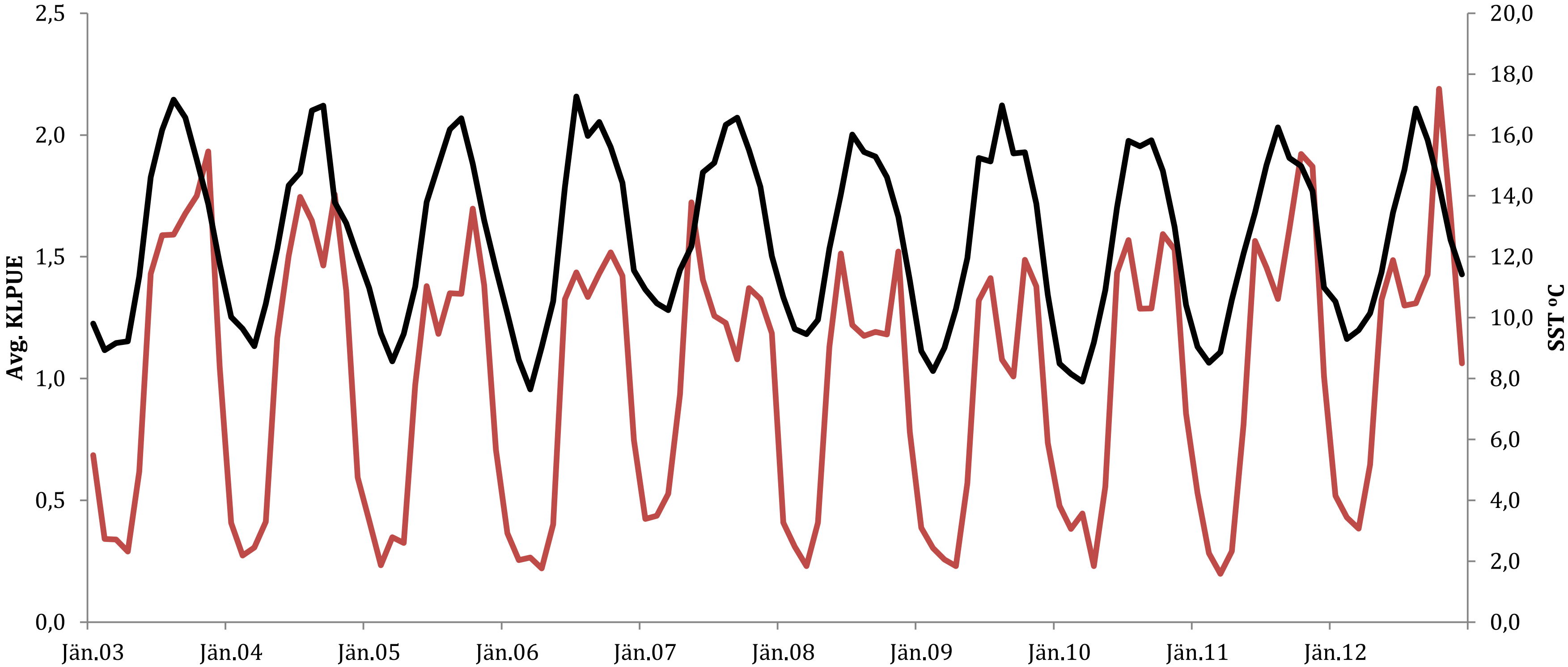

Figure 4.5. The mean monthly female KLPUE from 4 vessels in the IPA plotted with the mean monthly SST in degrees centigrade over a 10-year period from January 2003 to December 2012. Red line= Daily average female KLPUE from all vessels combined. Black line= average monthly sea surface temperature (ºC).

To calculate the relationship we performed a linear regression (standard least squares) on the mean monthly female KLPUE, per vessel, with mean monthly SST (Figure 4.6.). This correlation provided a regression equation of y=0.16x – 1.01, with R^2 =0.58 (n=430, p<0.0001) indicating that 58% of the total variation in *female KLPUE* can be explained by the linear relationship between *temperature* and *female KLPUE* with the remaining 42% of the variation in female KLPUE unexplained. A one-way ANOVA demonstrated a significant result, F(1,429)=585.5, p<0.0001 showing that the regression accounts for a significant portion of the variation between female monthly KLPUE and SST.

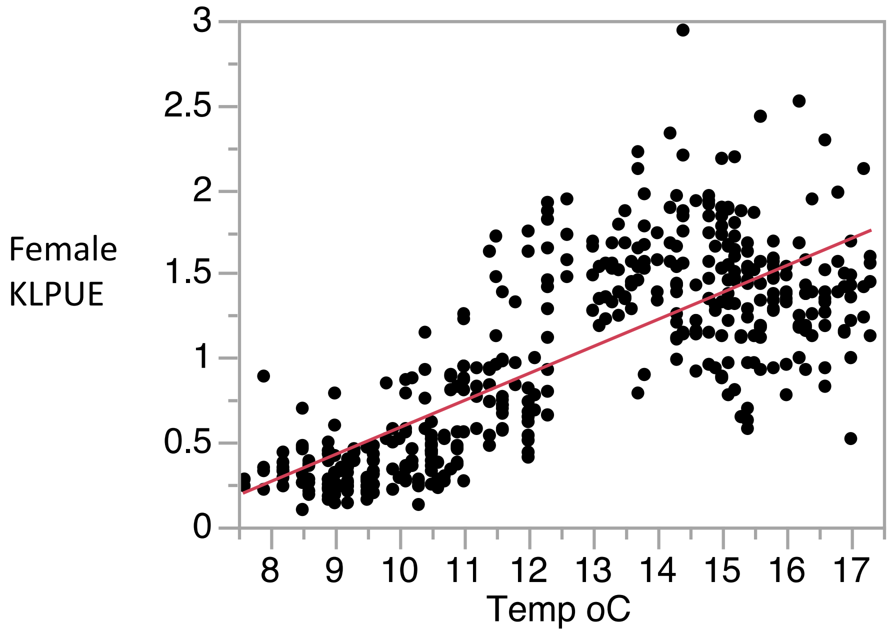

Figure 4.6. A linear regression of the mean monthly female KLPUE and SST.
(y=0.16x – 1.01, R^2 = 0.58).

Effect of temperature on male KLPUE

As with the female KLPUE, the mean monthly male KLPUE from 4 vessels in the IPA plotted against the mean monthly SST over a 10-year period Jan 2003 to December 2012 (Figure 4.7.) to elucidate the relationship between sea surface temperature and landings of male crabs. A visual inspection of the plot indicates a crude negative relationship between temperature and male KLPUE.

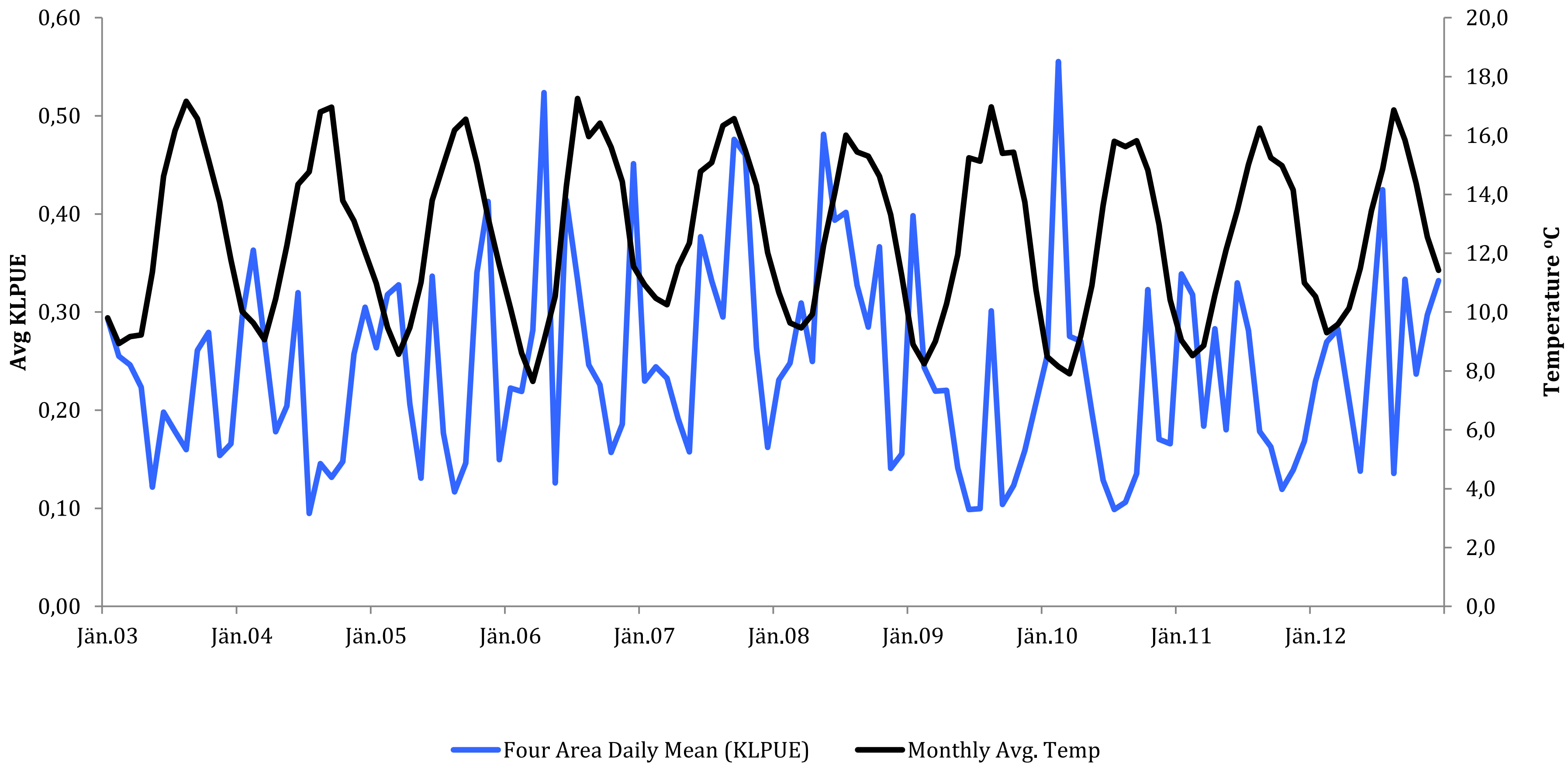

Figure 4.7. The mean monthly male KLPUE from 4 vessels in the IPA plotted with the mean monthly SST in degrees centigrade over a 10-year period between January 2003 and December 2012. Blue line= Daily average male KLPUE from all vessels combined. Black line= average monthly sea surface temperature (°C).

To calculate the relationship we performed a linear regression on the mean monthly male KLPUE, per vessel, with mean monthly SST (Figure 4.8.). The regression equation is y=-0.0045x +0.30, and an $R^2 = 0.003$ (n=429, p<0.2429). The ANOVA demonstrated no significant results, F(1,428)=1.37, p<0.2429 showing that the regression does not account for a significant portion of the variation between male monthly KLPUE and SST.

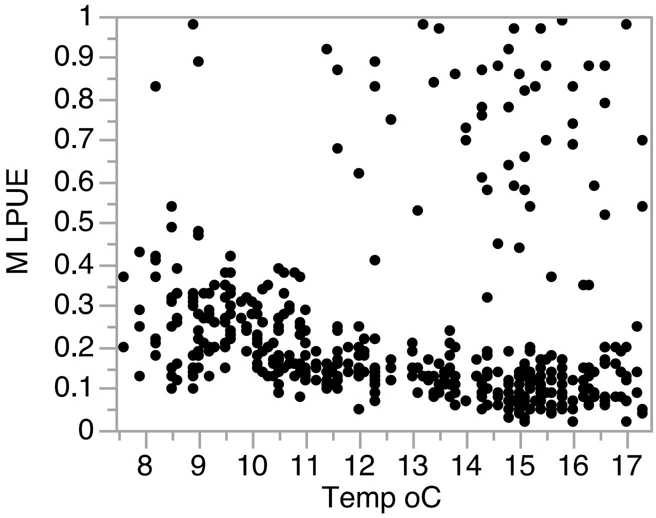

Figure 4.8. A linear regression of the mean monthly male KLPUE and SST. (y=-0.0045x +0.30, R^2 = 0.003).

However, the mean monthly male KLPUE and SST regression plot shows two distinct groups above and below ~0.5 KLPUE. To discover the origin of the group of plots above 0.5 KLPUE, regressions were plotted for individual vessels 1, 1a, 4 and 5 (Figure 4.9.).

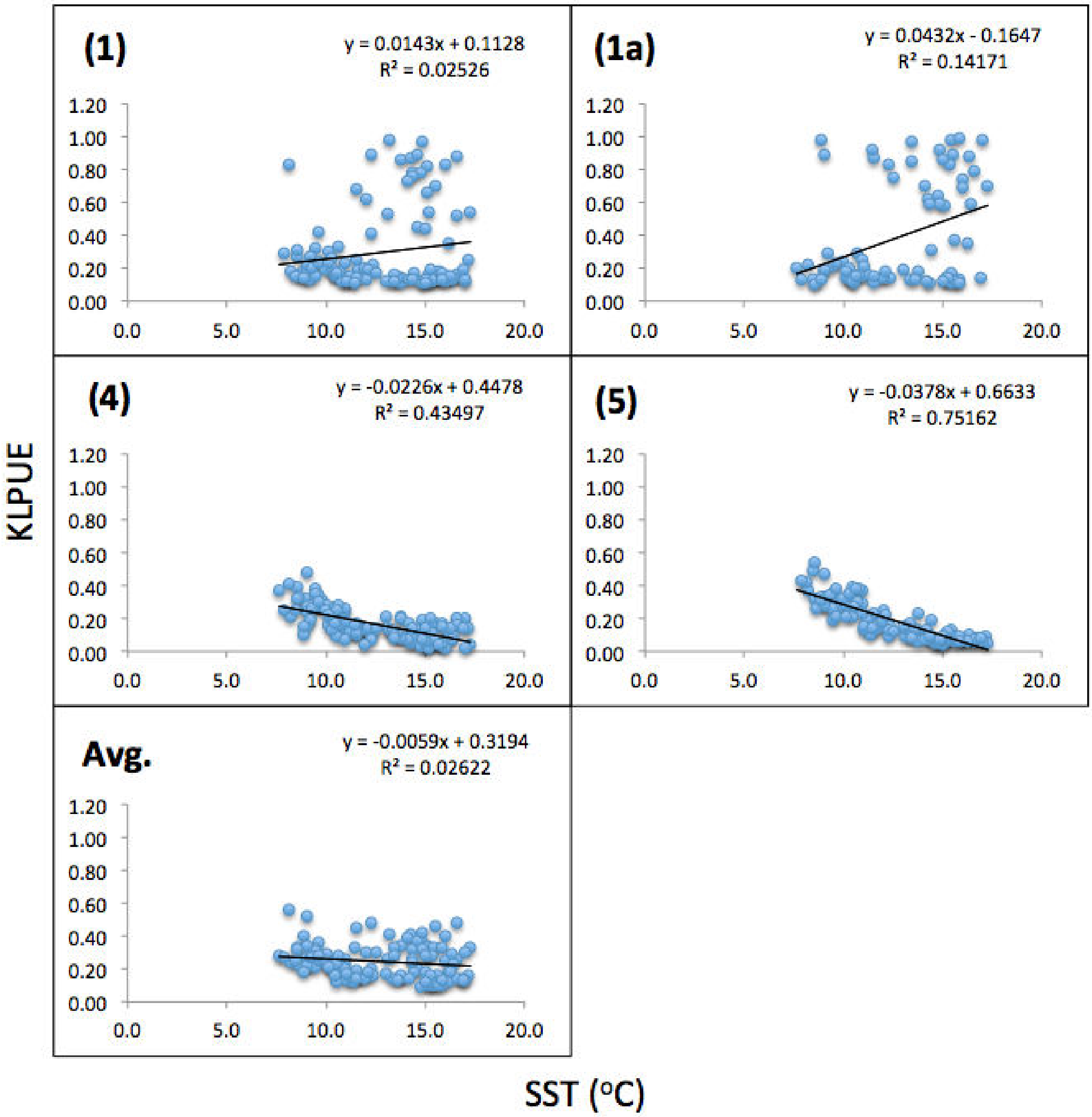

Figure 4.9. Linear Regressions of mean monthly male KLPUE and SST, for four vessels 1, 1a, 4 and 5. The fifth graph shows the daily average male KLPUE for all vessels, which fished plotted against temperature. N.B the number of vessel, which fished per day ranged from 1- 4.

The regressions from the plots of individual vessels show that the outliers plotted in Figure 4.9. (above 0.5 KLPUE), originate from areas 1 and 1a. The outliers came from the two areas which fish close inshore (<1.5 nm) and all lie above 0.5 KPUE. These outliers correlate with temperatures that were mostly above 12°C, which usually occur between the months of June and December. The outliers occurred in the months and years shown in Table 4.2. (for a full list of raw data see Appendix

D). We plotted the correlation of the male KLPUE outliers with sea temperature (Figure 4.10) however there was no correlation R^2 = 0.00143.

Table 4.2. The number of male KLPUE outliers above 0.5 removed per month and per year.

Month	**No. of Male KLPUE outliers**	**Years**	**No. of Male KLPUE outliers**
January	2	2003	2
February	1	2004	3
March	0	2005	3
April	2	2006	9
May	3	2007	10
June	11	2008	9
July	10	2009	2
August	5	2010	2
September	6	2011	2
October	8	2012	7
November	5		
December	4		

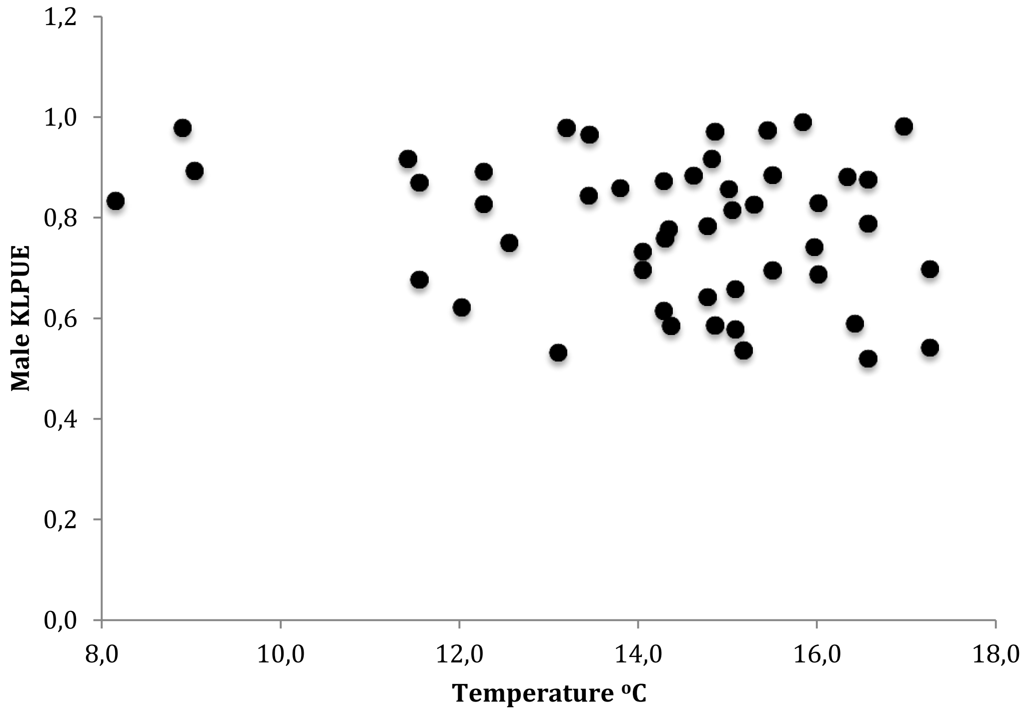

Figure 4.10. Correlation between outlying male KLPUE (above 0.5 KLPUE) and sea temperature. Y=0.0034x +0.67, R^2=0.00143.

The linear regressions for these two areas were then re-plotted without outliers (Figure 4.11.).

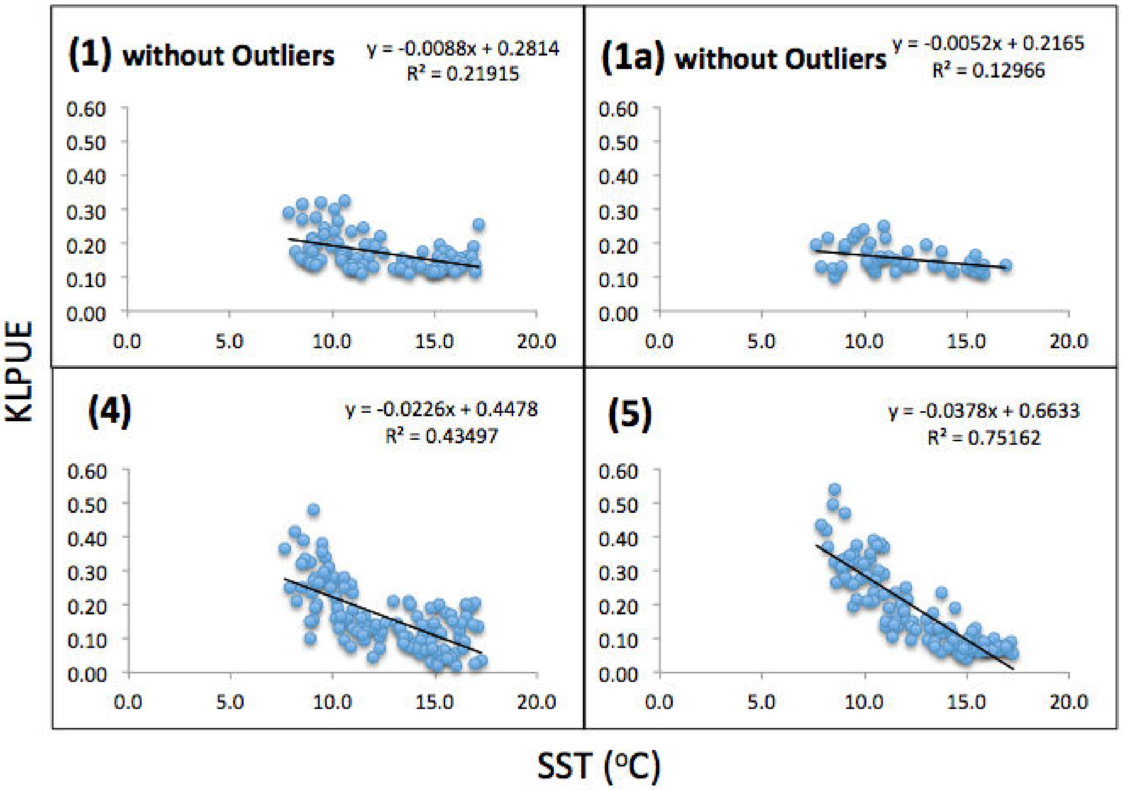

Figure 4.11. Linear Regressions of mean monthly male KLPUE and SST with outliers removed above 0.5 KLPUE, for four vessels 1, 1a, 4 and 5. N.B the number of vessel, which fished per day ranged from 1- 4.

The data combined from all four individual areas without outliers in area 1 and 1a now show a negative relationship of mean monthly male KLPUE with SST. Figure 4.12. shows the regression of data from all four vessels with the outliers removed.

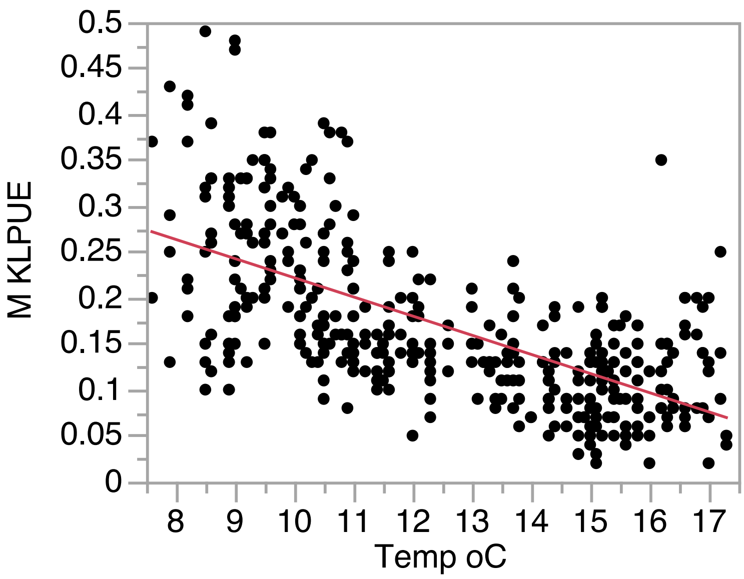

Figure 4.12. A linear regression of the mean monthly male (M) KLPUE (outliers above 0.5 KLPUE removed) and SST.

The linear regression without outliers now gives a regression equation of y=-0.02x+0.43, and an $R^2 = 0.408$ (n=370, p<0.0001) indicating that 41% of the total variation in *male LPUE* can be explained by the linear relationship between *temperature* and *male LPUE* with the remaining 59% of the variation in male LPUE remaining unexplained. The ANOVA demonstrated a significant result, $F(1,369)=255.09$, p<0.0001 showing that the regression accounts for a significant portion of the variation between male monthly KLPUE and SST.

Effect of Bathymetry on LPUE and DPUE

To test the effect of bathymetry on crab LPUE we used data from fisher's diaries, which was recorded daily over a 10-year period (2003-2012) from 4 vessels. The mean KLPUE was calculated for each month over the ten-year period. The average depth of each fisher's 'territory' was calculated and categorised into the same seven depth groupings as for the onboard data: 0-10m, 11-20m, 21-30m, 31-40m, 41-50m, 51-60m, 61-70m and 71-80m. The four vessels onboard from which, these data were collected, only fished in depth categories 21-30m, 41-50m, 51-60m and 61-70m. The mean monthly total kilogrammes of landings per unit effort for males and separately females combined over 10 years from four areas generated a sample of n=431. Each vessel did not record data in all months of the

10-year period, as vessels did not fish on days when the weather was too poor or were out of the water for maintenance.

Female KLPUE

The mean monthly female KLPUE were plotted into their corresponding depth categories. The highest mean KLPUE of 1.12 (± 0.62 s.d.) was found at a 61-70m depth, and the lowest mean KLPUE at 41-50m with a mean of 0.81 (± 0.44 s.d.) (See Figure 4.13.).

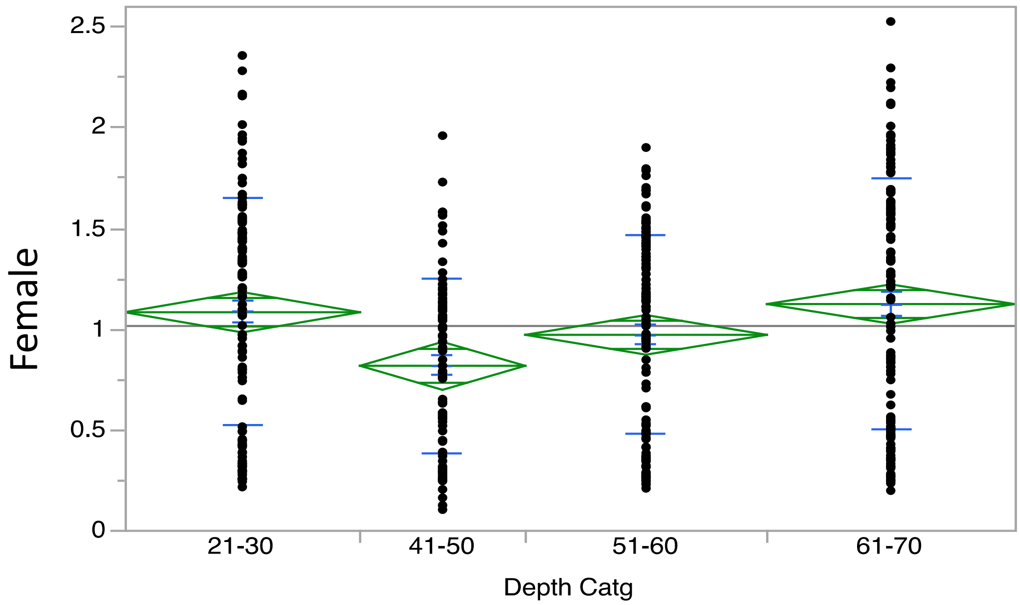

Figure 4.13. Average monthly female (F) KLPUE plotted from 4 vessels grouped into catch depth ranges: 21-30m, 31-40m (no data), 41-50m, 51-60m, and 61-70m.

A one-way ANOVA was performed on the monthly means of female KLPUE (n=431) with depth. The ANOVA yielded a significant difference between landings derived from the different depths, $F(3,427)=6.01$, $p<0.0005$. A post hoc Tukey test showed that the following pairs were significantly different from each other at $p<0.05$ (See Table 4.3.): 21-30m and 41-50m, and 41-50m and 61-70m, with the group mean for 41-50m being the lowest in all pairings.

Table 4.3. Results of a Tukey Test for the mean female KLPUE with depth. Non= non-significant results of Tukey test (p<0.05). Sig. (in Red)= significant difference between pairs of a Tukey Test (p<0.05).

	21-30m	41-50m	51-60m	61-70m
21-30m	-	Non	Sig.	Sig.
41-50m	Non	-	Sig.	Non
51-60m	Sig.	Sig.	-	Sig.
61-70m	Sig.	Non	Sig.	-

Male KLPUE

The mean monthly male KLPUE were plotted into their corresponding depth categories (Figure 4.14.). The highest mean KLPUE of 0.43 (± 0.16 s.d.) was found at a 51-60m depth, and the lowest mean KLPUE at 61-70m with a mean of 0.32 (± 0.09 s.d.) (See Figure 4.14.).

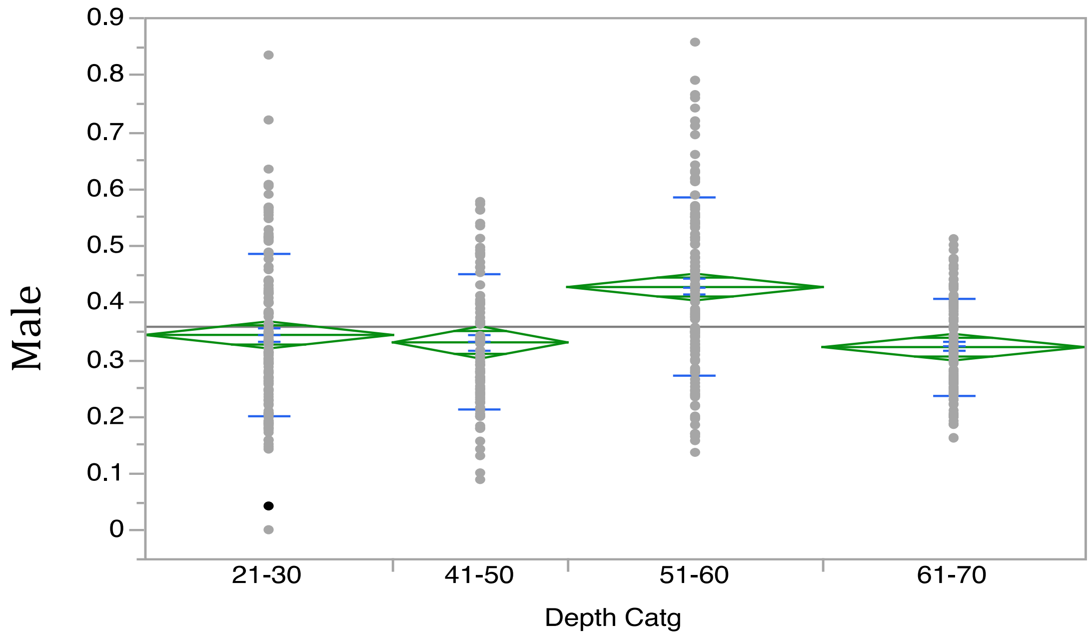

Figure 4.14. Average monthly male KLPUE plotted from 4 vessels by the catch depth ranges: 0-10m, 11-20m, 21-30m, 31-40m, 41-50m, 51-60m, 61-70m and 71-80m.

A one-way ANOVA tested whether the monthly means of male KLPUE (n=431) varied significantly with depth. The ANOVA yielded a significant difference between conditions, $F(3,427)=16.04$, $p<0.0001$. A post hoc Tukey test showed that the following pairs were significantly different from each other at $p<0.05$: 21-30m and 51-60m, 41-50m and 51-60m and 51-60m and 61-70m, with the group mean for 51-60m being the highest in all pairings.

Female DPUE relationship with depth

As the fishers did not record discards in their diaries we used the average female DPUE from each monthly trip to sea made by the observer and these data were plotted from the 9 vessels together with the corresponding catch depth category (Figure 4.15.).

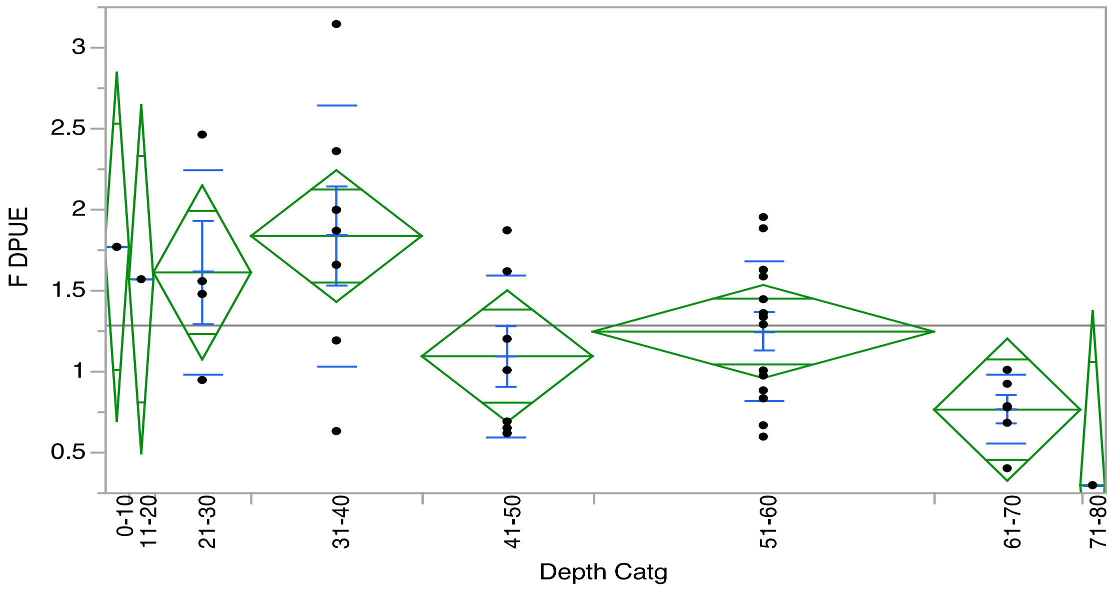

Figure 4.15. Average female (F) DPUE plotted from each monthly trip recorded on 9 vessels categorised into catch depth ranges: 0-10m, 11-20m, 21-30m, 31-40m, 41-50m, 51-60m, 61-70m and 71-80m.

The mean discards in Figure 4.15. show that means in the three shallowest depths are above the overall mean and those mean values below the overall average are all in the deeper water. The highest mean female DPUE 1.83 (± 0.81 s.d.) was recorded in the depth range of 31-40m with the lowest mean 0.29 (±- s.d.) recorded in the 71-80m category (See 4.15.). A one-way ANOVA was performed on the monthly means of female DPUE (n=42) with depth. The ANOVA yielded a significant difference between conditions, $F(7,33)=2.94$, $p<0.0166$. A post hoc Tukey test showed that the following pairs were significantly different from each other at $p<0.05$: 31-40m and 61-70m, with the group mean for 31-40m being the highest mean.

Male DPUE relationship with depth

The average male DPUE from each monthly trip was plotted from 9 vessels at its corresponding depth category (Figure 4.16.).

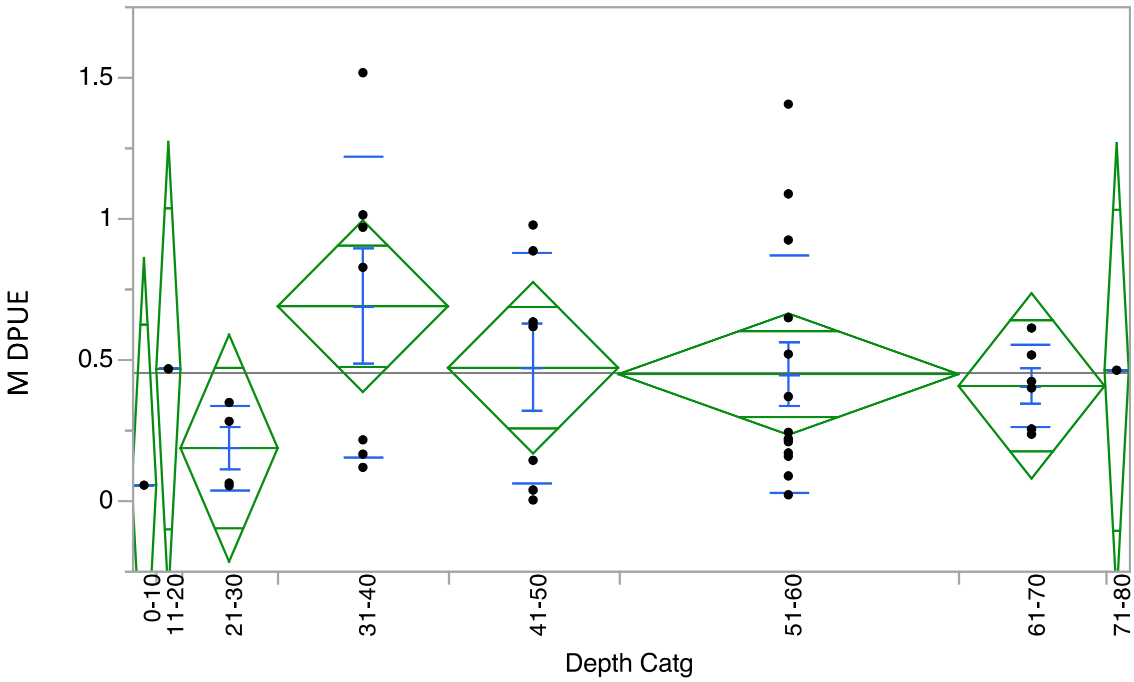

Figure 4.16. Average male DPUE plotted from each monthly trips achieve from 9 vessels categorised into catch depth ranges: 0-10m, 11-20m, 21-30m, 31-40m, 41-50m, 51-60m, 61-70m and 71-80m.

The highest mean male DPUE of 0.69 (±0.53 s.d.) was recorded in the depth range of 31-40m with the lowest mean 0.05 (no s.d.) recorded in the 0-10m category (See Figure 4.16.). A one-way ANOVA was performed on the monthly means of male DPUE (n=42) with depth. The ANOVA yielded no significant difference between depths ($F_{(7,33)}=0.77$, $p>0.6117$). All other one-way ANOVAs testing for variance between discards types such as female and male, small and soft crabs with depth were non-significant Table 4.4.

Table 4.4. A summary of the one-way ANOVA results for female small, and soft and male small and soft discards testing for a significant difference between the depths they were caught at in the IPA.

Discard Type	One-way ANOVA
Female Small	F(7,33)=2.30, p>0.0504
Female Soft	F(7,33)=1.52, p>0.1963
Male Small	F(7,33)=0.91, p>0.5092
Male Soft	F(7,33)=0.43, p>0.8773

The effect of Substrate on LPUE

We carried out a series of one-way ANOVA's to see if there was a significant difference between substrate types (rock, muddy sand and rock, and muddy sand) and landing per unit effort. We combined data from each month of onboard trips creating a sample n=42. We continued to use ANOVA's to test for variation between substrates for female LPUE and male LPUE (See Table 4.5.)

Table 4.5. A summary of the one-way ANOVA results for total LPUE, female LPUE and male LPUE testing for a significant statistical difference between substrate types in the IPA.

	Substrate	n	Mean	Std. Dev	ANOVA	Tukey HSD (Sig dif pairs)
Female LPUE	Muddy Sand	11	3.00	1.66	F(2,39)=10.74, p<0.0002	Rock and Muddy Sand
	Muddy Sand and Rock	7	2.86	0.89		Rock and (Muddy Sand and Rock)
	Rock	24	1.49	0.59		
Male LPUE	Muddy Sand	10	0.09	0.05	F(2,38)=2.59, p>0.0877	
	Muddy Sand and Rock	7	0.08	0.04		
	Rock	24	0.15	0.10		

One-way analysis of variation showed there were significant differences between substrate types for female LPUE and non-significant results for male LPUE. The female LPUE tests indicated there were two sets of significantly different pairs of substrates 'rock and muddy sand', and 'rock and muddy sand and rock'. In both rock had the lowest group mean, with the group means of muddy sand (3.00) and 'muddy sand and rock' (2.86) being similar. There were no significant differences between substrate types for male LPUE however the group mean for 'rock' was higher than the group mean of other substrate types.

The effect of substrate on DPUE

Lastly, we statistically compared discards types (small and soft) by sex on substrate type using one-way ANOVA's (Table 4.6.).

Table 4.6. A summary of the one-way ANOVA results for female and male small and female and male soft discards testing for a significant statistical difference between substrate types in the IPA.

	Substrate	**n**	**Mean**	**Std. Dev**	**ANOVA**	**Tukey HSD (Sig dif pairs)**
Female Small	Muddy Sand	11	1.12	0.50	F(2,39)=5.64, p<0.007	Rock and Muddy Sand
	Muddy Sand and Rock	7	0.51	0.21		Muddy Sand and Muddy Sand and Rock
	Rock	24	0.70	0.42		
Male Small	Muddy Sand	11	0.12	0.23	F(2,39)=9.73, p<0.0004	Rock and Muddy Sand
	Muddy Sand and Rock	7	0.10	0.04		Rock and Muddy Sand and Rock
	Rock	24	0.51	0.34		
Female Soft	Muddy Sand	11	0.65	0.59	F(2,39)=1.58, p>0.21	
	Muddy Sand and Rock	7	0.52	0.22		
	Rock	24	0.42	0.23		
Male Soft	Muddy Sand	11	0.07	0.08	F(2,39)=3.49, p<0.0401	Rock and Muddy Sand
	Muddy Sand and Rock	7	0.11	0.06		
	Rock	24	0.14	0.08		

There were significant differences between substrates for the following discard types: female small crabs, male small crabs and male soft crabs. For female small crabs the significant pairs were: 'rock and muddy sand' and also, 'muddy sand and muddy sand and rock', with 'muddy sand' having the highest group means in both instances. The significantly different pairs for male small crabs were: ‘rock and muddy sand’ and ‘rock and muddy sand and rock’, in both pairs the highest group mean was rock. When soft crab was analysed with substrate type female soft did not show a statistically significant difference between substrate types. However, male soft crabs demonstrated a significant difference between ‘rock and muddy sand’, with rock having the highest group mean.

Discussion

This study has for the first time elucidated the relationship between landing and discard rates and sea surface temperature, bathymetry and substrate type in the IPA. Below the relationships of these three abiotic factors with landings and discards are discussed in detail.

Temperature

Crabs are poikilotherms and according to Warner (1977) the underlying environmental factor driving the seasonal variation of the population dynamics of *Cancer pagurus* is likely to be temperature. Furthermore, Jeffries (1966) indicated that water temperature affected the walking activity of crabs in the same genus as *Cancer pagurus*, *Cancer irroratus*. More specifically, Aldrich, 1975 found that water temperature affects *Cancer pagurus’* locomotion and hence, foraging activity. Plotting the 10-year KLPUE data demonstrated a positive correlation between female KLPUE and SST, and a weak negative relationship between male KLPUE and SST. The low R^2 for females of 0.58 can be explained by reduced KLPUE over the summer months when the females are discarded as being soft due to their moulting period, rather than being counted as LPUE, they are counted as soft and artificially reducing the number of land-able crab for a short period. Thus if this short-term reduction in KLPUE did not occur the correlation would be stronger.

A number of outlying data points of male KLPUE were removed from the scatter to reveal a negative effect of SST on male KLPUE. These outliers were above 0.5 KLPUE. The distribution of outliers is predominant in the months of June and July and in years 2006, 2007 and 2008. There are several possible explanations of this occurrence. Firstly, as there was only one source of sea surface temperature data, there could have been anomalous temperatures recorded by the data logger. Alternatively, there are two possible biological explanations for these anomalies. We would expect to see a negative relationship between male KLPUE and sea temperature, however these outliers showed a high KLPUE with high sea temperatures, therefore we hypothesise that the shallow inshore area from which the outliers originate, may have become much warmer than the location where the temperatures were actually recorded, and consequently, effected the male crabs behaviour in such a way that increased their catchability. Alternatively, June and July, when the most outliers were recorded, is the peak mating season for crabs. We hypothesise that during this time, male crabs may have pursued females into pots to mate in spite of a high sea temperature. To rectify this variation it would have been pertinent to have location specific data for each vessel over the 10 years for which fishers collected landings data.

An explanation of the relationship between female KLPUE and temperature could be that females utilise an increased water temperature to increase their speed of movement to migrate, which in turn increases their catchability (Hunter *et al.,* 2013) due to the high turnover of crabs moving through the area. We hypothesise that due to the predominance of females in the *Cancer pagurus* catch (up to 95.6%) that males have shifted their timing of highest activity (and therefore catchability) to when females are in a state of torpor, and therefore into a period of least resource competition. This is called 'temporal niche partitioning' (Schoener, 1974), and crabs could be utilising sea temperature to calibrate this partition. This theory is further reinforced, as during the years of higher male KLPUE (2006-2009) there seems to be a reduction of female KLPUE (Figures 4.5 and 4.7.). This life history trait of crab is useful to fishermen as it sustains their business throughout the winter months when female LPUE is at its lowest. Male crabs contain more meat yield that females and therefore are more valuable per kilogram thus financially to some degree compensating for the lower catches of males over the winter.

It could be argued that crabs are reacting to day-length and not sea temperature. Many animal species have been shown to respond in various ways to changing photoperiod (Kenagy 1981, Silverin *et al.*, 1993, Gwinner 1996, Watari & Arai

1997, Last & Olive 2004) (from Murray *et al.* 2010) and therefore this abiotic factor could effect crab catchability and catch seasonality. However, Murray *et al.* (2010) detailed that further research was required to 'establish whether feeding activity and metabolism are linked to photoperiod or light intensity'. Nevertheless, *Cancer pagurus* are known to be nocturnal creatures (Ansell, 1973; Skajaa, 1998; Heraghty, 2013) and therefore their feeding activity and therefore catchability is unlikely to be effected by day length/ light intensity.

In conclusion, sea surface temperature is the main driver of the annual catch fluctuation (see also the model results in Chapter 6), as it positively affects female KLPUE and negatively affects male KLPUE. The relationship between temperature and KLPUE is important in predicting when fishers can expect to see varying sex ratios in their catch and can therefore focus their fishing efforts temporally, for modeling crab populations and for assessing the impact of increasing sea temperatures due to global warming, in years to come.

Bathymetry

Edwards (1966a) and Brown and Bennett (1979), reported that there was a positive relationship between mean carapace width and depth for *Cancer pagurus* off the south Devon coastline. Importantly, over a 6-year period Brown and Bennett (1979) found that in water <25m deep, the average size of male and female crabs, was 140mm, which today would be discarded as small (undersized). In their study, mean carapace width increased with depth to a mean of 175mm for males and 160mm for females at 25 to 55m deep, and 185mm (males) and 170mm (females) at >55m deep. As carapace width is positively related to age (Sheehy *et al.,* 1996), we infer that there is a movement of crabs to deeper water with age. This study did not collect carapace widths so we could not directly analyse the relationship of carapace width and depth. However, LPUE and small DPUE were analysed in relation to depth from which we can infer a size/depth relationship between small (less than MLS) and landed crab greater than MLS. The data used was from onboard vessels and separately, fisher's diaries.

Data gathered onboard

The highest mean total female DPUE was found at 31-40m and the lowest at 71-80m. This result correlates with an ontogenetic movement to deeper water with age. We would expect less small discards to occur in deeper water, as the crabs found in deeper water should be 'larger' and presumably over MLS. Furthermore, as crabs increase in size and age, they moult less frequently meaning there should be fewer soft crabs in deeper water where 'older and larger' crabs should be found. The only significant results between female discards at were at: 31-40m and 61-70m, with the higher mean being found at the former depth. Notably, there was a trend of steady decrease in female total DPUE through the depth categories from 31-40m to 71-80m (Figure 4.15.), consolidating the biological explanation above.

The highest mean male DPUE was recorded at 31-40m and the lowest mean at 0-10m. Again, the sample size of $n=1$ does not allow statistical analysis. As with female and total DPUE there was a trend of decreasing DPUE through the depth categories from 31-40m to 71-80m but no significant difference in means. More data per depth category were required. Both discard categories (small and soft) for males and females were analysed with depth and no comparisons were significantly different. However, female small DPUE was marginally not significant with a $p>0.0504$. Female small DPUE showed a trend of decreasing small DPUE from 31-40m through the depth categories to 71-80m, again, correlating with the explanation of movement to deeper water with age and size.

KLPUE relationship with bathymetry

A large sample size of data from fisher diaries ($n=431$) revealed that for female KLPUE the highest group mean was at 61-70m and lowest at 41-50m deep. There was an increase of female KLPUE from 41-50m through to 61-70m, inferring a movement to deeper water for females with age as more crabs were landed (and therefore over the MLS) with increasing depth. However, the mean KLPUE at 21-30m was not as expected and produced the second highest mean of all the depth categories. An explanation for this pattern of results is that the data from each depth was taken from just one vessel and therefore the fishing practices i.e. subjective nature of discarding could have increased variation in the results.

Further, there could be another environmental variable within the 21-30m depth, which influenced the unexpected higher landings than 41-50m. These variables could be a more favourable substrate type or higher food availability in Area 1 from which the data for 21-30m depth category originates. The relationship between female discards and depth also supports the above conclusion as discards decrease with depth.

The data shows that there was no relationship between depth and male landings. The landings of males in the 51-60m depth category were significantly different from the landings at all other depths. As above, the data for each depth category was taken from one vessel and therefore environmental variable such as substrate could have influenced the landings at this specific depth. As with male landings, there was no relationship between male discards and depth.

Despite a large data set (n=431) the method of categorising depths and its associated landings data could have led to erroneous results. To mitigate this problem, it would have been useful for fishers to record the average depth at which each string of pots was hauled. However, when fishers were recording landings data they were not aware that these data might be required for future analysis.

Substrate

There is very limited research into the relationship between substrate and catch, landings and discards of *Cancer pagurus*. The only research linking crab life history to substrate type is that by Howard (1982) studying the relationship between substrate and abundance of egg-bearing (ovigerous) female crabs. Our results showed that female catches, landings and discards and are (in most mostly categories: female LPUE and female small DPUE) significantly related with muddy sand. An explanation for a non-significant relationship between soft female and a particular substrate type could be that soft females moult anywhere irrespective of substrate type, as soon as they moult they need to mate and are usual guarded by a male at the stage. However, soft males are not guarded whilst vulnerable to predation during moulting and perhaps are required to be most selective about the substrate type they are on when moulting i.e. with somewhere to hide. Whereas male catches, landings and discard are linked to rock. These findings show that despite both sexes of crabs being caught on all substrate types, we can infer that there is a preference for muddy sand by females and rock for males. This information will be useful to program the IBM and also for fishers to target a specific sex if they are able to move their pots to a different substrate type within their 'territory'.

Criticisms

It would have been advantageous to record the bottom temperature per trip to sea. The temperature data used in this study was sea surface temperature (SST) from outside of the IPA (Plymouth), and as crabs exist on the bottom this could cause variation in our results. The relatively shallow depth throughout the IPA should mean the water column is well mixed and therefore there should not be a significant difference between surface and bottom temperatures (Holme, 1961) (See 'Methods and Study Area- *Sea Surface Temperature'*).

As in Chapter 3, some variation in the results of this study might be attributed to relatively small samples sizes especially with regards to the data collected onboard vessels. Furthermore, it would have been pertinent to collect carapace width of the crab catch to better analyse the relationship between crab size and depth.

The data from the EMODnet project (emodnetseabedhabitat.eu, 2016) used to analyse the relationship between landings and discards and substrate was initially gathered from predictive models created by the EMODnet project, with confidence levels of approximately 0.5-0.6 within our study area, likely leading to some variance in our work. Fishers state that substrate type can vary within a scale of a few meters and therefore our results may not be entirely accurate because of the data set used. Nevertheless, there is no fine scale substrate data available for the IPA so 'best available data' was used.

Conclusion

In conclusion, this study has shown that female landings have a weak positive correlation with surface sea temperature, whilst males have a weak negative correlation. Our findings on the relationships between landings and sea surface temperature would be useful to fishers because they could choose to target other fish until the sea surface temperature reaches a critical value (9- 11^{oC}) at a time when females are caught in large volumes. Local managers might use this studies data to plan their stock assessment sampling programme in line with sea temperatures.

This study showed that LPUE has a positive relationship with depth for males and females. Additionally, female DPUE had negative relationship with depth and there was no relationship between male DPUE and depth. Fishers could use this information to fish the deepest parts of their territories to increase landings and decrease discards and therefore using their time at sea to fish more effectively. This information along with the relationship between sea surface temperature and male and female landings will also be use to provide parameters to the IBM produced by P.J.B Hart.

We concluded that female catches, landings and discards and are mostly significantly related with muddy sand, whereas male catches, landings and discard are linked to rock. As with depth fishers could use this information to target a specific sex if they are able to move their pots to a different substrate type within their 'territory'. Whereas, if necessary managers might utilise this information to close or reduce fishing effort in certain areas to reduce pressure on female (or male) crabs. Additionally, the local IFCA should use the relationship we have established between landing and discards and bathymetry, and substrate to stratify their stock assessment sampling with the depth and substrate on which vessels fish to reduce confounding variables.

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Appendix D

The list of outliers removed (above 0.5 KLPUE) from the male KLPUE and temperature correlation (Table 4.7).

Table 4.7. The list of outliers removed (above 0.5 KLPUE) from the male KLPUE and temperature correlation, in date order with corresponding temperature in °C and KLPUE. Data in Red is from Area 1 and in Blue from Area 1a.

Date	Temp °C	KLPUE	Date	Temp °C	KLPUE
Sep-03	16.6	0.5	Oct-07	15.5	0.9
Oct-03	15.2	0.5	Nov-07	14.3	0.8
Jun-04	14.3	0.8	May-08	12.3	0.9
Nov-04	13.1	0.5	May-08	12.3	0.8
Dec-04	12.0	0.6	Jun-08	14.0	0.7
Jun-05	13.8	0.9	Jun-08	14.0	0.7
Oct-05	15.1	0.8	Jul-08	16.0	0.8
Nov-05	13.2	1.0	Jul-08	16.0	0.7
Apr-06	9.0	0.9	Aug-08	15.4	1.0
Jun-06	14.3	0.9	Sep-08	15.3	0.8
Jun-06	14.3	0.6	Oct-08	14.6	0.9
Jul-06	17.3	0.5	Jan-09	8.9	1.0
Jul-06	17.3	0.7	Aug-09	17.0	1.0
Aug-06	16.0	0.7	Feb-10	8.2	0.8
Sep-06	16.4	0.6	Oct-10	14.8	0.9
Dec-06	11.6	0.7	Jun-11	13.5	1.0
Dec-06	11.6	0.9	Jul-11	15.0	0.9
Jun-07	14.8	0.8	Jun-12	13.4	0.8
Jun-07	14.8	0.6	Jul-12	14.9	1.0
Jul-07	15.1	0.7	Jul-12	14.9	0.6
Jul-07	15.1	0.6	Sep-12	15.8	1.0
Aug-07	16.3	0.9	Oct-12	14.4	0.6
Sep-07	16.6	0.9	Nov-12	12.6	0.8
Sep-07	16.6	0.8	Dec-12	11.4	0.9
Oct-07	15.5	0.7			

Chapter 5

A comparison of Fishers Local Ecological Knowledge and Scientific Knowledge of the south Devon Crab Fishery

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Emma Pearson, Author. Ewan Hunter, Second Supervisor. Alan Steer and Kevin Arscott, fishers facilitating data collection. Paul J. B. Hart, Main Supervisor.

Abstract

Small-scale fisheries are often deficient in comprehensive landings and discard data, this is usually coupled with limited resources to manage such fisheries. Therefore all available sources of information should be explored before instigating new costly research, including Fishers Local Ecological Knowledge (FLEK). Fisheries scientists, eminent policy-makers and governance institutions have largely overlooked FLEK as a valid source of information. In the absence of empirically recorded data, FLEK can often fill data gaps in current understanding, which would otherwise be time-consuming or costly to gather as well as to provide additional knowledge to data and resource rich fisheries.

The current study sets out to assess the congruence of FLEK members of the south Devon crab fishery with current scientific knowledge and empirical data collected

onboard their vessels. We carried out semi-structured interviews to ascertain a wealth of FLEK. The knowledge captured led to a synthesis of south Devon crab FLEK creating a narrative of catch dynamics and crab movements. Three hypotheses on the effect of sea temperature, wind direction and pot type on Catch Per unit Effort (CPUE) were extracted from the interviews. These hypotheses were then compared against the current published scientific knowledge gathered from the literature, from data collected within the fishery between 2011 and 2012, and a time-series of data (2003-2012) from fisher's own landing records.

Results showed that FLEK from these fishers is congruent with previously published scientific information and locally collected data. Therefore with a mechanism of validation, FLEK could be used as a stand-alone data source and should be utilised where possible to support empirically designed experiments to inform fisheries scientists and managers in this area, and for local sustainability assessments. The benefits of this incorporation would be: a quick turn around time for results as data can be rapidly collected and analysed, reactive management as data collection and analysis is fast, cost savings, building relationships with fishers and most importantly the development of another bottom-up approach to achieving a sustainability in the IPA.

Introduction

Small-scale fisheries are often deficient in comprehensive landings and discard data, and this is usually coupled with limited resources to manage such fisheries. Due to the lack of resources centred on the management of these fisheries, all available sources of information should be explored before instigating new costly research (Berkes, 1999; Johannes *et al.,* 2000, Begossi *et al.,* 2008). One such emerging source of information used in fisheries science and management is Fisher's Local Ecological Knowledge (FLEK). FLEK has of course been present as long as the fishers themselves, yet FLEK has been largely neglected by not just the scientists at the forefront of fisheries research, but also by eminent policy-makers and governance institutions (Hind, 2014). For many years fishers had, at best, simply been asked to comment on the results produced by scientists rather than to actually contribute their own knowledge (Griffin, 2007, 2009; Stohr and Chabay, 2010). This is confirmed by Moshy and Bryceson (2016) who stated that, 'if Traditional Ecological Knowledge (TEK) is integrated into Conventional Science Knowledge (CSK) at all, it is usually either marginalised or restricted to CSK modes of interpretation, hence limiting its potential contribution to the understanding of social-ecological systems'. FLEK reporting the trends of the natural resource can provide valuable input during regulatory negotiations (Carr and Heyman, 2012), and scientific research (Bergmann *et al.,* 2004; Drew 2005; Hall & Close 2007; Shepperson *et al.,* 2014). In the absence of empirically recorded data FLEK can often be used to fill gaps in current knowledge, which would otherwise be time-consuming or costly to gather, or to gain a historical view of a fishery where a time-series of data had not been previously recorded.

Current Management

In English inshore waters the regulatory body responsible for scientific research and translating research into policy are the Inshore Fisheries and Conservation Authorities (IFCA). There are 10 regional IFCA's in England, with the Devon and Severn IFCA responsible for the management and sustainability of marine species within the fishery on which this study is centred. This IFCA maintain approximately 10 staff to enforce management and perform research in an area of about 3,306 km^2 along coastlines in the north and south Devon (DSIFCA, 2013). As such, the IFCA's are grossly under-staffed and under-resourced with an annual budget of just £694,000 (DSIFCA, 2016) for the conservation and enforcement tasks they are required to carry out. The lack of resources at the IFCA, are reflected in small-scale fisheries around the world, as Damasio (2015) reports there are barely any financial resources, staff, logistics, or skills in management agencies to collect fishery data and set catch limits, despite sustainability (or attainment of MSY) being of paramount importance to all fisheries in the EU by 2020 (www.ec.europa.eu [2016]).

An effective and inexpensive method for IFCA's to collect data would be to harness FLEK. By using FLEK the IFCA's would benefit from the chance to engage face-to-face with fishers, share knowledge and therefore build trust and long-term relationships (see Chapter 2). In turn, the use of FLEK in local management decisions also fosters engagement between fishers, scientists and managers and leads to co-management decisions rather than top-down implemented measures, as demonstrated by the GAP2 Project, GAP 1 Project and JAKFISH (See Chapter 2).

Fishermen as data collectors

Fishers are at sea more than any scientific researchers and often have decades of knowledge regarding all aspects of the fishery such as, seasonal changes in catch composition, and the impact of environmental variables such as sea temperature and wind direction on fish behaviour to name a few. The livelihoods of fishermen to a large extent rely upon extensive, accurate knowledge of these natural resources and phenomena, to profitably exploit the resource. Therefore, they are perfectly placed to collect data, which cannot be easily and/or inexpensively be collected by researchers.

At present inshore crab fishermen submit monthly shellfish activity return forms (MSARs), which indicate their catch per day (in Kg), per species, by sex. However the information is only specific to the scale of an ICES rectangle. The rectangle pertinent to the south Devon IPA is 29E6, which covers 3967 km^2 of English Channel; the IPA covers just 428 km^2, approximately 10.5% of this rectangle. However, fishermen are able to provide much finer scale detail regarding catch, discards and environmental data with specific GPS locations, which in turn would enable more accurate stock and contributing their years of FLEK to local management.

How reliable is FLEK?

Questions remain over the validity of FLEK as a tool for fisheries scientists and managers because the data is self-reported. Fishers are aware that their information might lead to management changes, which are not in their favour, and fear that commercially sensitive data might be passed to competitors. Consequently, fishers might convey misleading information to researchers and the authorities, so in the short term they can continue to fish at the same level. These issues are founded in previous mistrust of managers or the fishers might want to make the fishery appear more sustainable than it is. Nevertheless, in small-scale fisheries it could be argued that fishers are incentivised to report the truth, as usually they cannot fish elsewhere. FLEK is very localised, and the validity of FLEK in one area is not necessarily true of another within a small spatial scale. FLEK is based on the strength of observations; memory and accuracy of knowledge passed to those recording it, and therefore requires validation. This type of knowledge has been used to inform management and instigate new measures in several studies (Chemilinsky, 1991; Mackinson and Nøttestad, 1998; Gasalla and Tutui, 2006; Leite and Gasalla, 2013).

The present study sets out to assess the congruence of FLEK from members of the south Devon fishery with current scientific knowledge. This was achieved by carrying out semi-structured interviews with local fishers to ascertain FLEK. This knowledge led to a synthesis of south Devon crab fishers FLEK creating a narrative of the fishery's dynamics. Three hypotheses' were extracted from these interviews regarding the environmental factors affecting CPUE. These hypotheses were then compared against the current published scientific understanding gathered from the literature and from data collected within the fishery by an onboard observer between 2011 and 2012 (Chapters 3 and 4). We will look at the agreements and differences between the two sets of knowledge and discuss if and how FLEK can be utilised as a tool for fishery scientists.

Case Study: South Devon Fishery

The SDCSA is a unique group of well-organised inshore crab fishermen. As such the fishers have provided an ideal platform from which to gather FLEK and assess its use in fisheries science/management. SDCSA members have already demonstrated their ability to put into place long-term management plans and to establish novel fisher-directed management methods. For instance, during the 1970's they established, and have continued to operate several seasonally open and closed trawling zones interspersed with potting only zones. The stimulus for the creation of these zones was to mitigate gear loss from interactions with mobile gear (such as trawlers, seine netters and longliners etc.). These zones are collectively called the Inshore Potting Agreement (IPA). For detailed information of the study site see 'Chapter 1- The present south Devon crab fishery'.

This small-scale fishery has been established for centuries, and is even mentioned in the Domesday Book (Firestone, 1967). The local industry has, therefore shaped the establishment and location of surrounding villages, and the lives of many inhabitants either directly or indirectly associated with fishing activities (Fox, 2001). Furthermore, many of the fishers are third, fourth or fifth generation fishermen, reflecting the importance of the fishery to the local heritage and economics.

The fishery is situated within the western English Channel, as defined by CEFAS's stock assessment region, which is carried out every four years. Currently, the stocks for the western English Channel are rated as 'Good' with spawning stocks around the level required to produce Maximum Sustainable Yield (CEFAS, 2014). As detailed above the spatial scale for this assessment is the Western English Channel, which encapsulates a number of major crab fisheries in the south west of the UK (Plymouth, Newlyn, Lyme Bay etc.). As McKeown and Shaw (2009) demonstrated the population of crabs in the English Channel forms as single stock, and work by Hunter *et al*., (2013) has shown that almost all female edible crabs migrate from east to the west.

To work towards a sustainable fishery it would be more appropriate for fishers, scientists and managers, to understand the dynamics of the localised fisheries along the Channel, and to understand the effect of environmental factors on CPUE, LPUE and DPUE in each location, rather than manage at the scale of the western English Channel.

Materials and Methods

Fisher Interviews

To insure fishers were representatively sampled for semi-structured interviews, they were selected by dividing the fishery into 8 areas (Figure 5.2.)

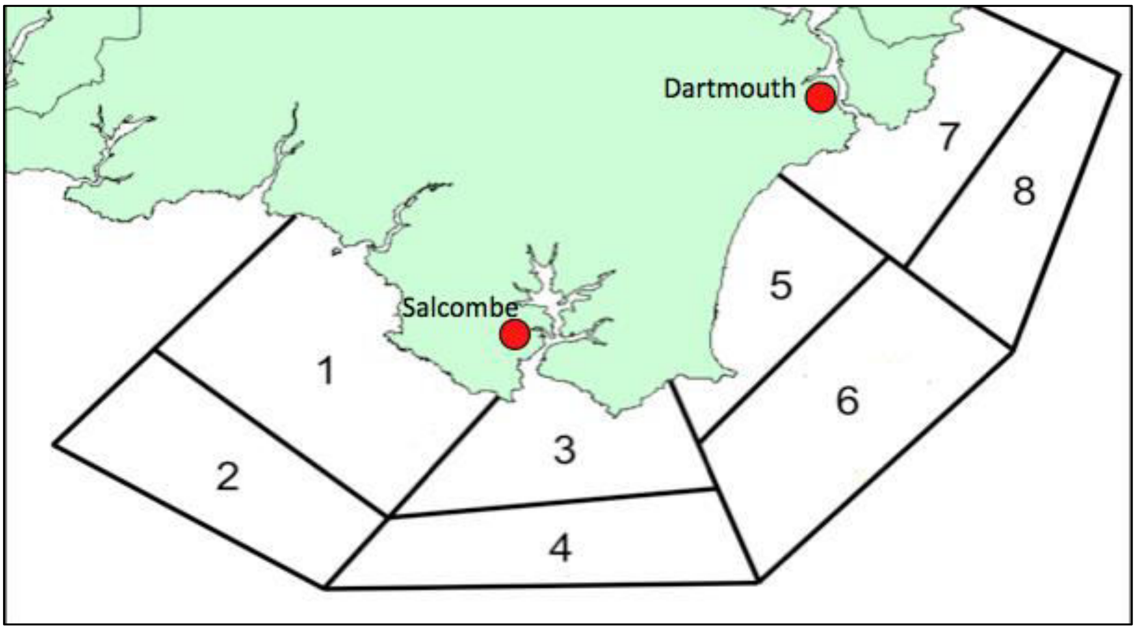

Figure 5.2. A map of the eight zones use to representatively sample the FLEK and catches of the IPA. The IPA was split into four zones west to east and two zones from ~0-3nm and ~3-6nm.

Information on the spatial distribution of SDCSA fisher's territories was obtained from '*The south Devon Shellfish Survey'* (Clark, 2008). The secretary of the SDCSA then provided a list member's contact information. A list of approximately the three to four fishermen who fished in each zone was then prepared. A fisher from each zone (Figure 5.2.) was chosen and contacted by telephone. The aim of the interviews was explained and each fisher was asked if they would be willing to participate. If a fisher declined to be interviewed, another fisher from the same zone was chosen at random and contacted as above (henceforth referred to as fisher 1-5).

A total of 5 fishers (~20%) agreed to take part in the interviews in February 2012 during the timeframe that fieldwork was undertaken. These fishers were from areas 1, 1a (the second fishers to want to participate from Area 1), 4, 5 and 8. Despite perseverance from the author repeatedly calling over 15 other fishers, a participant could not be obtained for each of the 8 areas. There could be several explanations for this lack of recruitment: 1) Fishers did not want their commercial sensitive knowledge formally recording, 2) fishers might not have be comfortable being interviewed, 3) they did not want to commit to an interview after working a long day at sea. Finally, the author carried out two-hour semi-structured interviews in fisher's own homes at a convenient time of their choice.

Ethical Statement

At the outset of each interview an ethical statement was read aloud (Appendix E). The statement explicitly explained the purpose of the interview, how the information gained would be used, and that the interview would be recorded on a Dictaphone. Fishers were informed that their information would remain confidential and by agreeing to take part in the interview were giving consent that the information provided could be used in this research project. Fishers were then offered the opportunity to ask any questions before the interview began.

Semi-structured interview

A set of questions for the semi-structured interviews were constructed by the author and reviewed by two independent social scientists. The interview questions can be viewed in (Appendix E). Questions were grouped into the following categories: population dynamics/crab distribution, environmental factors affecting crab distribution and the implementation of an individual based model.

Analysis software

Once the interviews were completed they were transcribed using F5 transcription software for Mac (audiotranskription.de). Each interview was transcribed in full and coded into the follow themes which emerged from the transcripts: catch in time and space, depth with age/size, bottom type, berried crabs, soft-shelled crabs, water temperature, soak time, discards, water temperature, tides, wind, pot type, and trawling.

The knowledge led to a synthesis of FLEK creating a narrative of the fisheries dynamics. Additionally, three hypotheses were distilled from the beliefs the fishers had concerning the way their fishery behaves:

H1. CPUE of female *Cancer pagurus* significantly increases once a critical water temperature of between 9 - 11^{o}C is reached in the spring in the IPA.

H2. An easterly wind has a negative influence on *Cancer pagurus* CPUE in the IPA.

H3. Parlour pots have a statistically significantly higher LPUE of *Cancer pagurus* than inkwell pots.

At a meeting of the SDCSA these hypotheses were put to the members who agreed that these hypotheses would be useful to explore. These three hypotheses were then compared to scientific knowledge from two sources; the scientific literature and from data collected onboard fishing vessels by the author.

For the source of and information describing the collection of onboard and fishers diaries data please see 'Chapter 3- Methods'.

Narrative of Fishers Local Ecological Knowledge

The interviews produced a mass of qualitative material that cannot easily be broken down. Some sociologists (most notably Flyvbjerg, 2001) have argued that significant parts of social scientific work can only be captured in narrative form. Following this line the themes that emerged from the interviews form the following headings, and within each heading we have synthesised the knowledge obtained from all five fishers into a narrative. The information contained within double inverted commas ("") are direct quotes from the fishers.

Fisher's demographics

The ages of the fishermen interviewed ranged from 42-55, all had been fishing full time for 25-35 years with most of this time spent fishing solely in the IPA. All were skipper/owners. Four of the fishers had multiple (3-5) generations of fishers in their family, with a remaining fisher having no family history in the industry.

Temporal variation in crab catch, landings and discards

Three out of five fishermen chose the 'time of year' as the most influential factor effecting crab catches, landings and discards. They stated that crab catch volume varies with time as a result of season, and ultimately sea temperature. This affects the locomotion of crabs so increasing their catchability. When the season 'starts' (when females begin to be caught in abundance in April/May) the fisher's feel the catches are higher in the west of the IPA (Salcombe) when compared to the east as the sea "warms from the west". Then 2-3 weeks after the initial abundant catches in the western IPA, the crab is caught in large volumes off Start Point, the approximate mid-point of the IPA.

Despite fishers observing an initial onset of catches in the western IPA, they held varying views on how the crabs moved through or within the IPA. Fisher 5 thought, "Crabs move in a SW direction down the Channel, which might follow depth contours. I think of the crabs as moving in a group, like birds/locusts with a nucleus". Whereas Fisher 8 though the crab moved inshore and then to the east, "I think that the crab comes inshore to Start Point, then fans out across the Skerries, to the Bell by the end of August, then to the deeper water at Dartmouth after the Regatta [last weekend in August]". Interestingly, Fisher 4 believed the crab was moving westward yet, "crab catches begin in large volumes in the western IPA, then 4-6 weeks later, begins in Dartmouth, this is driven by sea temperature". At the end of the main fishing season (December) fishers described that, "Catches are smaller in the winter months as the shoreline is more disturbed by high impact waves from storms, and fishers believe that during this time crabs move to deeper water for shelter".

When asked to describe the dynamics of discards throughout the year fishers imparted the following knowledge:

The volume of discards varies with time of year. Specifically, they reported the following: Fisher 1 stated “November is the month with lowest discarded crab, with about 20% of the catch discarded, then in June 30-35% is discarded, with even more discarded in July at about 60% because crabs are soft then”. Fisher 1a reiterated this point and said, “More crab is retained than discarded in June and in July more crab is discarded than retained”. When crabs have moulted or been buried for several months and have not eaten, they are initially very active in their search for food, and therefore their catchability is increased.

Fishers specified that the location of different sizes of crabs vary with time. As the season progresses (meaning April to November) there is less small crab caught month-on-month. Another fisher’s comment substantiates this, “small crab is not as prevalent in the summer months, when large volumes of crab start being caught”. However, Fisher 1 believed there is a brief period in summer when larger migrating females are caught inshore and he thought this shoreward movement was to mate. A final comment made on the relationship between the movement of crabs and size was that, “larger crabs move into deeper water in the summer/autumn, to a smoother substrate [sand]”.

Fishers reported that soft crabs are caught all year round, and the time of moulting is independent of location or substrate type. They stipulated that, “when females are soft-shelled and therefore able to mate, then males will be present to guard and mate with them, this is demonstrated as we almost always see males in pots when there is a soft female there as well”.

The variation in the proportion of males and females in the catch was described by fishers as being predominately males between January to March in a ratio of 60:40 males to females, then from April to December as predominately females.

Spatial variation in crab catch, landings and discards

Fishers divulged their knowledge on the spatial movements of crabs within the IPA. They reported that small crabs (undersized) are caught abundantly inshore on rocky substrate and fishers called this 'breeding stock' but when challenged on this term indicated they meant juveniles. There was a consensus that the largest crabs in the IPA are found off Start Point on the 6nm Limit, and that there is a size/depth relationship for crabs. They had observed that, "small crab is caught inshore and larger crab is found further out", although Fisher 4 thought substrate affected the size of crabs more than depth. Fishers believed that mating takes place close into the shore with Fishers 1 thinking that this could be within half a mile of the shore, with larger crabs migrating inshore to mate.

In terms of geography, Fisher 5 thought south Devon has a good fishery [at MSY] as it is a headland out into the Channel, and the migration route of crab passes through the IPA. This combined with deep warm water, a good food supply, suitable breeding (and burying) grounds and effective past management (no trawling thus preserving ground features) leads to good catches. Fisher 1 attributed good catches in the IPA to, "a combination of depth, sea temperature, and currents have led to a favourble spawning location for females and favourable grounds for the settling of juveniles, therefore retaining the population".

Environmental variables

Substrate

Two out of five fishers rated substrate type as the factor, which most affected crab distribution in the IPA. Some fishers had perceived that during the spring male crabs are caught in a higher abundance on a rocky substrate compared to other substrate types, whilst others thought this was the case all year round. More specifically, they stated that "small males are prevalent inshore throughout the year" and that "smaller crab is found on harder, rocky ground and in the western IPA this area is called the 'Rutts'". Smoother bottom types e.g. sand and mud, produce catches of larger female crabs, whilst mixed substrates produce a smaller female crab.

When fishers were asked if there was a relationship between substrate type and berried females they thought that "females crab bury themselves on the soft sandier, muddier ground, and are not seen on the harder or gravelly ground so much". They observed that once female crabs cease to be caught in large volumes on sand, "they will not be caught again in large volumes on this substrate type until the season begins in April/May", once the berried females come out of a state of torpor. Fisher 4 thought that "marginally more berried crab is caught on sand, but it is caught everywhere". Other fishers had observed that females are caught on harder ground (rock) in the early part of the year, then move to reefs, and later move south onto the sand, where they buried themselves over winter. Other pertinent information given by fishers regarding substrate type was that the substrate they fish on can vary on a small spatial scale (within meters) and they almost always have multiple substrate types within the length of one string (approximately 1.5km). Furthermore, Fisher 5 said that, "the pits of sand banks fish better than ridges", and attributed this to the fact that the pits are sheltered against currents and [carrion] food falls into the pit bottom, creating a "favourable habitat". All fishers were keen to specify that the IPA, and by virtue, the act of fishing with pots in the IPA protects the reef features, as the presence of pots stops trawling.

Tides

Fishers have observed that, "crabs are caught in high abundance on various states of tide depending on time of year, as crabs feeding patterns are tide related". There seems to be an "optimum tide for catching a large volume of crab", but this varies temporal and spatially. Fishers 1a and 5 commented that in the area they fish that, "early in the year the biggest volumes of crab are caught on a jumping tide [as the tide increases from a neap to a spring tide], then as the year goes on it is caught on the highest tides. As catch rates start to drop after (December) the largest catches are caught as tides begin to reduce [from a spring to a neap tide]". Fisher 1 pointed out that, "When tides run hard, but not excessively hard, crab feed and consequently are caught in large volumes". Fisher 8 added that when tides are excessively hard for example on a spring tide, catches are small as crabs shelter from strong currents and do not enter pots or vessels simply do not go to sea.

Fisher 4 also added “a southwest swell always brings large catches, on his fishing grounds [approximately 6nm south of Salcombe]”.

Wind

All fishers established that the direction of the wind results in varying catches abundances, and that an east wind is detrimental to catch volumes and that a south-southwest wind is associated with higher catches. Importantly, all fishers said that wind speed is not as key as its direction in effecting catches. Fisher 8 thought that, “wind to the south of east does not negatively affect catches. However, if the direction of the wind is north of east-northeast this reduces crab catches. Fisher 4 found that a southwest wind with a swell means good catches, but if the wind is from the southwest without a swell, this will not lead to increased catches”. The reasons for east wind negatively effecting catch volumes as suggested by all the fishers interviewed are that east wind produces a lower air temperature, and pushes water onto the coastline meaning that the waves are shorter and therefore choppy, disturbing the benthos. The influence of wind on catches is investigated in detail later. Obviously, as with large tides, strong winds prevent fishers going to sea and thus limits yearly catch totals for inshore vessels. Fishers feel their catches are 'capped' or 'regulated' by the weather giving them a quota of days at sea per year (approximately 90-125 days).

Sea Temperature

All fishers stated that crab distribution is strongly affected by sea temperature. Fisher 8 thought that a lower than average water temperature stunts the growth of crabs. There was a consensus, that crab movement and hence catches do not begin to be significant until a critical water temperature is reached at approximately 9-11°C, usually between April-May. Four out of five fishermen chose water temperature in their top four factors affecting crab catches. A decline in the female catch from October to December correlates with a lowering of water temperature. Catches in April heavily depend on water temperature and whether it has reached the critical temperature to stimulate crab movements, which fishers estimated to be between 9-11°C. Fishers believe that large catches begin first in the spring in the western part of the IPA. They speculate that the sea becomes warmer in the west first, and therefore catches begin in the west. This creates the illusion that crabs move into the IPA from the west.

Depth

As described under '*Spatial variation in crab catch, landings and discards*', fishers describe a relationship between crab carapace size and depth. They have observed that smaller crabs are caught inshore in shallow water, with larger crabs further out on 6nm limit, with very few small crabs caught towards the 6nm limit.

Fishing Strategies

Soak time affects the number of crabs caught as a result of pot saturation. Fishers employ a longer soak time in the winter compared to the summer as in their opinion, crabs move more slowly because of lower sea temperatures. Fishers stated that soak time in winter is typically 5-7 days, whereas the average soak time in spring and summer is 2-3 days. When catches are large in the summer boats will try to clear pots every day. Fisher 1a believed that after 3 days of soak time "you do not catch a lot more". Soak time also depends on number of sets of gear fishers have, as fishers with two sets of gear will have at least, a two day soak time per set, as they will fish each set on alternative days. In winter, the implication of a soak time of 5-6 days is that females may develop into a berried state whilst in the pots from October to December.

Further, fishers stated that, "the condition of the pot (age, weed, holes etc.) has more of an affect on crab catches, than type of pot used [parlour or inkwell] to catch the crab". Parlour pots are used for targeting lobsters and crabs simultaneously, whereas inkwells are used to solely target crabs. All fishers agreed that parlours have higher catch rates compared to inkwell pots.

The effect of trawling

Trawling, and especially scallop dredging destroys the habitat of crabs, and indiscriminately catches and/or kills any animals caught as bycatch and this adversely affects the catch quantities of the potters (Eno *et al.,* 2001). Within the IPA these processes are location specific, for example Fisher 5 stated that they did not suffer the affects of trawling, as they do not fish near seasonally open trawling areas. However, fishers that work near the corridor, a seasonally open area of the IPA to trawling (see Figure 5.1), report that when scallopers and trawlers have fished heavily in the area, there are very small catches of crabs for several days in the nearby potting only areas. All fishers strongly believed that trawling is much more detrimental to the sustainability of crabs in the IPA than their own potting activity.

Current Management

Three of the five fishers thought that the use of a Minimum Landing Size (MLS) was the management measure that most contributed to the current level of sustainability in the fishery [and rest of the western English Channel]. They also pointed out that as discarded crabs are returned to the sea alive this will contribute to the sustainability of the fishery and of course the IPA itself has preserved the crab's habitat and food supply by closing areas to trawling.

Level of adherence to management measures

All fishers believed that current management measures were largely adhered too. 80% of the fishers interviewed believed that the subjective nature of deciding whether a crab is soft-shelled, meant that on occasion marginally soft crabs are landed when they should have been discarded. Fisher 5 summed up the answers given by others on the current level of adherence to management measures in the IPA when he said, "I would like to think that most of the people that fish in the IPA are sensible and adhere to the rules, for the sake of their own livelihoods. Every industry has its own rogues but they are a very small minority. The very nature of how close-knit our industry is they would soon be found out". Fisher 1 added that if the crabs, which are landed, are of poor quality then the processors would not accept them and so this encourages the adherence to the current management measures.

Other general information

During the interview process several additional observations were made, which do not fit into the categories above and these were:

- Catches per pot have remained constant for the last 10-15 years but there now are fewer boats fishing.

- Fisher 8 observed that there was a 7-year pattern between his highest total annual catch and that these highs depended on good spawning years followed by 7 years for the crab cohort to be recruited to the fishery. This cycle was driven by sea temperature.
- Landings in 2008 were artificially low as the factory, which processes and purchases the majority of the crabs burnt down and therefore fishers did not go to sea as often as normal as they were without the normal purchaser for a large quantity of their landings.

- Fishers agreed in general, with the pattern of the catches, landings and discards revealed by the data collected onboard their vessel by the author of this study (Chapter 3 and 4). They judged that the pattern is a true representation of the whole fishery in the IPA.

Hypothesis Testing

Three hypotheses' were extracted from the interviews regarding the environmental factors affecting CPUE. These hypotheses were then compared with the current published scientific understanding gathered from the literature and from data collected within the fishery by an onboard observer between 2011 and 2012, and from data extracted from fisher's diaries for the period 2003-2012.

Sea Temperature affect on crab catches

Hypothesis one: CPUE of female *Cancer pagurus* significantly increases once a critical water temperature of between 9 - 11^{o}C is reached in the spring, in the IPA.

Fishers gave the following statements with regard to sea temperature:

- Crab landings vary with the time of year, and this variation is synchronous with the change in water temperature.

- There is consensus by fishers that female crab movements and hence catches do not begin significantly until a critical water temperature is reached (9-11°C). This usually occurs between April-May, when the crabs begin to move after overwintering in a state of torpor.

- As sea temperature decreases in November to December and cools below 9-11 °C the catch of crabs is significantly reduced compared to times when the temperature is above 9-11 °C.

Scientific Literature

The scientific literature was reviewed for the effect of sea temperature on crab behaviour with the following results: *Cancer pagurus* are poikilotherms (Aldrich, 1975). Accordingly, the temperature of the ambient seawater in which *Cancer pagurus* exists directly affects the organism's behaviour. Affecting the locomotion, foraging activity consequently catchability of the species. Sea temperature also act as an environmental cue for *Cancer pagurus* to trigger certain behaviours such as egg brooding in females and pit digging in both sexes (Warner, 1977). Research on other crustaceans also suggests a relationship between sea temperature and their locomotory and feeding behaviour. For instance, the effect of temperature on the activity of Atlantic rock crabs (*Cancer irroratus*) was observed by Jeffries (1966). He compared the walking activity at temperatures of 6 °C, 14 °C, 22 °C, and 28 °C. The mean percentage activity was highest (80%) at 14 °C and decreased as follows: 22 °C (65%), 6 °C (50%) and 28 °C (5%). Rebach (1974) also experimentally tested the effect of temperature on the locomotory activity of Hermit crabs (*Pagurus bernhardus*). They found that activity gradually decreased as the temperature of beakers containing the crabs was cooled. All hermit crabs retreated into their shell and ceased activity at a mean temperature of 3.2 ± 1.1 degrees. However, hermit crabs continued to elucidate a righting response until 2.0 ± 1.2 degrees. Edwards (1967), was the first to investigate the link between sea temperature and the catch abundance of *Cancer pagurus*. He stated, 'the yearly regularity of the rise and fall in catch suggests it is related to the rise in temperature of the sea'. He conducted laboratory based feeding experiments at varying water temperatures. He discovered that crabs (the sex was not stated) held at 15.5°C ate 46% of the food supplied to them, but at 4.5°C only 1% of the food was consumed. Edwards also observed that at temperatures below 3.8°C, crabs that were usually active at higher temperatures, became immobile and stopped feeding. Further, experiments by Aldrich (1975) demonstrated that as the water temperature at which *Cancer pagurus* is kept increases, their oxygen consumption and food intake increases. The work of Edwards (1967) and Aldrich (1975) shows that *Cancer pagurus* is more likely to be feeding at an optimum temperature, which will increase the chance that crabs will discover baited pots and be caught. More recently, CEFAS (MF1103, 2008) tagged 150 female *Cancer pagurus* with Data Storage Tags (DST Tags), which continuously recorded temperature and pressure whilst the crabs were at liberty in the English Channel. They found that burying by female *Cancer pagurus* began at 13± 1.5°C. Females started to become active again and feed after their brooding period at 11 ±2°C recorded in the spring. More recently, CEFAS (MF1103, 2008) discovered that *Cancer pagurus* tagged with DST tags, which were released in the eastern English Channel, migrated with a seasonal temperature cycle.

The research of Edwards (1967) and CEFAS MF1103 (2008) support the hypothesis of the fishers that there is a critical sea temperature at which *Cancer pagurus* cease to be buried in the sand (in a state of torpor) and begin to move and start feeding again, increasing the likelihood that they will encounter and enter pots.

Overwintering by burying in the substrate has been shown to decrease the predation on hermit crabs (*Pagurus berhardus*) and presumably other crab species (such as *Cancer pagurus*) while the crabs are in a state of torpor (Rebach, 1974). In this state the crabs cannot move at a speed to escape predators due to low sea temperatures and therefore effectively bury and camouflage themselves to reduce the risk of predation.

Data gathered on-board local fishing vessels

To compare FLEK with empirical data collected specifically in the IPA, we plotted the average monthly KLPUE for males and females from the fisher diaries from four crabbing vessels (1, 1a, 4 and 5) collected between 2003-2012. It should be noted that the graph displays KLPUE and does not include discards. The average monthly sea surface temperature was calculated from a wave buoy monitor in Start Bay (50° 17.50'N, 003° 36.97'W) in the eastern IPA was then superimposed onto the graphs (See Figure 5.3.).

The onset of the female crab season starts with a sudden increase in KLPUE in April to May (Figure 5.3.). This is correlated with the sea surface temperature of ~10°C. KLPUE for females continues to increase until June when the sea surface temperature is an average of 14°C. Female KLPUE is then reduced over the summer months for a short period, due to moulting and mating behaviours (See Chapter 3) and peaks at its highest in October correlating with a sea surface temperature of 16°C, then drastically drops in November and December as sea surface temperature falls to 12 °C and 11°C respectively.

The average male KLPUE is much lower than that of the females and has a seemingly negative correlation with sea temperature (Figure 5.3.). The peak male catches occur during the winter (January to April) whilst the sea surface temperature is at its coldest (9-10°C). As sea surface temperatures warm in the spring and summer months the male KLPUE decreases to its lowest point in July at sea surface temperature of 16°C. After July, as the sea surface temperature begins to decrease, male KLPUE increases month-on-month until the late winter.

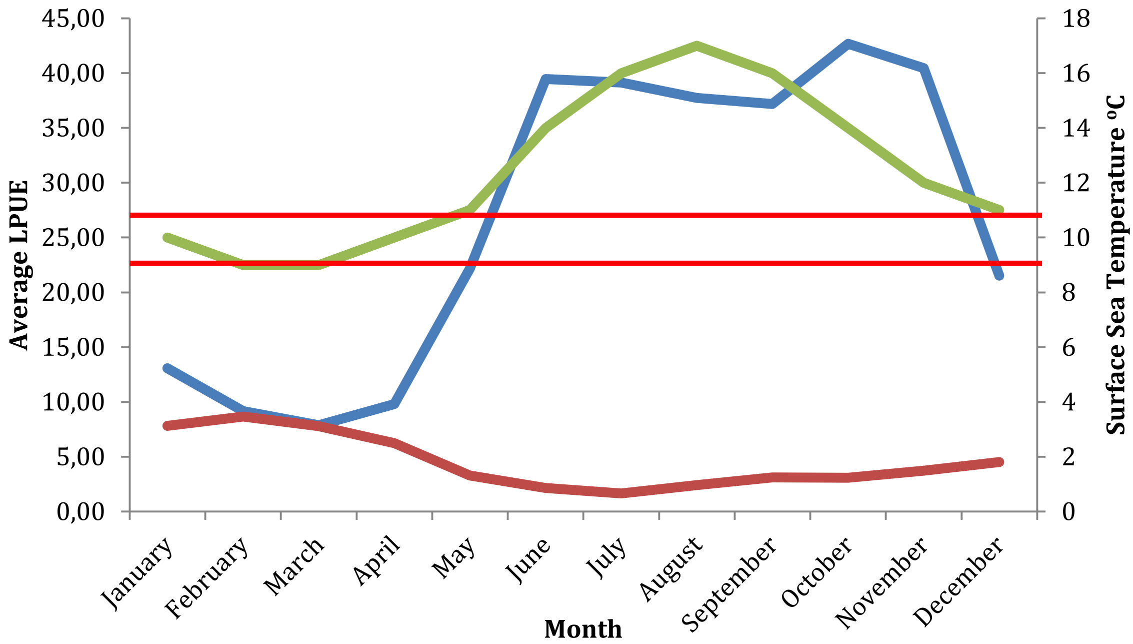

Figure 5.3. The average monthly KLPUE for female and male Cancer pagurus from 2003-2012 plotted with mean monthly sea surface temperatures within the IPA. Legend: Blue (Average Monthly KLPUE for females), Dark Red (Average Monthly LPUE for males) and Green (Surface Sea Temperature in ºC). Red parallel lines indicate 9 and 11ºC.

To further examine the affect of sea temperature on KLPUE a correlation was plotted separately for each sex (see Figure 5.4. and 5.5.).

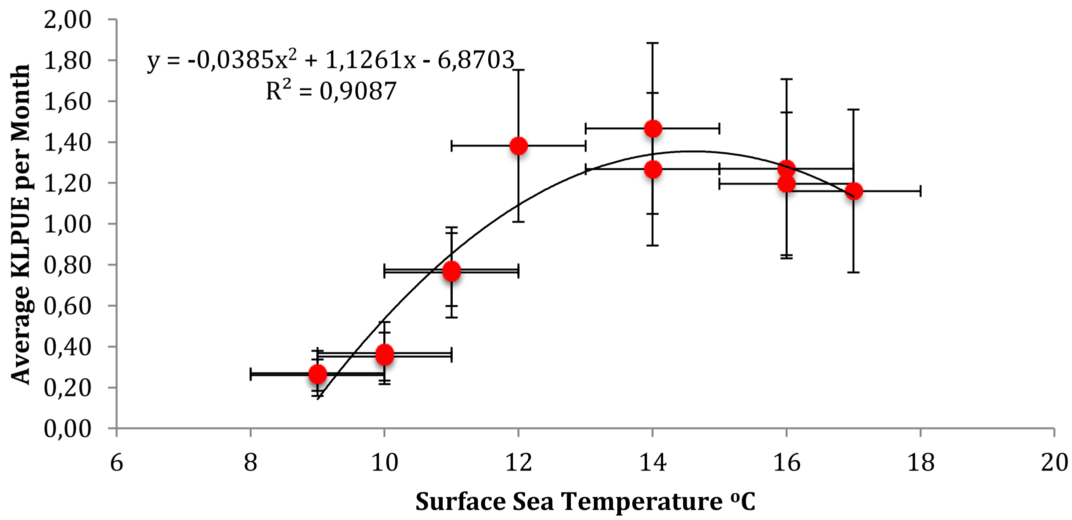

Figure 5.4. Correlation between temperature and female KLPUE with ± sd. Legend: Red circles (Avg. monthly KLPUE for females). Black line= line of best fit.

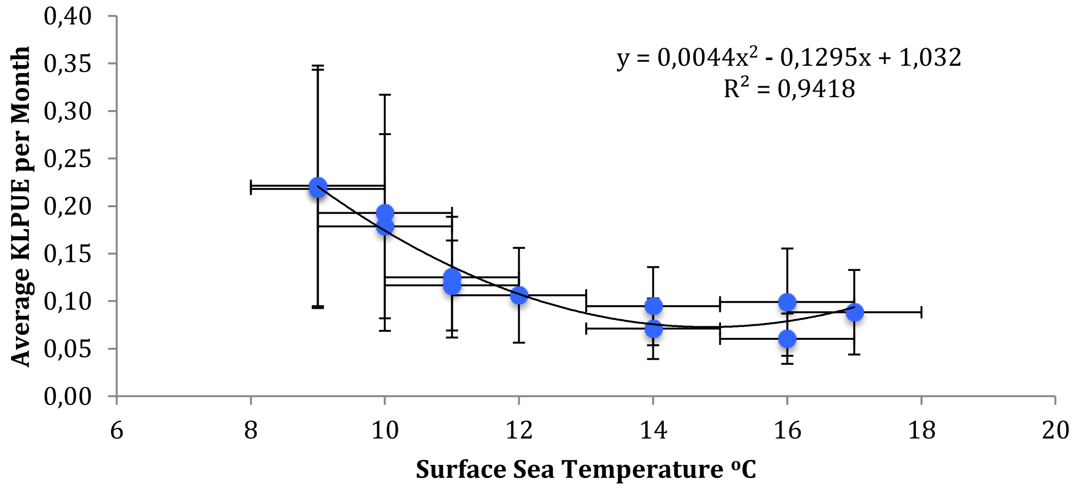

Figure 5.5. Correlation between temperature and KLPUE of male edible crabs with ± sd. Blue circles (Avg. monthly KLPUE for males). Black line= line of best fit).

A positive correlation 'Female KLPUE = -0.93 + 0.17*Temperature - 0.04*(Temperature-12.42)^2' between sea surface temperature and LPUE for female edible crabs was produced from 10 years of fisher's diaries data, within the IPA, the fit of the curve is shown by the ANOVA F(2,9)=45.17, p<0.0001 and an R^2=0.91. Conversely, a negative correlation 'M KLPUE = 0.36 - 0.02*Temp + 0.004*(Temp-12.42)^2' between sea surface temperature and LPUE for male edible crabs was produced the fit of the curve is shown by the ANOVA F(2,9)=91.94, p<0.0001 and an R^2=0.95.

Both the scientific literature and fisher's diaries data demonstrate that we can accept the alternative hypothesis that there is a critical sea temperature at which female LPUE increases significantly. In the case of the fishery within the IPA this is on average 9-11°C as shown in Figure 5.3.

Wind Direction affect on crab catches

Hypothesis Two: An easterly wind has a negative influence on *Cancer pagurus* CPUE in the IPA.

Several fishers claimed that wind direction affected their catches as summarised below:

- The various directions of the wind result in varying CPUE.
- Most noticeably an easterly wind is detrimental to catch abundance.
- The wind speed is not as important as direction of the wind in affecting catches.
- Wind south of east does not negatively affect catches as severely as if the direction of the wind is north of east.

Scientific literature

The scientific literature was reviewed for the effect of wind direction on crab CPUE. One of the major factors limiting the amount of crabs that can be taken from a fishery during a year is the number of days at sea achieved by each fishing vessel. Wind speed largely determines the state of the sea and ultimately whether a vessel can operate safely enough to fish. In addition to wind speed, the direction of the wind is an important factor in determining the effect wind has on sea state. While studying lobster fishermen Drinkwater *et al.,* (2006) documented that 'wind is often observed to be an important determinant of catch rate' and 'many [fishermen] note that winds from a particular direction result in good catches, while winds blowing from the opposite direction drive catch down'. Drinkwater *et al.,* (2006) found that their empirical data supported fishermen's observations of the effects of wind on lobster catch at one out of two study sites, off the Eastern Canadian coast.

Their results showed that one of the study sites (Baie de Chaleur, Canada) where the coastline ran west to east, with land to the south, an eastward wind would be correlated with warmer water and conversely a westward wind would be correlated with colder water due to the Ekman effect. The Ekman effect causes water to move at a net direction of 90^0 clockwise from the direction of the wind in the northern hemisphere and 90^0 anti-clockwise from the wind in the southern hemisphere due to the Coriolis Effect. In the case of Baie de Chaleur, an eastward wind blows the warmer surface layers of water shoreward creating a downwelling and thus increasing the bottom temperature by causing water surface layers to sink. The converse holds true for a westward wind, as the water moves from the coast, cold water moves up from the bottom, producing colder seas. It was then hypothesised that the warmer or colder bottom temperatures altered the foraging activity of poikilothermic lobsters accordingly and increased the catchability when bottom temperature was increased (Morgan, 1974).

Data gathered on-board local fishing vessels

To investigate the hypothesis outlined by Devon fishers that an easterly wind has a negative effect on the LPUE of *Cancer pagurus* compared to winds from other points of the compass, we used 4.5 years worth of wind direction and speed data from a coastal weather station (location: 50^{o}.384’N -3^{o}.520’W) from October 2007 to December 2012, on the coast bordering the IPA (wunderground.com). Data was recorded automatically every hour and a daily average wind direction was calculated automatically by the website. The daily averages were then categorised into 16–compass point directions (N, NNE, NE, ENE E etc.). The data within each wind direction category were averaged as the number of data points in each wind direction category was variable. Wind direction data were plotted against the corresponding average daily LPUE of male and female combined from four fishing vessels within the IPA over the same time period as the available wind data (October 2007 to December 2007) (Figure 5.6.).

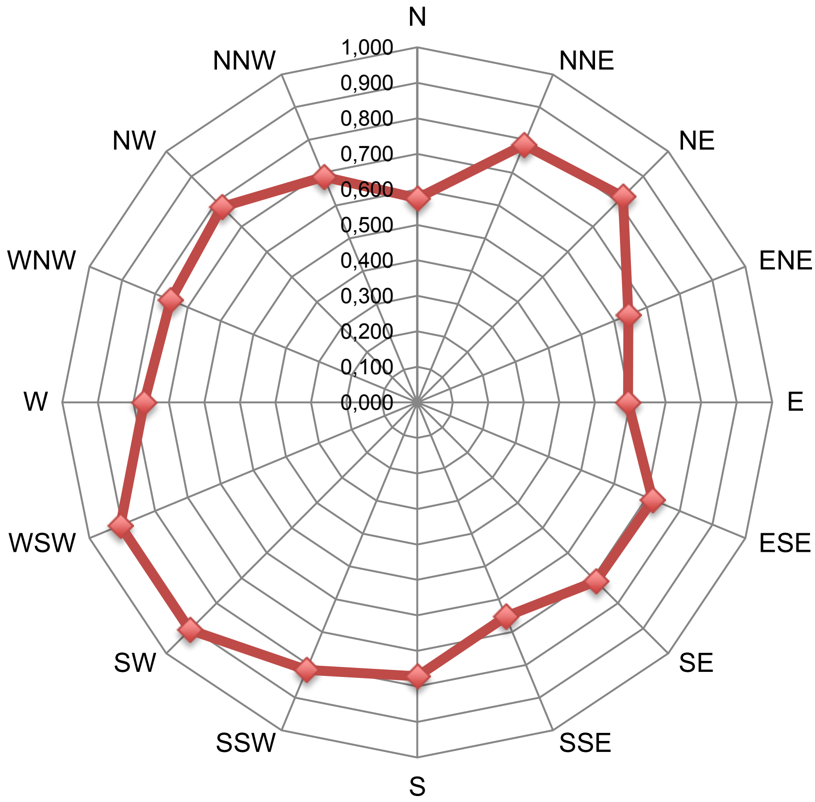

Figure 5.6. The average wind direction of LPUE of Cancer pagurus within the IPA from October 2007 - December 2012. The rose diagram displays 16 compass points on the x-axis, and 0-1 on the y-axis. Red Diamonds= Average KLPUE.

The wind rose diagram in Figure 5.6. reveals that the highest daily average LPUE produced by fishers in the IPA occurred when the wind was in the southwest (0.906) and west-southwest (0.905). Conversely, the lowest daily average LPUE occurred when the wind was in the north (0.575) and east (0.594).

Table 5.1. The average LPUE for crab ranked from highest to lowest and associated wind direction.

Wind Direction	Average KLPUE	s.d.
SW	0.906	0.562
WSW	0.905	0.511
NE	0.820	0.639
SSW	0.815	0.531
NNE	0.786	0.490
NW	0.779	0.518
S	0.772	0.518
W	0.770	0.501
WNW	0.752	0.487
ESE	0.718	0.574
SE	0.713	0.547
NNW	0.688	0.530
SSE	0.653	0.499
ENE	0.644	0.555
E	0.594	0.424
N	0.575	0.461

The average KLPUE were ranked from highest to lowest with the associated wind direction (Table 5.1.). FLEK claimed that easterly winds, and specifically, those winds north of east, were associated with reduced crab catches. Table 5.1. demonstrates that an east wind and east-northeast wind were ranked in the bottom three KLPUE's when KLPUE is ranked in descending order with its corresponding average wind direction. However, NE and NNE winds were ranked as 3rd and 5th highest KLPUE coupled with wind directions.

To establish whether the correlation between wind direction and KLPUE was significantly different from the average KLPUE, we carried out an angular-linear correlation. This produced a (χ^2 (df=2, N= 2)= 5.977, $p < 0.05$), showing that there is a significant difference in LPUE with wind direction from the average, with a pattern that supports the fisher's experiences.

Effect of pot type on CPUE

Hypothesis Three: Parlour pots have a significantly higher LPUE of *Cancer pagurus* than inkwell pots.

Fishers gave the following views when asked which, if any types of pots caught more crabs:

- Fishers believed that parlour pots catch more crabs per unit effort than inkwell pots. They hold this view as parlour pots have two compartments. Crabs entering the parlour pot have to walk through one compartment into the second compartment to reach the bait. Therefore there are two compartments to contain the crabs compared to one compartment in inkwell pots, decreasing the chances of escape. Further, the entrance to inkwell pots is located on the top of the pot and therefore a crab attempting to enter the pot must climb up the netting and fall into the pot. The entrance of a parlour pot is usually situated approximately 2.5 to 5cm above the base of the pot and could be more accessible.

Scientific Literature

The scientific literature was researched for the effect of pot type on CPUE and the following information was found: Pots are utilised to catch target species, which are attracted to the pot by the lure of an odour plume emanating from the bait. As such, the species, which are caught by this method, elicit active movement towards bait and are captured once they have entered the pot and reached the bait/odour source (Edwards, 1967). When compared to other types of fishing gear, pots often produce a lower CPUE (Watson *et al.,* 2006) however, they exhibit a number of benefits; they capture live, high quality (undamaged) target species (Cruz and Olatunbosun, 2013), discards are widely thought to survive (as demonstrated in mark-recapture experiments e.g. Hunter *et al.*, 2013), and pots have a low impact on the benthos (Eno *et al.,* 2001). In an operational context pots are easy to manoeuvre, fairly low cost (compared to other gear types) and hardwearing. Due to the aforementioned benefits the pot gear type has been altered and adapted in many guises to target specific species. The two types of pot used off Devon are illustrated in Figure 5.7.

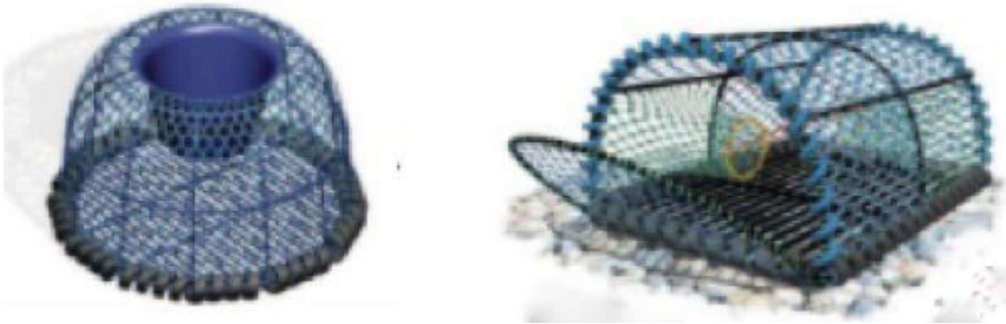

Figure 5.7. Inkwell pot (left) diameter approximately 1m, height 0.65m. Parlour pot (right) length 1m, width 0.5m, height 0.55m (right). (Source: Anonymous (2016)).

Inkwell pots have one entrance on the top of the frame and one internal chamber, whereas, parlour pots have a side entrance and two internal chambers. The target animal entering a parlour pot has to negotiate its way to the second chamber to feed on the bait and then cannot return once it has entered this chamber. Perhaps due to the specificity of the inkwell and parlour pots to the crab and lobster sector in the UK, there is no research into their comparable efficiency. However, in Iceland, Cruz and Olatunbosun (2013) tested the efficiency of two similarly designed pots called Conical (A) (like inkwell) and Carapax (B) (like parlour) (see Figure 5.8.)

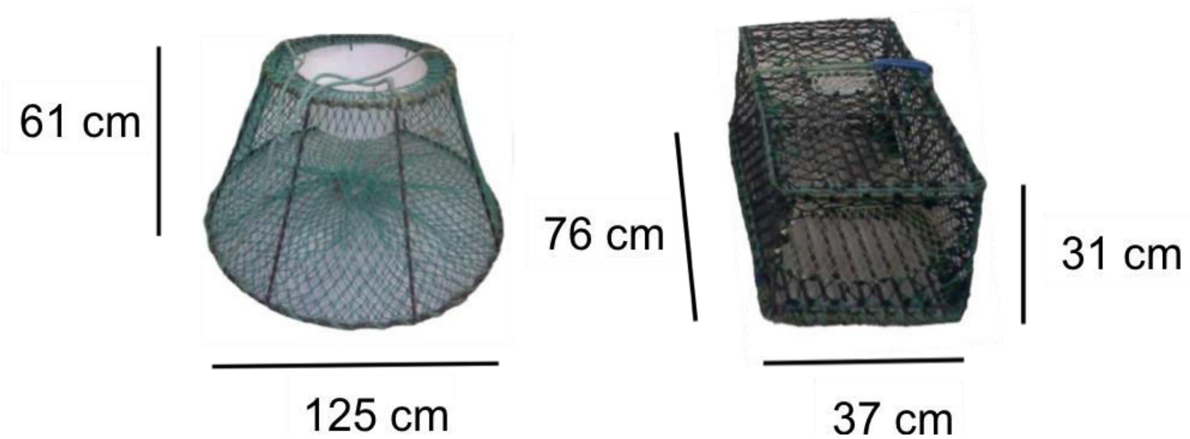

Figure 5.8. (A) A conical pot similar in shape to the inkwell pot used in the UK. (B) A Carapax pot similar to the parlour pot. Source: Cruz and Olatunbosun (2013).

Cruz and Olatunbosun (2013) sampled 24 stations (pots) and caught a number of green (*Carcinus maenas*), rock (*Cancer irroratus*) and spider crabs (*Maja squinado*).

They found that the Carapax pot (B) produced higher individual crab numbers caught per pot and higher weights per pot than the Conical pot (A) when soak time remained constant. Their study then tested the comparable efficiency of both pots at 3 different depth ranges (1-9m, 10-18m and 19-27m). The Carapax pot (B) recorded a higher average catch per pot than the Conical Pot (A) summing all species of crab at all three depths.

The available scientific literature supports the hypothesis of the fishers that parlour pots (or similarly designed pots) have a higher CPUE than inkwell pots.

Data gathered on-board local fishing vessels

To investigate the hypothesis from the fishers that parlour pots catch more crab per unit effort compared to inkwell pots, we compared the observed onboard catches. A total of 55,490 crabs were caught while an observer was at sea between July 2011 and June 2012. Crabs were counted on 9 vessels in 11 locations within the south Devon IPA. The LPUE and DPUE values were derived from 12,806 (82.06%) inkwell pots and 2799 (17.94%) parlour pots. In total, 44,558 (80.30%) crabs were caught in inkwell pots and 10932 (19.70%) in parlour pots.

Several two-tailed, unpaired *t*-test's were performed to establish if the CPUE, LPUE or DPUE from inkwell or parlour pots were significantly different for: total crabs caught, males, females, crabs discarded, small crabs, soft crabs and berried females, the *t*-tests are summarised in Table 5.2.

Table 5.2. The two-tailed, unpaired t-test results for LPUE and DPUE for inkwell and parlour pots between July 2011-June 2012 within the IPA. Red text indicates the highest group mean between inkwell and parlour pot.

	Pot Type	mean	sd	t-test	Significant
LPUE	Inkwell	3.38	1.33	t=2.09, p=0.037 n = 170	Yes
	Parlour	3.81	1.30		
FEMALE LPUE	Inkwell	2.91	1.26	t=0.81, p=0.421 n=170	No
	Parlour	3.08	1.38		
MALE LPUE	Inkwell	0.51	0.45	t=2.89, p=0.004 n=170	Yes
	Parlour	0.73	0.55		
DPUE	Inkwell	1.51	0.93	t=2.09, p=0.038 n=170	Yes
	Parlour	1.81	0.93		
SMALL DPUE	Inkwell	0.90	0.72	t=2.82, p=0.005 n=170	Yes
	Parlour	1.24	0.84		
SOFT DPUE	Inkwell	0.64	0.50	t=1.07, p=0.288 n=170	No
	Parlour	0.57	0.35		
BERRIED DPUE	Inkwell	0.00	0.01	t=1.27, p=0.206 n=170	No
	Parlour	0.01	0.03		

The results in Table 5.2. show that in all the categories apart from soft DPUE parlour pots caught more crabs per unit effort than inkwell pots. Interestingly, parlour pots produce fewer soft crabs per unit effort when compared to inkwell pots. Additionally, parlour pots also produce significantly different catches and discards in the following categories: LPUE, male LPUE, DPUE, and small DPUE.

Discussion

FLEK has been passed down through multiple generations of fishermen. Only in recent years, has this knowledge begun to be captured and used to inform management decisions (Hinds, 2014). IFCA's are under-resourced and under-staffed for the enforcement and conservation tasks within their remit. This paper demonstrates how it is possible to generate hypotheses from FLEK and test them against information gathered from the scientific literature and onboard data collected from the fishery itself, a relatively inexpensive and relatively quick process. These activities led to the validation of FLEK, which can then be used in stock assessments and in the creation of future management decisions. Below we discuss the results of three hypotheses generated by fishers about crab behaviour and the environmental factors affecting CPUE, LPUE and DPUE.

Temperature

The first hypothesis deriving from fishers was: (H:1) CPUE of female *Cancer pagurus* significantly increases once a critical water temperature of between 9 - 11°C is reached in the spring, in the IPA. Published studies show that the activity of poikilothermic crabs is dependent upon the ambient water temperature (Aldrich, 1975). This has been demonstrated in various crab species such as Atlantic rock crabs (*Cancer irroratus*) (Jeffries, 1966) and Edwards (1967) on *Cancer pagurus*. These studies support the SDCSA fishermen's hypothesis that sea temperature effects crab movement and feeding but there is no previous research available to allow comment on why 9 to 11°C should be the range defining the onset of significantly increased CPUE outlined by the fishers in the IPA. Two possible reasons for this temperature range are: 1) this is the temperature above which the crabs can move to a food source without the cost of movement outweighing the energy value of the food, and 2) above 9-11°C the crabs can move fast enough to avoid predators most of the time.

Ten years of fisheries diaries LPUE data plotted against sea surface temperature indicated that there was a positive correlation of female LPUE with sea temperature, and conversely, a negative correlation with male LPUE with sea temperature. A reason for the positive correlation of female LPUE with sea temperature is that female migration is temperature dependent (Hunter *et al.,* 2013). Female edible crabs move from east to west down the English Channel in a contranatant driven migration. Therefore there is an almost continual flow of female edible crabs into the IPA, throughout the year. This flow of crabs would be reflected in their catchability and therefore CPUE/LPUE. We know from (CEFAS MF1103, 2008) that female brooding is temperature dependent and occurs at 9 ±2 °C this would explain the decrease of CPUE in the winter months when sea temperature is 9 – 11 °C. However, according to Hunter *et al.,* (2013) male edible crabs do not migrate and 'moved less far than females, and exhibited mainly local, undirected movements'. We theorise this is because male edible crabs have evolved to not migrate on a large spatial scale, as they do not produce larvae and therefore do not need to move west to offset the displacement of larvae by the current moving north-east up the Channel. We suggest that males simply mate with females that are migrating through their locality. As a result of the local movements of males we cannot attribute the variation in catchability of male crabs in the IPA to a temperature dependent migration. We theorise that the negative correlation of sea temperature with male CPUE and LPUE is associated with competition for resources such as food and space with the more abundant females. Figure 5.3. shows that male LPUE is the inverse of female LPUE. Male LPUE is highest during the winter months when females are in a state of torpor, and not foraging for food and therefore display their lowest LPUE of the year, likely a purposeful behaviour to increase their access to resources called 'Temporal Niche Partitioning' (Schoener, 1974) (see Chapter 4). This type of portioning behaviour is also supported by the work of Hines (1987) who found that blue crabs (*Callinectes sapidus)* in Chesapeake Bay (USA), 'partitioned habitats within the Rhode River sub-estuary by size, sex, and moult stage'.

It should be noted that female crabs are caught throughout the year even in the winter when they are brooding eggs, suggesting some movement. During this colder part of the year their CPUE is drastically reduced, but Hunter *et al.,* (2013) showed using DST tags that small fluctuations in depth data (>0.5 m) during the brooding period of females demonstrated that brooding females are not completely inactive and perhaps are moved by storms or other infrequent events such as the need to respond to predator attacks and of course not all females spawn eggs each year.

What has been written so far discusses the reasons for the general pattern of behaviour by male and female crabs in relation to sea temperature. However, fishers stated a critical temperature between 9-11 ^{o}C as critical for the onset of an increase or decrease of CPUE/LPUE. Both the literature and the analysis of fisheries diaries data support this hypothesis. The reason for the onset of significant increase in catches of female crabs when the sea temperature rose above 9-11^{o}C is most likely to be their awakening from a state of torpor. Hunter *et* *al.,* (2013) recaptured two crabs with DST tags (Data Storage Tags) in the western English Channel. They found that these stopped moving between 25th November 2008 and 12th December 2008 and continued to be in a state of torpor for 177 ±24 days (until approximately May-June 2009). Importantly, they found across all the DST tags recovered in their experiment (n=10) that 'temperature at brooding onset was 13 ±1.5°C, and 11±2°C when feeding recommenced.'

The FLEK hypothesis proposed by fishers was that catches per pot of *Cancer pagurus* significantly increase once a sea temperature of between 9 and 11°C is attained. We can conclude that the fisher's knowledge is congruent with what is known from the literature and with data collected on-board vessels within the IPA during this study.

Wind

The second hypothesis extracted from fisher interviews was (H:2) that 'an easterly wind has a negative influence on *Cancer pagurus* CPUE in the IPA'. Drinkwater *et al.,* (2006) demonstrated that due to the Ekman Effect some wind directions will produce warmer seawater, and other wind directions will produce colder sea water, which co-vary with time of year. As discussed in the previous section crab activity is dependent on the ambient water temperature, which can be affected by wind direction, with certain wind directions being more dominance at particular times of the year, so influencing crab activity and catchability.

In this study data from fisher's diaries (KLPUE) was analysed with daily wind direction data showing that wind direction does significantly affect landings. Specifically, a wind from the north produced the lowest LPUE and, winds from an easterly direction (E, ENE, SSE, SE, ESE) were ranked in 5 out of the 8 lowest LPUE values. A possible explanation of why easterly winds negatively affect crab LPUE in the IPA can be derived from a consideration of how the Ekman Effect might influence water temperature (Figure 5.9. See also Drinkwater *et al.,* 2006). The south Devon coastline within the boundary of the IPA has two general directions. The western side of the IPA has a coastline at predominately 310° and the eastern half of the IPA has a coastline of 40° (See Figure 5.10.).

During a phase of easterly wind, the wind would hit the land at approximately 40° in the east of the IPA. According to the Ekman Effect in the northern hemisphere the wind will move the water on the surface of the sea and in turn, the movement of each deeper layer of water molecules will be moved by the friction from the layer above. Energy is lost between layers and the deep layers will therefore move less than the ones above. If the water is deep enough, deeper layers of water can flow in the opposite direct to the surface layers. However, the net direction of water transport due to the Ekman Effect (in the northern hemisphere) is 90° clockwise from the wind direction, with the surface layers moving at 45° from the wind direction (Figure 5.9.).

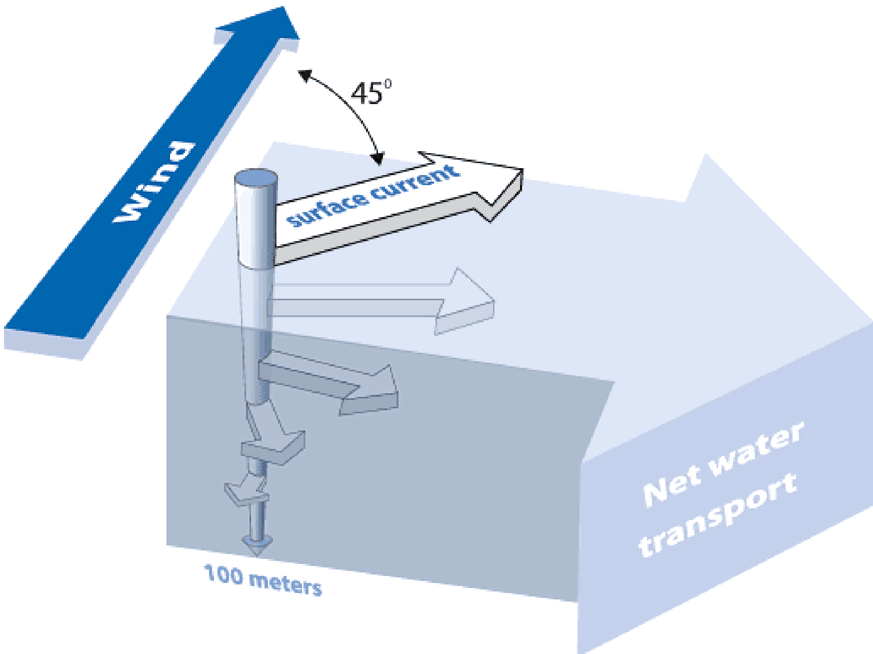

Figure 5.9. A visualisation of the Ekman Effect. Each subsequent layer of water moves slower than the one above. Therefore deeper layers can flow in the opposite direction to the direction of the wind). Source: www.oceanservice.noaa.gov/education/kits/currents/media/supp_cur05e.html

In the context of the coastline in the eastern IPA lying at 40°, and 310° in the western IPA, an easterly wind will move the surface layer at an angle of 45° clockwise from the direction of the wind, resulting in a net movement of water at 90° to the wind and towards the coast (See Figure 5.10.)

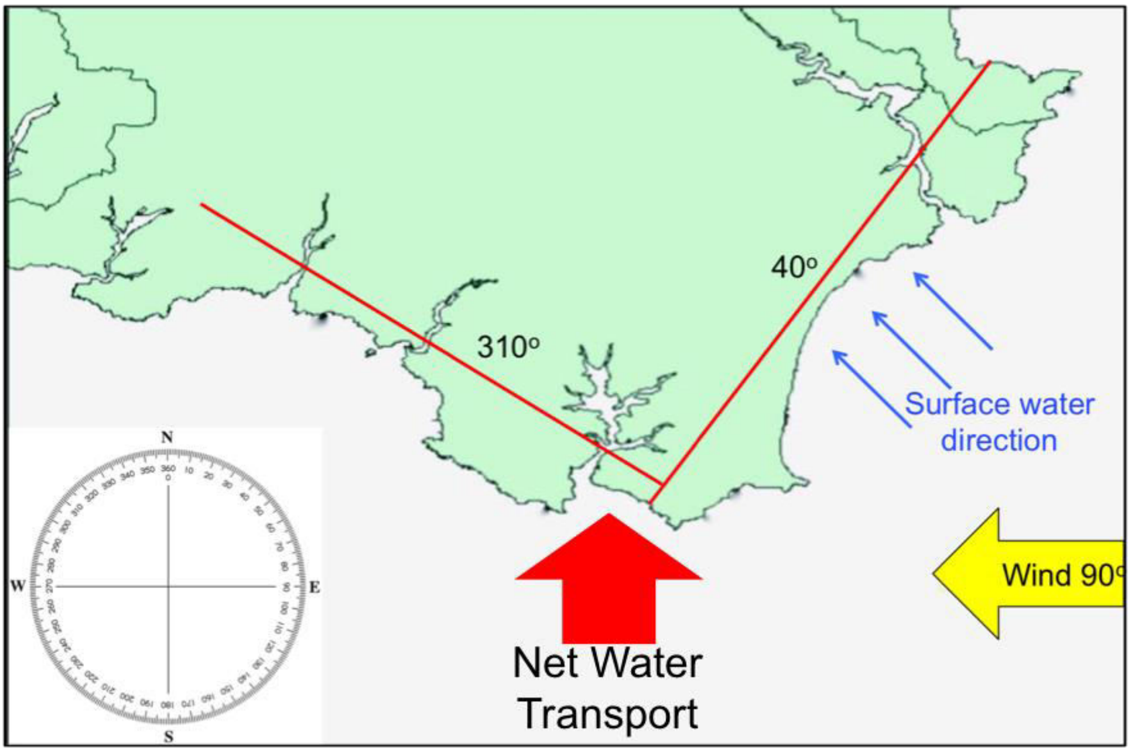

Figure 5.10. The coastline of south Devon, UK. The red line represents the angle of general direction of the coastline relative to north. The yellow arrow shows the direction of an east wind and the blue arrows show the direction of surface current as a result of the Ekman Effect.

Therefore an east wind would blow warmer surface waters towards the coast creating a downwelling. This downwelling then keeps the warmer water on the surface, at shallow depths like the eastern IPA (20-30m where catch data was recorded) and keeps the cold water in the lower layers. This phenomenon also means that nutrient rich waters from the bottom are not moved up the water column into the shallow inshore waters of the IPA, reducing productivity.

Conversely, the wind direction, which created the highest LPUE, was from the southwest. This moves the warm surface currents away from the coast and causes an upwelling of cold water. Upwellings reduce the temperature of the surface water and transports nutrient-rich subsurface water into the sunlit layer of the ocean, resulting in high productivity.

A further explanation for east winds creating low LPUE is that during an easterly wind in the eastern half of the IPA wave height is increased as water is being pushed, into ever shallower depths towards the land, it is very turbid, causing crabs to take shelter and not feed, reducing their catchability. This turbidity is the same reason why fishers do not fish in easterly winds. This oceanographic explanation of the effect of an easterly wind on the IPA supports the hypothesis of fishers that easterly winds negatively affect their CPUE.

Northeast and north-northeast winds were ranked as 3rd and 5th highest LPUE's, which were not expected results. This phenomenon could be explained as a north wind hitting the eastern IPA would produce a net water transport of 90^{o} clockwise from the direction of the wind and therefore in an westerly direction and away from the coast in the western IPA, causing an nutrient rich waters to upwell increasing productivity and potentially and LPUE.

The wind direction, which produced the highest LPUE, was from the southwest. This supports three fishermen's views that southwest winds produce the best catches in their territories, which are in the western IPA. They stated, "you can have a gale of wind from the south west and they all say you know you are going get a good catch".

A possible source of error within the analysis of wind direction data with LPUE from fisher's diaries was that fishers did not record soak time data for each daily LPUE. Therefore during analysis we correlated wind direction, with the day the gear was hauled, and was not possible to take the wind direction throughout the soak time of the pots into consideration. Additionally, the wind data was recorded automatically every hour and a daily average wind direction calculated, therefore our results do not include variation of wind direction just the average direction. Further, the attribution to higher or lower catches to wind direction by explanation through the Ekman effect could be flawed as 'vertical movements of ocean waters into or out of the base of the Ekman layer amount to less than 1 meter per day' (Britannica.com, 08/07/2016), and therefore the most likely reason for reduced catchability during an easterly wind is water turbidity.

On the basis of the above information we can conclude that initial investigations show that the fishers hypothesis is congruent with the current scientific literature and data collected onboard vessels within the IPA during the present study.

Pot Type

The third hypothesis distilled from fisher interviews was (H:3) that parlour pots have a significantly higher LPUE of *Cancer pagurus* than inkwell pots. Both the literature and the analysis of primary onboard data from this study indicate that parlour pots produce a significantly higher LPUE for total catch, for males, DPUE and small DPUE than inkwell pots. Consequently, parlour pots also catch more crabs that are discarded and specifically more small crabs than inkwell pots. This information accepts the fisherman's alternative hypothesis that parlour pots catch a higher CPUE than do inkwell pots, although, this study demonstrated that inkwell pots caught more soft crabs per unit effort than inkwell pots.

The results found by Cruz and Olatunbosun (2013) confirm the beliefs of the south Devon fishermen that inkwell pots are less effective than parlour pots, and therefore produce lower CPUE. It is thought that the parlour pot (like Carapax) produce higher numbers of crabs per unit effort for several reasons; the entrance is positioned on the side of the pot allowing an easier excess to the pot for the crabs, more bait can be added to parlour pots and the parlour pots have two internal chambers, which create an extra barrier for crabs to negotiate before escaping.

In conclusion, in the IPA fishers should choose to fish with parlour pots to maximise overall CPUE for both sexes. However, parlour pots also have a higher discard per unit effort than inkwell pots, which from catch handling point of view means more time spent removing crabs that have to be discarded.

A potential issue with the above data is that it does not consider the increase gear selectivity of parlour pots as they are fitted with escape gaps. It is a Devon and Severn Inshore Fisheries and Conservation Authority byelaw (22 a, b and c) that all parlour pots should have an escape gap fitted allowing undersized crabs to escape through a gap of 84 mm x 46mm at the base of the pot. This increases the selectivity of the pot restricting its catch to crabs mostly above MLS (Brown, 1982). This indicates that parlour pots without escape gaps might have caught more small crabs.

A source of error in the analysis of the pot type with LPUE data was that we did not take the soak time of pots into consideration as information on the soak time of each string was not available. We also did not have information on the size of the pots to allow a consideration of the effects of pot saturation, or data to consider if there were dominance effects from lobsters or large male crabs in the pots affecting whether smaller males and/or females to enter the pot or information on the type of bait used and therefore its potential affect on LPUE.

Criticisms of the study

More general issues with the interviews, which form the basis of this paper, are outlined below:

- Many fishers did not respond to telephone requests for interviews, despite being called on numerous occasions. This led to a small sample size (n=5) approximately 20% of the SDCSA vessels.
- The interviewer was inexperienced in conducting semi-structured interviews and therefore could have asked leading questions.
- The semi-structured interviews did not capture the full extent of the fisher's knowledge. The interviewer had spent many months onboard the interviewee's vessels before the interviews and had previously had hours of informal conversations on the topics included in the interview. As a result, the fishers' answers might not have been as explicit as the interviewer expected as there was already a level of understanding between them and therefore the in depth knowledge was not captured in the transcripts. This error can also be attributed to the inexperience of the interviewer.

It should be noted that the data taken from fishers' diaries was initially collected purely for each fisher's own records and they did not expect this time series of data to be used as part of a scientific study, therefore it is likely that the information they contain is an accurate record of LPUE.

Conclusion

We have shown that FLEK from Devon fishers is congruent with previously published scientific information and with data collected within the area, during and previous too this study. This source of data should be utilised where possible to support empirically designed experiments to inform fisheries science and management.

FLEK and fisher's own catch records should also be incorporated into local sustainability assessments. The benefits of this incorporation would be a quick turn around time for results as data can be quickly collected and analysed, reactive management as data collection and analysis can be fast, cost saving, building relationships with fishers and most importantly the development of a bottom-up approach to achieving a sustainable fishery. As stated by Dubois *et al.,* (2015), 'the use of knowledge in this context is not only about the validity of knowledge claims, but increasingly about mobilising knowledge in support of fishers' participation in management discussions'.

Wider Implications

The wider implications of this study are that FLEK pertaining to the effect of environmental factors and fishing gear within the IPA could be incorporated into fisheries science and management. In terms of this study, the FLEK acquired from fishers in the IPA will be used in in the creation of an Individual Based Model recreating the basic dynamics of the fishery.

Lastly, fishers enjoyed the experience of being able to discuss aspects of the fishery that they had not thought about previously and also valued the ability to put their knowledge to good use. For most fishers it was the first time they had been interviewed in depth about the resource they exploit and they valued the opportunity to contribute their knowledge to the modelling and a potential management process and this helped to build trust between fishers and scientists.

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Appendix E

The semi-structured interview questionnaire used by the author to interview five fishers from the south Devon crab fishery to harness their FLEK.

<u>Collecting Fishers' Knowledge from South Devon Edible Crab Fishing Community.</u>

Aims of the interview:

- Collect fishers' knowledge to contribute to IBM model of crab distribution.

LEK on following topics to be collected:

- Population Dynamics/Crab Distribution
  - Seasonal and Spatial variation in crab distribution
  - Historical knowledge of crab landings
- Environmental Factors affecting crab distribution
  - Tides
  - Bottom Type
  - Wind/Weather
  - Temperature
- Implementing the model
  - Perceived validity by fishermen
  - Adherence

Methodology

- Semi-Structured Interviews (approx. 1- 1.5 hour/s)
- Recorded on Dictaphone.
- Reassure fishermen their information will only be used in my PhD work.

Script – to be spoken to interviewees.

Thank-you for agreeing to participate in this interview. The purpose of this interview is to collect fishers' knowledge of the resource they use and to integrate this knowledge into a model of crab distribution. By fishers' knowledge, I mean, all the years of knowledge you have collected, on factors like how the weather effects catch, and where is best to put your pots etc. Fishers' know infinitely more about all aspects of the fishery than scientists ever could as they work in the environment everyday. So I'd like to try and collect the knowledge you have and integrate it with the science I have, to hopefully come up with a fisher directed stock assessment that works scientifically and practically- and is useful!

The model that I will be using to assess if the fishery is sustainable or not, is really very simple. As it is impossible to know exactly how much crab (the technical word for this weight measurement is biomass) there is in the IPA at any one time the model looks at what factors increase the biomass (or amount of crab) and decreases the biomass.

The factors that can increase the biomass of crab are immigration and growth. By immigration I mean crabs in their adult and larval form entering the IPA from outside the IPA for example, in the current or by migration. And growth- is obviously the increase in size/weight of the crab and hence biomass.

The factors that can decrease the biomass of crab in the IPA are emigration (adult crabs and larvae leaving the IPA), natural mortality (crabs that die of natural causes, e.g. disease, old age etc.), and obviously by being caught by fishermen (which is why I was on your boat).

So we put all these factors into the following formula:

Crab Biomass=
Immigration + Growth –Emigration – Natural mortality – Catch

and the fishery is sustainable if: Immigration + growth is greater than emigration - natural mortality – catch.

and the fishery is not sustainable if: Immigration + growth less than emigration - natural mortality - catch, then the fishery is not sustainable at that time.

In simple terms if what comes out is more than what goes in, the fishery isn't sustainable. Conversely, if what goes in is more than comes out then the fishery is sustainable- and more could be caught!
We'd then like to invent a method by which you wouldn't need much help in doing our own assessments of whether what comes in is more or less than what is going out. This would hopefully empower fishers' to show the government or associated parties, you are being proactive in looking after your fishery, ensuring its sustainable for the future (both you and the crabs), and possibly getting the perks that go with it like an increased price at market etc.

So for the model and fisher directed stock assessment to be successful and used when my PhD is over, I think its key to work together at every stage possible to developing the model and assessment method. Hopefully in the longer term this will ensure it's correct and fit for purpose!

With this aim in mind I have designed a series of questions relating to the seasonal and spatial changes in crab distribution, how crab catches are influenced by environment factors, and other issues such as management measures to collect your knowledge to put into the future work.

In light of this would you mind sharing your knowledge about these aspects of the fishery, and adding to the information I've learnt onboard boats in the last year?

The answers given from this interview will be used to form questions that I will test with the data I have collected on board and incorporated into the design of the model. Your answers will remain confidential and by taking part in this interview you are consenting to the use of the information you provide for the purpose of this independent research. Do you have any questions before we begin?

Section 1: Personal Information

1. Name
2. (Do you mind) Age?
3. How long have you lived in the South Hams?

4. How long have you been fishing/crabbing here?
5. Any experience of other types of fishing/boats or crabbing in different locations?
6. Are you a skipper?
7. Are you a boat owner or hired skipper?
8. How many generations of fishermen have there been before you in your family?
9. Do you have any friends or relatives who will continue to use the fishery after you retire?
10. Do you have any relatives presently working in any other aspect of the fishing industry?
11. How did you get into fishing?
12. Have you ever had the chance to take any formal courses on marine ecology or anything marine related?

Section 2: Spatial Mapping of Fishing Areas
(I will use this data to see if certain areas/bottom types mean more/less crab is caught)

13. Here is a map of the area where you fish with your strings drawn on as a point of reference. Could you draw on the map the different bottom types that surround your fishing area?

14. Add any extra information on to the map that you think is important in influencing crab distribution for example; Mussels beds, high number of brittle stars on pots, wrecks etc.

15. Indicate which strings to the best of your knowledge fish the best and worst and tell me why. Does this change seasonally?

16. (If Skipper) How did you come to fish on the grounds you have your pots on?

17. Where do you think the most and least crab is caught in the IPA? Why? How does this change within a season? Has this changed in the time you have been fishing?

18. Where do you think the largest and smallest crab is caught in the IPA? Why? How does this change within a season? Has this changed in the time you have been fishing?

19. What effect do you think depth has on crab size and behaviour?

20. Where do you think the soft crab is caught in the IPA? Why? How does this change within a season? Has this changed in the time you have been fishing?

21. Do you think there is a preference for certain grounds for male/female crabs? Hard/Soft crab? Berried Crab? Small/Larger crab?

22. How do you think crab behaviour is affected by current flow?

23. How do you think crab behaviour is affected by tides?

24. Send a letter to each fishermen in the area and ask them to give me GPS of own strings- need idea of total number of pots in IPA – show Clark (2008) diagram as add changes)

25. If you could fish anywhere in the IPA where would it be and why?

Section 3: Environmental Factors influencing crab distribution

26. List ALL the factors that you think influence crab distribution and abundance. (Explain the difference between distribution and abundance)

27. From that list choose the 3-4 factors that most influence crab catch and tell me why you think this is.

28. If you could have me answer 3 or 4 questions about the fishery, what would they be?

Section 4: Specifics (Relating to answers in Sec. 3)

29. In terms of geography, what do you think South Devon has a crab fishery?

30. What do you think the reason is that a fishery has been here for so long?

31. Do you think the fishery at its current rate of fishing is sustainable?

32. From my year onboard crabbers I have identified four aspects of the fishery that have little or no previous research. These are:

    - The movement of the crab over a yearly cycle. (Seen data on this)
    - The effect of tides on the number of crab caught (What is your knowledge of this phenomenon?)
    - Effect of wind directions on number of crab caught (What is your knowledge of this phenomenon?)
    - The effect of sea temperature on crab movement/catch. (What is your knowledge of this phenomenon?)

Section 5: Catch Data – Season variation/ Crab movement

(This is the data we have so far… comment on accuracy?)

33. This is a graph showing the variation of crab retained/landed over the year I was at sea. How do you think it reflects the truth?

34. This is a graph to show how the sex ratio of crabs landed changed over the year- is it what you would expect?

35. Here are two graphs to show the % of retained and discarded crab for male and separately female per month over the year? – is it what you would expect?

36. Here are two graphs to show the proportions of reason for discards for male and separately female per month over the year? – is it what you would expect?

37. Could you supply me with days at sea over a season at a later date please? Have a form to supply to collect this data.

38. Could you supply historical data on catches for the past 10 years - how to do this – select random dates? Have a form to supply to collect this data.

39. Have you noticed any patterns or cycles in crab landings over the time you have been fishing?

40. From your knowledge how does crab move and is distributed over a season throughout the IPA. Start in April with females.

Section 6 – Management and model
This project is aimed towards producing a method, which fishermen can use to calculate a sustainable catch level for the coming season, using historical data collected in the local area. This method of management would hopefully ensure the future sustainability of the fishery in terms of crab stocks and fishers' livelihoods. So here are a few questions on the management measures for Edible Crab in South Devon.

41. From the management measures used in the IPA, which do you, think aid sustainability and which do not. Why?

42. In general do you think there is adherence to current management measures within the IPA? Why?

43. Would you be prepared to be involved in setting up and running a management system for the crab fishery?

44. How do you think it might work?

45. How do you think other fishermen might feel about this?

46. Would you be prepared to collect data necessary for running a local management system?

47. If fishermen collected data, and devised management measures, what do you think effect of adherence to these regulations would be?

Section 7- Model
The aim of this project is to devise a method which fishermen can use to collect and very easily analyse their own data – and set the next seasons catch quota. This would hopefully demonstrate to the government, and associated parties that you were doing all you could to ensure the fishery is sustainable.

48. Would you be in favour of a fishermen driven fishery assessment?

49. How useful do you think this tool would be to the fishermen in the IPA?

50. Fishers' advice and knowledge will be very important in the success of the model and fisher directed stock assessment. Can you think of any ideas, suggestions, and advice now?

Any other comments? Is there anything that I have missed from the questions that you feel is important to any aspect of the fishery or to what we are trying to achieve via this model?

Thank you for your time.

Chapter 6

The model fisherman: integrating catch data and FLEK from a participatory research project into an Individual Based Model.

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Emma Pearson, Author. Ewan Hunter, Second Supervisor. Alan Steer and Kevin Arscott, fishers facilitating data collection. Paul J. B. Hart, Main Supervisor.

Abstract

Financial resources, staff, logistics, and skills within marine management agencies for the collection of catch data and to set catch limits are scarce, despite the aim in the EU of achieving sustainable fisheries by 2020. Due to the lack of resources available for fisheries management, all available sources of information should be explored before instigating new costly research. An effective and relatively inexpensive method for the Inshore Fisheries and Conservation Authority (IFCA) to manage the south Devon fishery sustainably would to be to use an Individual Based Model to allow a fisher-directed stock assessment. The development of an IBM for a local, small-scale fishery fosters engagement between fishers, scientists and managers and leads to co-management decisions rather than top-down implemented measures, as demonstrated by the GAP1 and GAP2 Projects, increasing a sense of ownership and stewardship in the local area.

The system to be modelled in this chapter is the female crab fishery in the Inshore Potting Agreement area and its immediate surroundings off south Devon, UK. The system includes the crabs, the fishers and the environment in which they are operating. Data used in the IBM were taken from a number of sources; catch and discard data was sourced from onboard trips with fishers and 10 years worth of fishermen's diaries. Environmental data such as sea temperature was procured from external institutions and vital knowledge on crab life history parameters were taken from the literature. Professor Hart developed and coded the IBM using NetLogo software, with the lead author co-developing the model and contributing data, parameters, and mechanics of how the crab population should behave. The south Devon crabbers contributed their catch data, FLEK and feedback on how the model might work.

We demonstrated that through the development of the IBM that, working closely with local fishermen, a relatively inexpensive and fast method of catch recording and collation of environmental data from freely available sources, it is possible to produce an IBM of a small-scale fishery to test the effect of varying factors such as sea temperature, substrate and immigration rates on the crab population and eventually with further work its level of sustainability. Unfortunately, without firm parameters for a stock-recruitment relationship we are not able to make the model predictive to produce a sustainable level of fishing mortality for the stock at this time.

Introduction

Damasio *et al*., (2015) reports that there are limited any financial resources, staff, logistics, or skills in management agencies to collect fishery data and set catch limits, despite it being of paramount importance that fisheries be managed to achieve MSY in the EU by 2020 (ec.europa.eu [2016]). The IFCA responsible for the conservation and enforcement in south Devon is grossly under-staffed and under-resourced with an annual budget of just £694,000 to manage, enforce and conserve 3,306 km^2 of seas on two disconnected coastlines (DSIFCA, 2016). Due to the lack of resources centred on the management of fisheries, all available sources of information should be explored before instigating new costly research (Berkes, 1999; Johannes *et al.,* 2000, Begossi *et al.,* 2008). An effective and relatively inexpensive method for IFCA's to manage the south Devon fishery sustainably would be to use an Individual Based Model (hereafter referred to as IBM) to support a fisher-directed stock assessment. The development of an IBM for local small-scale management not only fosters engagement between fishers, scientists and managers and leads to co-management decisions rather than top-down implemented measures, as demonstrated by the GAP 1 and GAP2 Projects, and JAKFISH (See Chapter 2) but also enables fishers to visualise the spatiotemporal dynamics of their fishery as a whole. Fishers from the south Devon fishery have previously demonstrated their openness to new ideas by the development of pioneering management measures to solve local fishing conflicts with the establishment of the IPA in the 1970's (Blythe *et al*., 2002).

Models which use individual agents as a basic unit such as in an IBM, have been developed for use in an ecological context since the early 1970's, but only since Huston *et al*., (1988) have IBM's been widely accepted as a form of ecological modelling (DeAngelis and Gross, 1992; Shugart *et al*., 1992; Van Winkle *et al*., 1993; Grimm, 1999; Huse *et al*., 2002; Grimm and Railsback, 2005; DeAngelis and Mooij, 2005). In a review of the use of IBM's in an ecological context, (Grimm, 1999) found that 19 out of 50 papers published between 1989-99 on animal species were in relation to fish species, demonstrating the applicability of this form of modelling to this study.

What are Individual Based Model's?

IBM's are sometimes referred to as 'Agent Based Models' (ABM) and are in essence, 'simulations based on the global consequences of local interactions of individual members of a population' (Grimm, 1999). Illustrations of the 'individuals' that can be modelled are diverse, for example, cars in a queue of traffic, ants in a nest or even predator/prey relationships. The individuals (also referred to as 'agents' or in NetLogo, 'turtles') have a set of state variables (crab demographic i.e. size and sex) and behaviours and exist in the 'world' a visual and spatial representation of the real environment. Individuals interact simultaneously with each other and with their abiotic environment, which consists of multiple equally sized 'patches', which are characterised by parameters, for example, depth, temperature and salinity, with 'individuals' eliciting behaviours (from coded rules), such as movement, foraging, growth and reproduction.

Why use an IBM?

Scientists use IBM's to study many complex ecological, social, or socio-ecological systems (Grimm *et al*., 1999). IBM's allow researchers to study how system-level properties emerge from the adaptive behaviour of individuals (Railsback, 2001; Strand *et al*., 2002) as well as how the system affects individuals (Grimm, 1999), local interactions among individuals, and the adaptive behaviour of individuals (DeAngelis and Mooij, 2003, DeAngelis and Mooij, 2005 and Grimm and Railsback, 2005) cited in Grimm *et al*., (2010). The property of 'emergence' of complex behaviours from relatively simple activities (Simon, 1996) is probably the most powerful attribute of IBM's.

Emergence is defined as the outcome of 'interactions among objects at one level give rise to different types of objects at another level (Gilbert and Troitzsch, 2005). Or put another way, a process where complex entities, and patterns, become apparent through interactions among simpler entities, that in themselves do not demonstrate these properties. The higher-level events are more than the sum of their parts.

At the beginning of the GAP2 Project a model representing the dynamics of the crab fishery was not in existence, therefore an IBM was designed and coded by

Professor Hart with assistance from the author and members of the South Devon and Channel Shellfishermen's Association (SDCSA). The model considers local environmental parameters on bathymetry, substrate and temperature, and crab behaviours such as, direction and speed of crab movement, FLEK, and crab behaviours elicited by environmental conditions such as egg brooding and recruitment.

Previous uses of an IBM for fish and crab populations.

To demonstrate suitability of an IBM for this study, we considered previous work involving the modelling of fish and more specifically, crab behaviour using IBM's. Fish population models have been reviewed, in depth by DeAngelis *et al*., (1990); van Winkle *et al*., (1993) and Tyler and Rose, (1994) all cited by Grimm *et al*., (1999). All of these papers use Individual-Based simulation modelling to track the attributes of individual fish through time and aggregate the outcomes of these interactions to generate emergent insights into population function (van Winkle *et al*., 1993). The systems modeled by the aforementioned authors are wide ranging, with systems from the accumulation of polychlorinated biphenyl (PCB) in lake trout (*Salvelinus namaycush*) (Madenjian and Carpenter, 1993) to size-dependent predation of spot fish (*Leiostomus xanthurus*) (Rice *et al*., 1993).

More specific to crab populations, an IBM was developed by the South Carolina Blue Crab Regional Abundance Biotic Simulation Project (SCBCRABS) (clemson.edu/SCBCRABS) in 2007. This project focussed on the Ashley River, South Carolina, USA and was created to 'predict population abundances of blue crabs (*Callinectes sapidus*)' as well as to 'determine how disturbances such as fishing pressure, hurricanes and droughts might influence these populations.' The IBM modelled an area of river measuring 184km^2 with patches containing environmental parameters such as depth (reflecting the general pattern of depth in the river), temperature (changes on an annual sine curve calibrated for the Ashley River), salinity (set to vary temporally and spatially within the river over the year) and dissolved oxygen (negatively correlated with temperature and salinity). The male, female and juvenile blue crabs, as well as crab pots were represented as Figure 6.1.

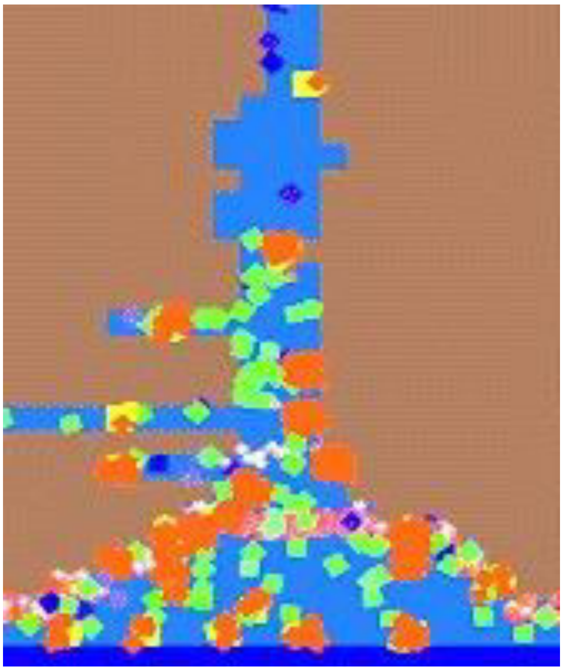

Figure 6.1. A visual depiction of the SCBCRAB individual based model.
Brown = land, Blue = water, Blue diamonds = male blue crabs, Green diamonds = female blue crabs, Red diamonds = juvenile blue crabs. Yellow squares = empty pots, Orange squares = pots with crabs.
Source= clemson.edu/SCBCRABS/index_files/ModelDescription.htm

The behaviours of crabs were programmed to move on a weekly basis, grow (as a function of their current age/size and temperature), and reproduce (between May and October only). The 'number of offspring and probability of larval release were dependent on the female's life stage and age' and mortality was a function of the probability of disease, predation, temperature, salinity, dissolved oxygen, population density and getting caught in a pot (set at 0.2). Only adult crabs could be caught in pots. Lastly, the model enabled immigration of post-larvae from areas external to the model, to be recruited to the fishery. The variables, which could be altered by the end user of the model, were: initial number of juveniles, initial number of adults, crab density, number of traps/pots, trapping probability, and birth and immigration rates. Further the environmental variables of temperature, salinity and dissolved oxygen levels could be altered. Outputs such as number of crabs caught per pot, number of crabs per region of river, total numbers of crabs that have died and importantly, total population were monitored by the model and can be saved as an external Excel sheet for analysis. Overall the model enabled the variation of the aforementioned inputs to test the impact of these variables on the total blue crab population in South Carolina. The model in full can be viewed and operated from the following website (also see Figure 6.2.): clemson.edu/SCBCRABS/index_files/ResearchSimulation.htm.

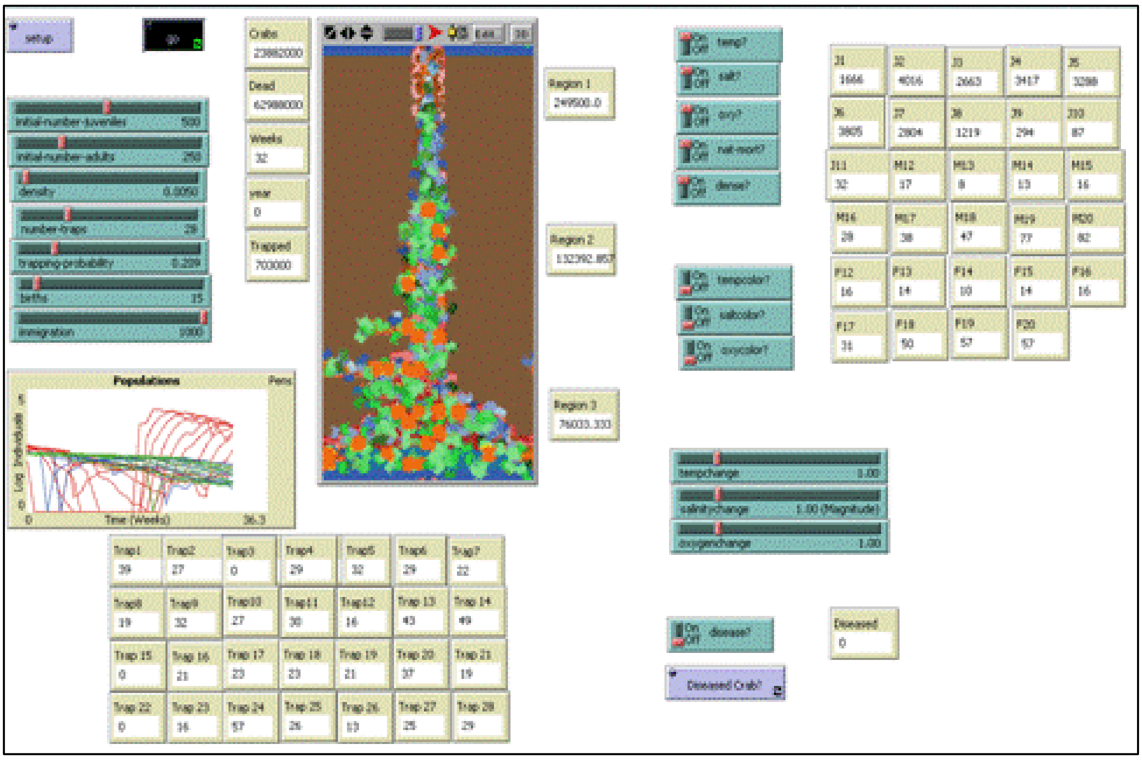

Figure 6.2. The NetLogo interface for the SCBCRABS Project. Input variables, which can be adjusted, are in green boxes, and outputs are in beige boxes. Source: clemson.edu/SCBCRABS/index_files/ModelTutorial.htm

The advantages and disadvantages of using complex models to simulate ecological scenarios have been widely debated and reviewed (Jørgensen, 1992; Liebhold, 1994; Logan, 1995; DeAngelis and Mooij, 2003; May, 2004 and Grimm *et al*., 2005). One of the advantages of using an IBM is that all individuals within the model are tracked across time and can also be tracked in space and are built from the bottom-up. In contrast top-down, differential models average characteristics across populations and attempt to simulate changes in these averages for the whole population, losing the emergence of individual interactions. Further, the IBM method 'provides a framework within which researchers conceptualise the natural processes, design their research, analyse results, and combine empirical studies and modelling in a synergistic manner' (van Winke, 1993), and they can incorporate any number of individual-level mechanisms (DeAngelis and Grimm 2014). Additionally, by using NetLogo to develop IBM's there is the ability to visualise the outputs of the model while it is running.

There are however some disadvantages of modelling using an IBM. There is a trade-off between the level of complexity of the model to give a true reflection of the situation being modelled, and the ability to gather accurate data in adequate detail, and then analyse what is emergent from the model. Other disadvantages outlined by Grimm *et al.*, (1999) are that IBM's are more complex in structure than analytical models, they have to be implemented and run on computers, and IBMs are more difficult to analyse, understand and communicate than traditional analytical models (Grimm *et al.*, 1999). Hence, Grimm *et al.*, (2006) developed the Overview, Design concept and Details (ODD) Protocol, a standardized method for communicating and describing IBM's (see below). Despite these disadvantages, due to the many aforementioned advantages and flexibility of the IBM approach we will use this method to model the south Devon crab fishery.

Rationale for model

It is the aim of this chapter to present data and set the context for an IBM, which could be used to understand the factors affecting the crab fishery and ultimately to assess the sustainability of the south Devon crab fishery. The ultimate purpose of the model is to enable fishers to use their own catch rates to set future individual quotas, thus, in theory creating a sustainable fishery. The software used to program the IBM is NetLogo (Wilensky, 1999).

Sources of Data and Knowledge for the Model

We used knowledge from the scientific literature (Chapter 1), onboard spatiotemporal catch and discard data and data from fishers diaries (Chapter 3), along with environmental data (Chapter 4), and FLEK from Chapter 5 to develop and test the model. Throughout we worked closely with fishermen from the fishery to integrate their knowledge and detailed feedback into the model (Table 6.1.).

Table 6.1. The type of knowledge and data we used to develop the model and how it was integrated into the IBM.

Type of Knowledge/ Data input	**Source**	**Information used**	**How was it integrated?**
Onboard Data	37 trips onboard vessels within IPA over 1 year	Recording number of crabs landed and discarded per pot	Set likely catch rates (fishing mortality) and used to estimate total crab abundance in IPA. Fisher diary data provided the annual cycle of catches that the model had to reproduce.
Fishers Diaries	5,170 days at sea from 4 vessels, over a 10 year period	Recording landings by sex in kg.	
FLEK	Semi-structured interviews with 5 fishers from the IPA regarding all aspects of the fishery.	Fishers outlined the importance of depth to the movement of different sized crabs, substrate type and maximum number of crabs that could be caught per pot (pot saturation) to make the IBM model more realistic. Also suggested hypothesis they had observed which were compared to empirical data e.g. east wind reduced CPUE.	Into the IBM model and in Chapter 5 FLEK synthesis of the fisheries dynamics.
Sea Surface Temperature	10 years of sea surface temperature recorded 3.5nm south of Rame Head, Plymouth.	Avg. monthly sea temperature	Used to set yearly temperature cycles with variation.
Substrate Data	EMODnet Project	Seabed substrate type in IPA and surrounding area.	Mapped onto IBM and affects females movement to more 'favourable' habitats and suitable substrate to bury for winter.

Map of the IPA	SDCSA Chart 2014	Showing seasonally open and closed areas to trawling and boundaries of the IPA.	Map IBM world. IPA boundaries, outside IPA and land.
Movement Behaviour of female crabs	Hunter *et al*., (2013)	Southwesterly movement of female crabs down the English Channel without a return migration.	Used to code female crabs to move west of north and south line, when deciding to move to the next patch.
Burying of females	CEFAS MF1103 (2008)	Critical sea temperature (< 9oC)	Use to set point in yearly temperature cycle when female crabs stop moving and find a soft substrate to bury and brood their eggs until the next spring.
Literature	Sheehy and Prior (2008)	Natural mortality rate 0.2	Used to set level of crabs dying naturally each day

Before and during the development of the IBM we invited fishers of the SDSCA to attend several seminars on how we thought the model might work and later how the model had progressed. We actively encouraged all the fishers who attended these seminars to give their feedback on the model. For example, fishers outlined the importance of depth to the movement of different sized crabs, which we had not included in the model before their suggestion, they also suggested we include substrate type and maximum number of crabs that could be caught per pot (pot saturation) to make the model more realistic.

Description of the Model

To create a common format by which IBM's and ABM's are described, Grimm e*t al.*, (2006) designed a standard protocol for the description of all IBM's to make them easier to understand and replicate, which they called the Overview, Design concept and Details (ODD) Protocol, which is explained in Table 6.2. Below we use this format to describe the model of the south Devon crab fishery. P.J.B. Hart described this ODD with the author co-developing the model and contributing data, parameters, and mechanics of the crab population should behave. Furthermore, the south Devon crabbers contributed their catch data, FLEK and feedback on how the model might work.

Table 6.2. A summary of Overview, Design concept and Details (ODD) Protocol for the standardisation of describing IBM models (adapted from Grimm et al., 2006).

Overview	Purpose	Why there is a need for a model and what it will show.
	State variables and scales	Characteristics of individuals (entities)
	Process overview and scheduling	What processes occur e.g. Growth, movement and in what order.
Design Concepts	Design Concepts	A list of up to 9 factors to consider when describing the model.
Details	Initialisation	Information on the set up of the model e.g. how many crabs are present at the beginning of the model.
	Input	Information such as data on environmental variables, e.g. annual temperature cycle.
	Submodels	Detailed description of the factors in the 'Process overview and scheduling' section.

Overview

Purpose

The system modelled was the female crab fishery in the Inshore Potting Agreement area and its immediate surroundings off south Devon, UK. The system included the crabs, the fishers and the environment in which they operate.

What was to be learnt from the model?

(1) We wanted to know how the crab catch depends on the immigration and emigration rates of female crabs into and out of the IPA area. (2) To discover the immigration and emigration rates that sustainably support present catch rates. (3) To understand how female overwintering behaviour is influenced by temperature and how this influences catches. (4) To examine how bottom type and depth affects the distribution of crabs and the catch.

Entities, state variables and scales

The model included:

Environment - The seabed is characterised by substrate type and depth. The seabed was divided into patches of equal size, each labelled by a code characterising each patch, so it is identifiable. Daily sea surface temperature was universally provided for all patches by an input file as a fixed annual cycle from historical temperature recordings just outside of the IPA (3.5nm south of Rame Head, Plymouth).

Crabs – these were all assumed to be female and were divided into three arbitrary size groups and it is assumed that all three sizes are over Minimum Landing Size (MLS).

Fishers – information included was: where they fished in the IPA and the number of pots they fished and in which patch these pots were found. The model worked on the assumption that all traps were cleared each day. Although this is not true, the outcome was the similar enough to modelling the real fishing pattern of each fisher.

Scale – Geographic – the IPA area and some of the sea surrounding it was divided into 120 patches (West to East) x 80 patches (North to South). Each patch had sides of 500m and therefore covered an area of $0.25km^2$.

Each patch contained information on:

- Whether it was inside or outside the IPA, or whether it was on land.
- Type of bottom substrate
- Sea depth
- Number of pots fished

Time Scale – the time scale was one day (24h) so changes happening within a day were not accounted for in the IBM. The program kept track of days and years, and run of the program is currently set at 15 years.

Process overview and scheduling

For the model the following entities with the actions they executed can be found in Table 6.3.

Table 6.3. The entities with the actions they executed in the IBM.

ENTITY	ACTION
Crabs (turtles)	Move, choose a substrate, choose a depth, respond to competitors, hibernate, die naturally, be caught in a pot, and leave the area.
Fishers/Pots (turtles)	Catch crabs that move onto the patch where a pot is placed.
Sea bed (patches)	Become available to crabbers (for areas of IPA that are open to trawling for some of the year – this refinement is not yet implemented), substrate type, temperature, depths, and location in/out of IPA or land.

Movement of crabs - varied with reproductive state (season), the number of competitors in the same patch, substrate and depth.

New crabs - appeared on the eastern and southern margin of the area modelled and the numbers entering were linked to temperature dependent reproduction/recruitment 5 years previously.

Design concepts

Basic principles - The model investigated how the crab catch from the IPA was a function of immigration and emigration rates for individuals to and from the exploited area. The immigration rates were linked to recruitment of new crabs from the east and south and these new recruits were of mixed sizes. The size distribution of the recruits was linked to the numbers of crabs surviving from the previous year and the number of newly recruited crabs of the smallest size. This last number was a function of the sea surface temperature five years previously. Sheehy and Prior (2008) present evidence to show that crabs recruit to the fishery at age 5 and this underlies the relation between recruitment and temperature. The size of the crab on entry to the modelled area determined how it moved, with small crabs favouring shallower depths, larger crabs keep further out and all sizes kept moving west until they got to the time of the year when hibernation started. All females stopped moving for the winter period. The model can be used to explore the relationship between the immigration rate, the rate of movement of crabs through the area and the catch taken by the fishery.

Emergence – What was expected to emerge from the model? The distribution of female crabs across the IPA and surrounding area, together with their sizes, will be an emergent property of the model. This in turn will produce the spatial and temporal pattern of catches across the IPA.

Adaptation - What adaptive behaviours do agents have to improve their fitness? The crab distribution was steered by bottom type and depth. Crabs were influenced in their decisions by whether it is time to hibernate and how many other crabs are in the same patch. The fisher's behaviour was not explicitly modelled. The original intention was to do so, but crabs were caught whether the fisher went to sea or not, so at present there is just a maximum number of crabs a pot can hold per day and the assumption that all pots are emptied each day.

How were the behaviours modelled? The crabs made their choices on the basis of what they were trying to achieve, although the choices were oversimplified. Ultimately day-to-day crab movement is probably dictated by food availability, which would allow them to maximise growth rate. At present we do not know enough about the feeding behaviour of the crabs or the distribution of their food, to model foraging behaviour in detail.

We represented the consequences of growth by ensuring that the new crabs entering the area in the east were distributed across a range of sizes representing the size–frequency distribution in the population (Brown and Bennett, 1980). Females decided which patch to move to on the basis of its substrate type, temperature, and depth and how many other crabs are on the patch (competitors).

Objectives - What measure of future success of the crabs is incorporated in the decision process? For the crabs, the choices we modelled were mostly about choosing the right habitat. Although not modelled explicitly, these choices were those that brought about good growth, strong survival and ultimately successful reproduction. We assumed that habitat choice was positively correlated with fitness in the Darwinian sense. There was also a need to take account of the number of crabs on a patch. Favourable patches with the most suitable substrate will attract more crabs than will less favourable patches. The more crabs there are on a patch then of course the feeding rate will drop, so we had to incorporate a mechanism that allowed individuals to assess the number of competitors and change their behaviour accordingly. As we do not know enough about this aspect of crab behaviour there would be an opportunity here to test the consequences of different decision rules.

The variables chosen to represent the agents (fishers and crabs) were those that we knew about with some confidence. As already mentioned, it would be ideal to have the crabs choose patches on the basis of food availability but we do not know enough about crab feeding behaviour or food distribution to be able to model this level of detail. Making the crabs choose one substrate over another contains the hidden assumption that some substrates have more food than others. Presumably a crab that is on a patch with good food availability will not need to move on so rapidly. It would be easier to choose a range of variables for the fisher but the crab fishery is unlike most fisheries in that the fisher has little possibility of changing the location of his gear in response to crab distribution. In days gone by, when there were fewer crabbers with fewer pots, fishing effort would have been shifted around the IPA area to follow the best fishing areas but this is no longer possible.

The objective measure changed with the reproductive state of the female crabs. Their choice of substrate and the rate of movement changed once the females had eggs. When they found a soft substrate, they stopped moving to brood their eggs over the winter and spring months.

Learning – crabs did not change their adaptive traits as a result of learning.

Prediction – A crab predicts future fitness through its decision rule to pick the next patch with the best substrate and depth. The best substrate in the non-reproductive period of the year is the one that gives the best feeding opportunities. There was a high level of competition on the best sites and the need to reduce this competition by moving will predict that the crabs will be driven to move from where they are, so generating the continuous movement observed. Of course the rule of 'move to the best patch' will not necessarily mean that all crabs will move from east to west, as observed in the tagging programme. We imposed a movement rule, that given that a female crab wanted to find a better patch with less competition she could only choose the neighbouring patches to her north, south, northwest, west and southwest. This limit may seem arbitrary but was given a good biological basis by proposing that the female has to do this to ensure that her eggs are released in the west so that the current flowing east up the English Channel will keep her offspring in the appropriate habitat. This westward movement could also explain why they keep moving and one might expect a female to move less when already in the west than when further east up the Channel (Hunter *et al*., 2013). As our model covers an area, which is only 60 km wide, a large differential in the need to move west might not be expected. This behaviour is a prediction about the habitat and its relation to the future fitness of the individual incorporated into the adaptive behaviour of the crab.

Sensing - Crabs were able to sense the substrates of the neighbouring patches and how many other crabs were on the same patch as themselves. How they did these tasks is not explicitly modelled, they just 'know'.

Interaction - Crabs interacted with each other on a given patch. When they looked around for a new patch to move to, they looked at not only the substrate type but also how many other crabs are on the new patch and then choose the 'right' substrate with the fewest competitors and at the 'right' depth. The model did not deal with the exact mechanism of the competitive interaction between individuals. This could have been by direct interactions over food or by resource depletion both of which happened at a scale below that of the model.

Stochasticity - A random number generator was used to determine whether or not a crab would die on a given day and the same is true for the capture of crabs in pots. This introduction of a stochastic element represented the chance of death by natural causes and the fact that the crab encountering a pot was to some degree due to chance.

There was also stochasticity in the realised daily temperature and the realised temperature during the larval phase of the life history. The random element in daily temperature introduced stochasticity into whether or not crabs stopped moving and buried in the sediment which was temperature driven.

Collectives - The initial development of the model had no collectives that acted as a unit. There were size classes of crabs but these did not behave as a group.

Observation - Output from the model, included crab catches, the rates of crab movements by size and the distribution of crabs over the IPA by size. Detailed catch per day, per vessel data is output to an Excel file for every day of the year and year of the simulation, which can then be analysed.

Details

Initialisation

Each run started with a predetermined number of crabs, which was set on sliders on the NetLogo interface. The crabs were located randomly across the modelled area. Sliders also set the temperature below, which crabs bury, and additionally, the probability of each size of crab being caught. A final slider set the level of natural mortality. The model is ran for 6 years to allow for the 5-year temperature/recruitment program to take effect before recording outputs.

Input data

Whether or not a patch was in or out of the IPA, or on land, was defined by a colour code read from a data file. Seabed type, depths and temperatures were also read from a file. The number of pots on each patch was also input from the data file.

Submodels

Crab movement - For all types of crab, female, large/small, the individual first found out how many other crabs were in the same patch. The number then determined the probability that the crab would move or stay. Given that it was going to move it searched the patches in the arc that is 180ª to the west of it and then moved to the patch with the most appropriate substrate and with the least number of crabs. If the neighbouring patches had the same substrate as the current patch the crab was on, it chose which patch to go to at random. There were separate rules for each size of crab. Small crabs for example were biased towards moving into shallow water whilst the large crabs went for deeper water. Females move towards a suitable substrate to bury themselves when the temperature dropped below a set value determined on a slider and once buried ceased moving until temperatures rose again in the spring.

Crab catch - After the crabs have moved, the catch sub-model came into effect. For each crab, if it had landed on a patch containing pots it was subjected to a probability of capture. The sub-model kept a tally of how many crabs had been caught by all the pots on a patch in one day and once a maximum had been reached (pot saturation) the probability of a crab being caught fell to zero. The next day the probability of capture returned to its set level (assuming fishers have emptied the pots).

Fisher behaviour - The model worked on the assumption that all traps were cleared each day. Although this is not true, the outcome was the similar enough to modelling the real fishing pattern of each fisher.

Natural mortality - At the end of each day, each crab had a probability of dying from natural causes. For each individual crab a random number was selected and if it fell below the critical value set on a slider, the crab died and was removed from the fishery. If a crab landed in one of the patches on the westerly or southerly edge of the modelled area, it always died, so simulating the loss of crabs from the system, as they moved in a westerly direction through the area.

Generation of new crabs - The final element of the day's business was the generation of new crabs. These appeared on the eastern and southern edges of the modelled area and they had a size distribution determined at first by the slider settings but thereafter by the numbers recruiting from the previous year. The number of new crabs immigrating was a variable that could be altered at the initialisation.

We could have a number exactly replacing those removed that day from the stock in the modelled area, either by fishing or natural mortality, or the input of new crabs could be lower or higher than the numbers lost. This input of new crabs was a critical variable in how the system worked, as sustainability assumes that the input of new crabs is sufficient to maintain catches on a stable level, or at least fluctuating about a mean that has no upward or downward trend. The input of new crabs was changed to achieve stability in catches and then the immigration rate necessary to achieve this was matched with immigration rates obtained from the tagging programme (CEFAS MF1103, 2008). If the latter are not sufficient to maintain the fishing rate then we have a measure of the sustainability of the fishery.

The Netlogo interface and 'world'

The visual output of the Netlogo world without crabs covering the area is displayed in Figure 6.3. The world also shows the seasonally open and closed zones of the IPA and the spatial distribution of fishing vessels.

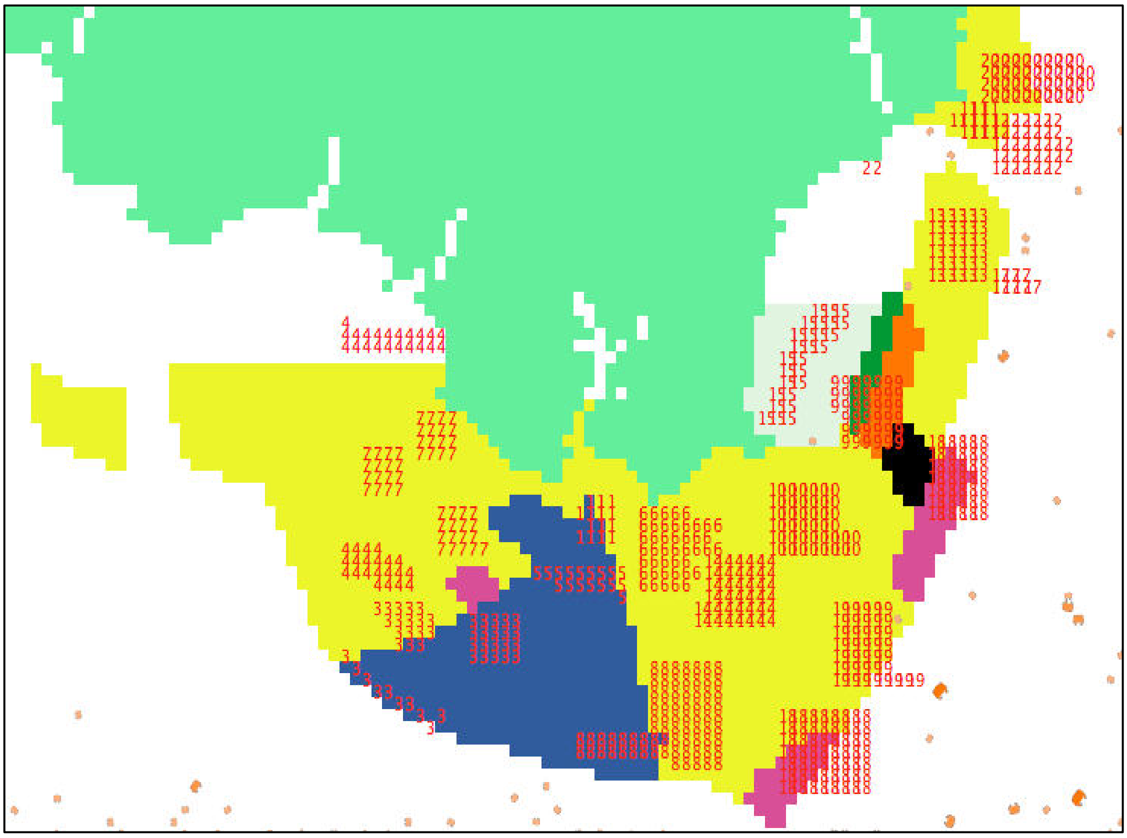

Figure 6.3. Screen shot of NetLogo 'world' showing the IPA area colour coded to signify when the area is available to crabbers. Light green is land. White areas are open to anyone whilst yellow areas are only ever open to crabbers. Other colours signify areas that are open to towed gear for some of the year (See Chapter 1). The numbers in red display the spatial distribution of the vessels in the IPA.

The complete Netlogo interface is shown in Figure 6.4. The interface includes sliders (in green boxes) which can be adjusted at the initial set up of the model to vary values of factors such as mortality, the number of recruits entering from the east and south, fishing mortality and the temperature at which crabs will hibernate. The beige boxes indicate outputs from the model such as graphs of catch and number of crabs in the world at any one time, additionally there are counters showing the total number of crabs in the world and total catch.

Figure 6.4. A snapshot of the model after 10 years and 275 days. The sliders in green boxes are adjustable at the set up of the model: m=probability of natural mortality per day, q1-3= probability of being caught per day, hibernation-temperature= temperature at which crabs do not move, recruits1-3= number of crabs immigrating from the east, recruits1s-3s= number of crabs immigrating from the south. Beige boxes show outputs such as: Current Year= current year of the models simulation. Catch graph= total number of each size class which has been caught per day (Blue=R1 (Small), Red=R2 (Medium), Green=R3 (Large)), Number of crabs= Total number of crabs in the 'world' on any one day. SS & hibernation temperature=Constant blue line= Hibernation temp set by slider, Red Line=

variation of sea surface temperature from input file, stepped blue line = sea surface temperature five years previous to the year shown. Number of crabs= number of crabs present in the 'world' categorised by size (Blue=R1 (Small), Red=R2(Medium), Green=R3(Large).

The Netlogo 'world' also has layers of bathymetry (Figure 6.5.) and substrate (Figure 6.6.) coded from an input file as seen below. Overlaid on to these maps is the spatial distribution of vessels fishing for crabs in the IPA (also Figure 6.7.). These layers are not visualised whilst the model runs but each patch contains information of substrate type and depth, which affect crabs behaviour.

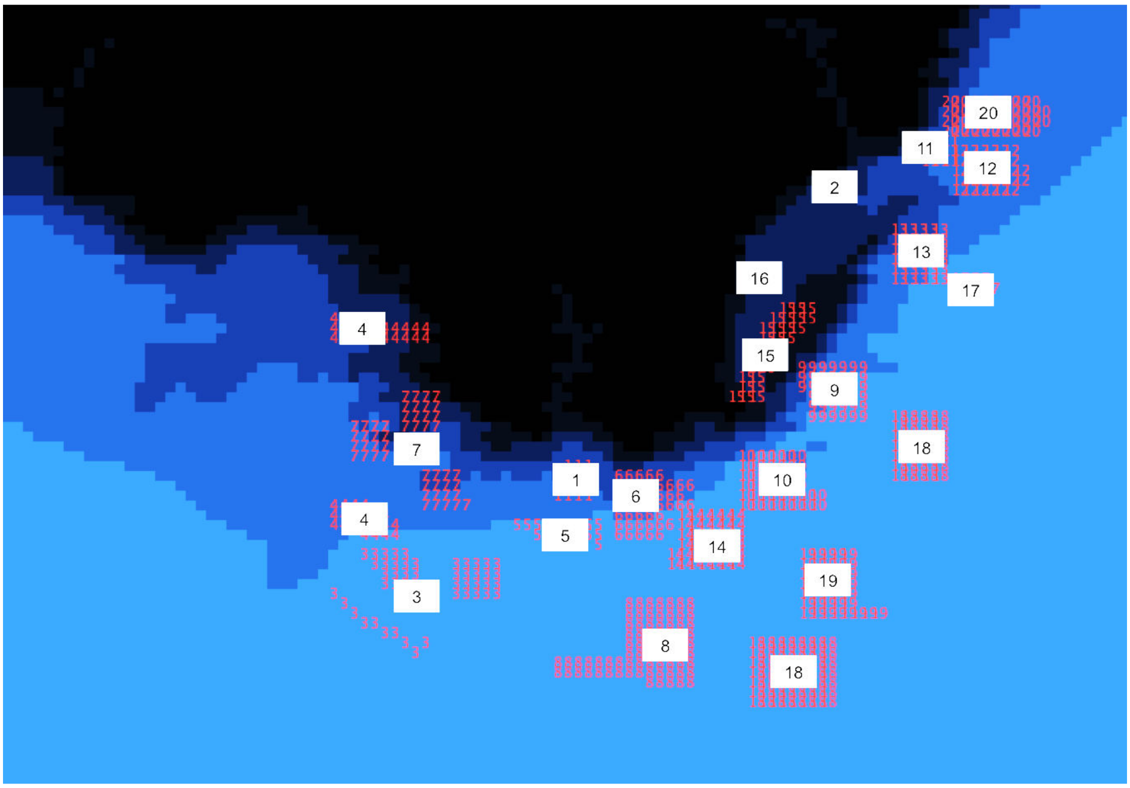

Figure 6.5. The modelled world displaying the spatial distribution of vessels and various depth contours within the IPA. Land = black, navy= <20m, pale navy= 20-30m, mid blue= 30-40m, palest blue >40m.

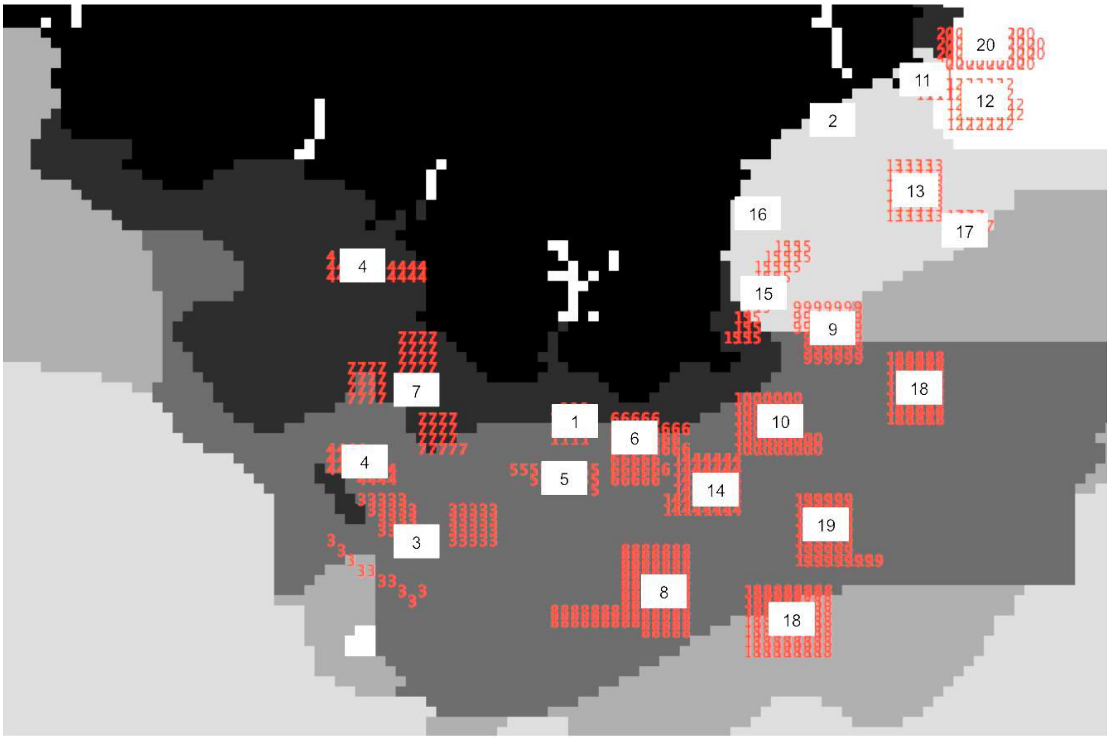

Figure 6.6. A map of the substrate types within the IPA. Darkest grey is rock, the next shade of grey down is gravelly sand, the next down is slightly gravelly sand, the next sand, the next muddy sand, then sandy mud and the lightest is mixed sediments.

The spatial distribution of all the fishing vessels within the IPA is shown in Figure 6.7. The 20 vessels and their corresponding fishing 'territories' were taken from Clark (2008) and verified by the SDSCA fishers. The four vessels, which contributed data from long-term fisher's diaries from Areas 1, 1a, 4, and 5 are referred to as Vessels 4, 7, 8 and 10 in the model. These vessels are all grouped in the west of the IPA this should not convey any confounding variables as the vessels are on a variety of substrates and fish at numerous depths. Nevertheless, these were the only diaries we could access. As we have 10 years of real landings data we can compare this to the outputs of the model to assess the ability of the model to recreate the catches seen in the real world.

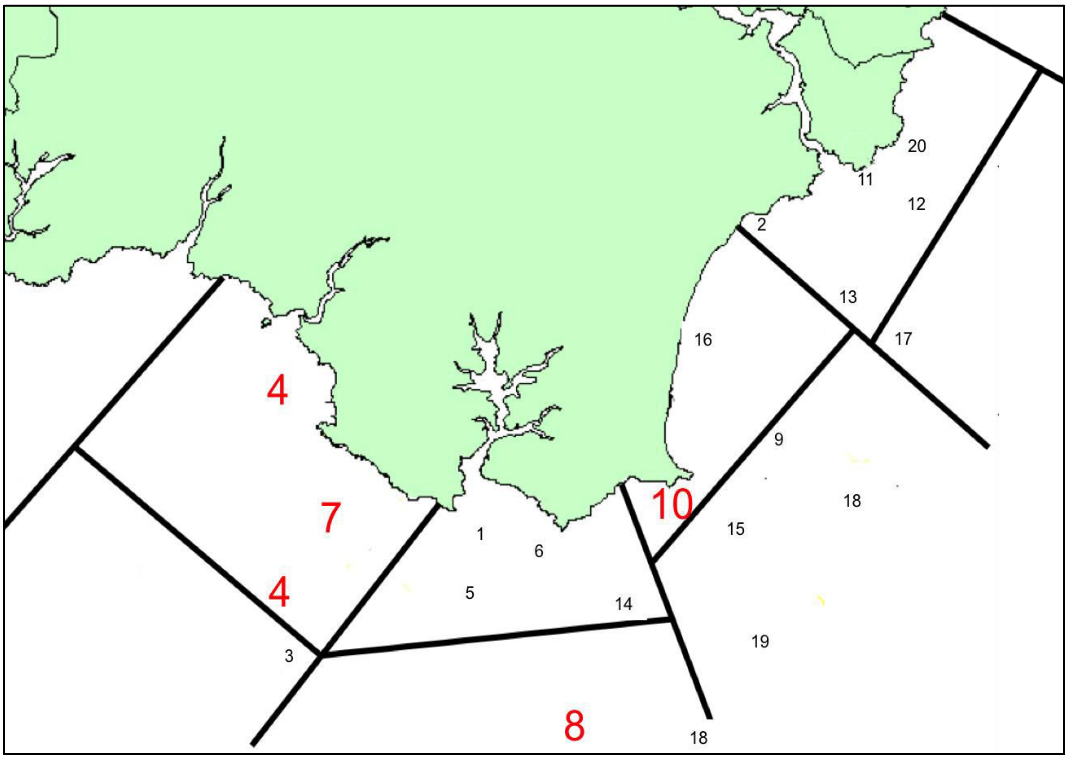

Figure 6.7. The spatial distribution of vessels within the model. Repeated numbers (i.e. 4 and 18 show fishers with two sets of gear). Red numbers indicate those vessels that contributed fisher's diaries (Vessel 4 = Area 1, Vessel 7 = Area 1a, Vessel 8 = Area 4, Vessel 10 = Area 5).

Outputs of the model

To investigate if the current model outputs are congruent with that of empirical data from landings recorded we compared the catch per day output of the model with real data from 10 years of fisher's diaries. The model was run for 16 years. The model does not employ the submodel for the relationship between temperature and number of recruits until year 6 as any given years recruitment is linked to the sea temperature 5 years previous. Therefore to gather a 10-year data set we ran the model for 16 years only analysing years 6-15. Below are the model's catch per day outputs for each vessel (n=20) which fishes in the IPA (Figure 6.8.).

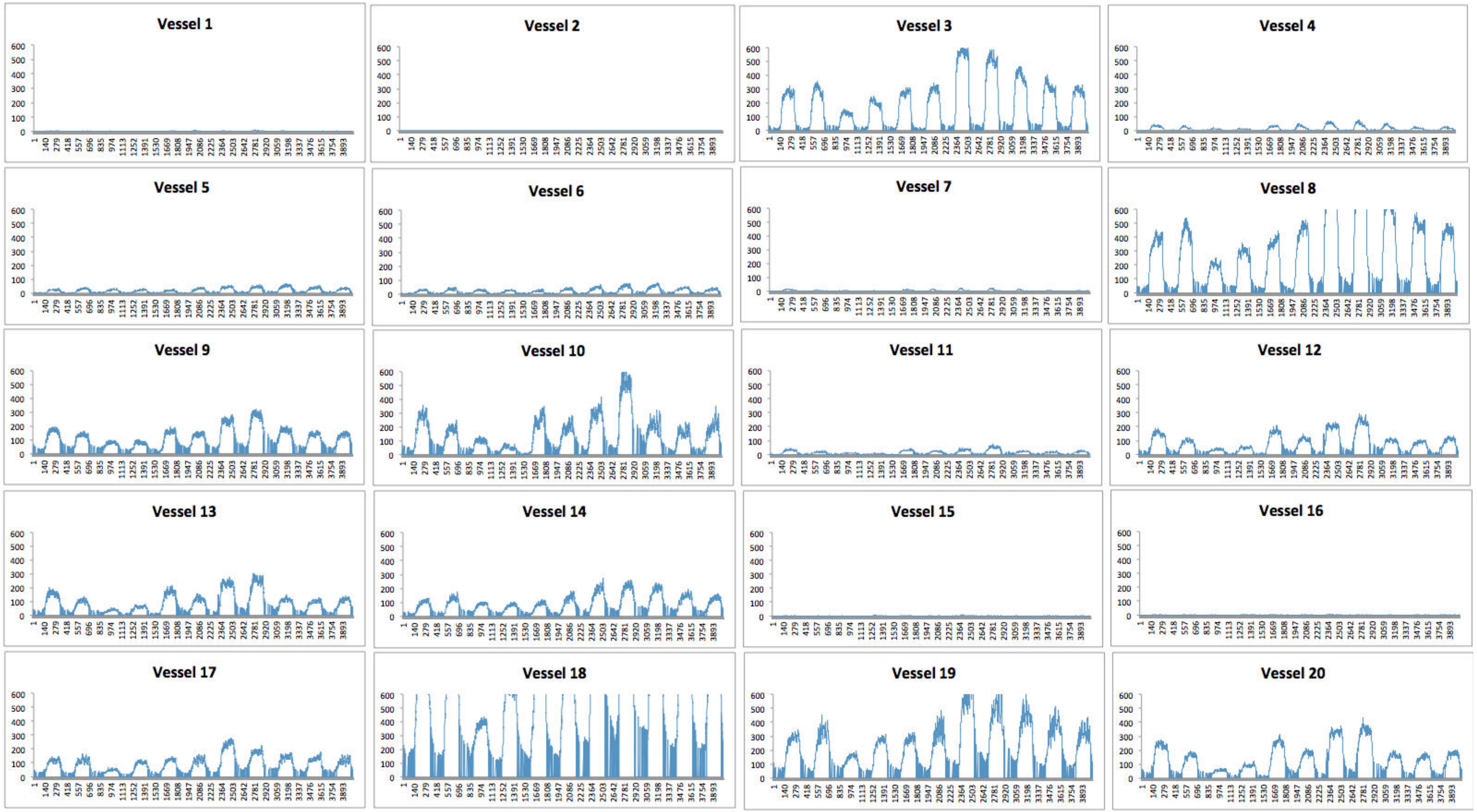
Vessel 1
Vessel 2
Vessel 3
Vessel 4
Vessel 5
Vessel 6
Vessel 7
Vessel 8
Vessel 9
Vessel 10
Vessel 11
Vessel 12
Vessel 13
Vessel 14
Vessel 15
Vessel 16
Vessel 17
Vessel 18
Vessel 19
Vessel 20

Figure 6.8. The total catch per day, per vessel of crab over a 10-year simulation. The x-axis shows day number and y-axis number of crabs caught per day. For ease of comparison the y-axis is scaled to 600 crabs per day. Vessels 8, 18 and 19 exceeded this range, with catches peaking at 1710 crabs per day.

The graphs indicate the spatial distribution of the crab within the modelled world. The positions of the vessels can be seen in Figure 6.7. The graphs clearly demonstrate that the vessels (8,18 and 19) which fish on the southeastern edge of the IPA have the most exposure to immigration from the south and east and have by far the highest catches per day. Conversely, those vessels, which operate furthest inshore (1, 2 6, 11, 16) and in Bigbury Bay (4 and 7) display the smallest catches. Lower catches are likely seen in inshore areas as the patches further offshore have caught high numbers of crabs, further explanations could be the preference of only small crab for shallow inshore depths and a unsuitable substrate. This is congruent with the results demonstrated by onboard data on Chapter 3 with the least female LPUE being caught 0-3nm from the shore compared to 3-6nm from the coastline.

Three size classes of crabs are used in the model (Blue=R1 (Small), Red=R2 (Medium), Green=R3 (Large)). The catch per day per vessel of each of these size classes can be seen in Figure 6.9.

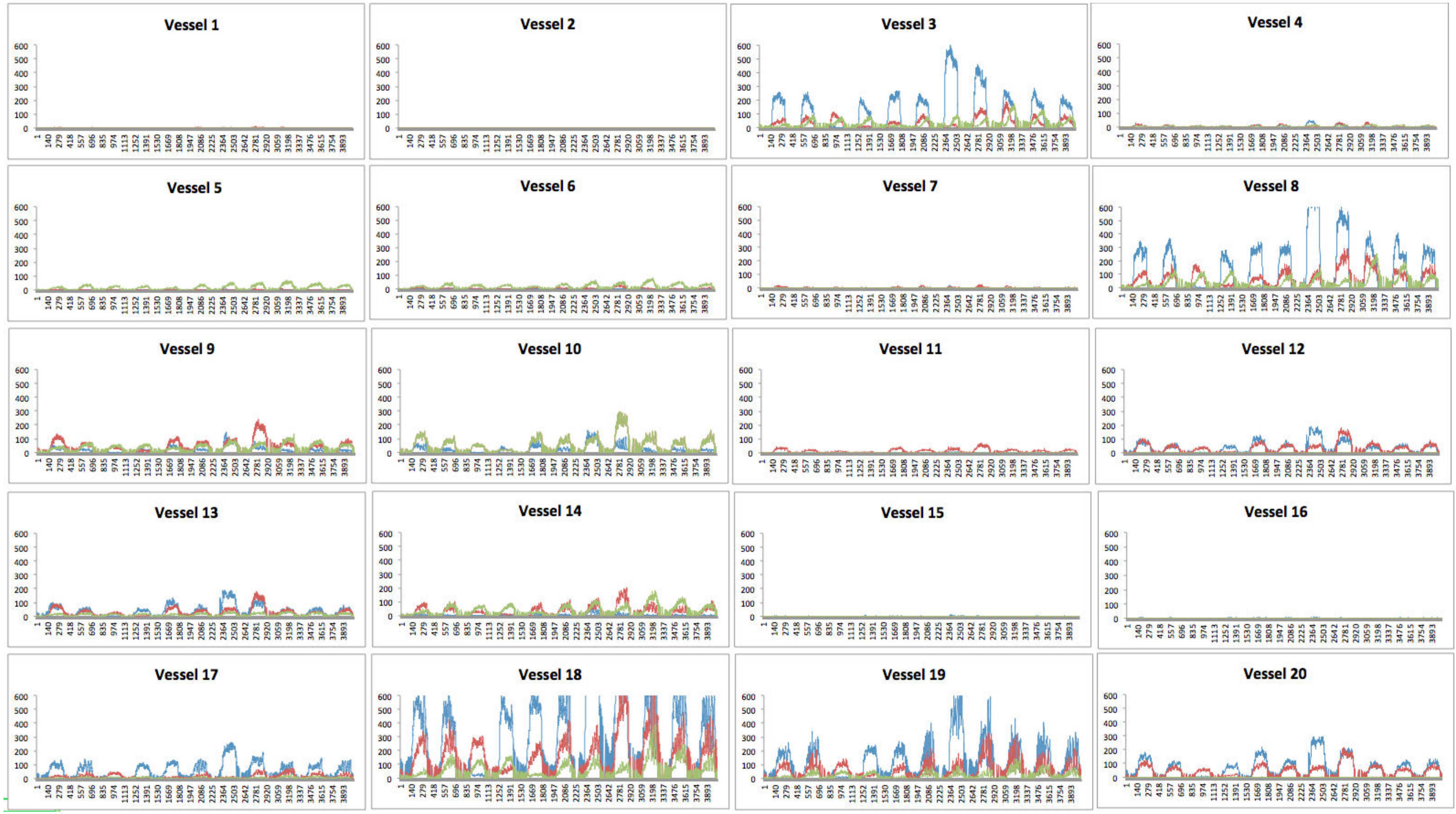
Vessel 1
Vessel 2
Vessel 3
Vessel 4
Vessel 5
Vessel 6
Vessel 7
Vessel 8
Vessel 9
Vessel 10
Vessel 11
Vessel 12
Vessel 13
Vessel 14
Vessel 15
Vessel 16
Vessel 17
Vessel 18
Vessel 19
Vessel 20

Figure 6.9. The total catch per day, per size class, per vessel of crab over a 10-year simulation (Blue=R1 (Small), Red=R2 (Medium), Green=R3(Large)). The x-axis shows day number and y-axis number of crabs caught per day. For easy of comparison the y-axis was scaled to 600 crabs per day.

The size class distribution largely reflects the depth contours of the IPA, for example the highest numbers of 'large' crabs were caught by the outer most vessels (3, 8, 18, and 19). This is likely due to the fact that the model codes for crabs of small size to choose the shallowest depths, medium size to have a preference for depths 20-30m and the largest sized crabs to prefer the deepest depths in the IPA.

To directly compare the data from fisher's diaries to the model's outputs we plotted the kilogrammes per day of vessels fishing areas 1, 1a, 4 and 5 over a ten year period and compared these graphs with the number of crabs caught per day in the model for vessels 4, 7, 8 and 10 respectively (Figure 6.10.).

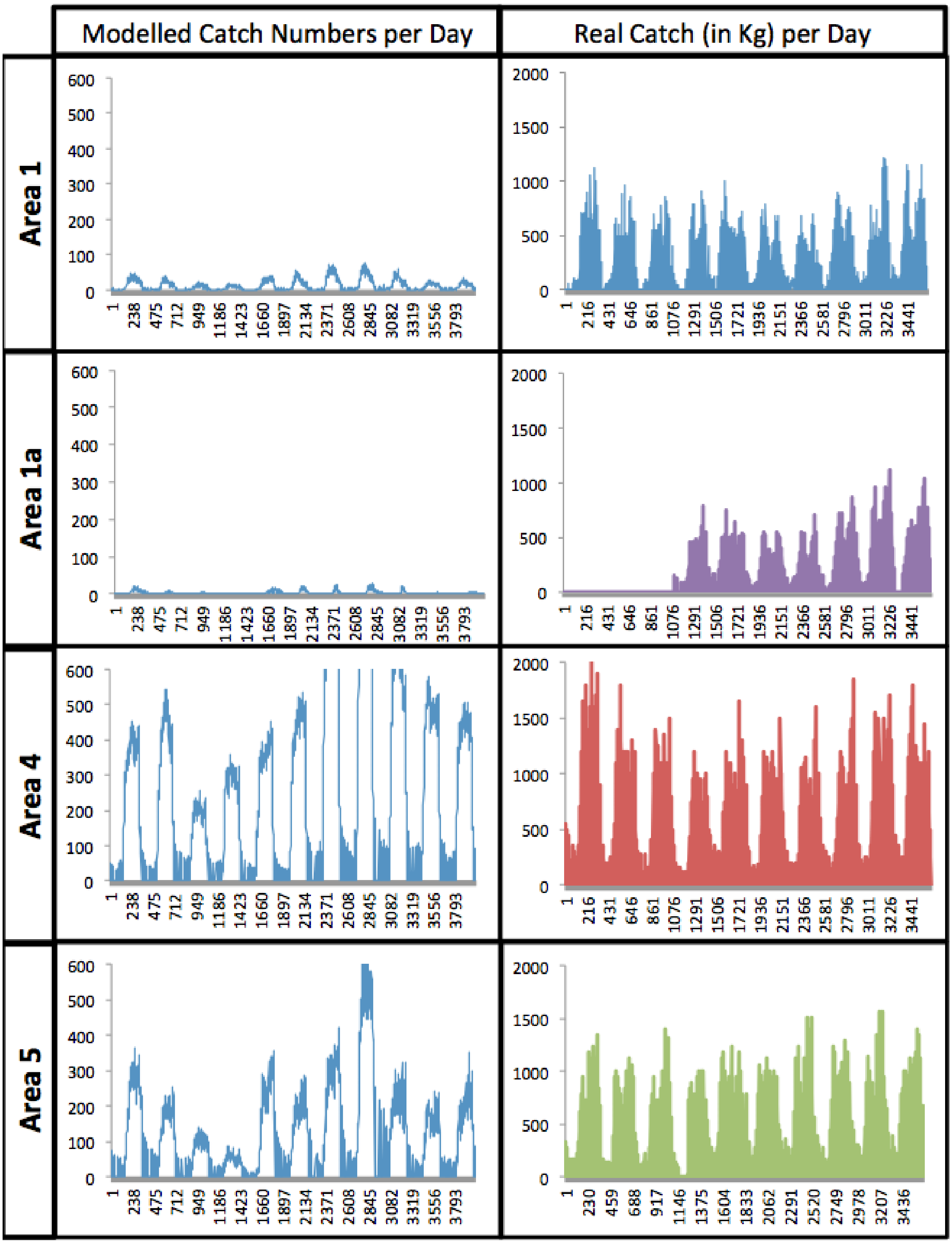

Figure 6.10. The modelled catch and real catch data per day. Left column= Modelled catch data for a 10 year run. Right column= Data from fisher's diaries showing 10 years worth of landings data. N.B. The modelled catch data is recorded in number of crabs caught and the fisher's diaries data in kilogrammes per day. The temperature regime at the time a year class was formed is the same for the modelled and actual graphs.

The model does not demonstrate a true reflection of the number of crab we estimate to be inside the IPA at any one time and is set to model approximately 10% of the whole population due to limitations of computer processing power. Consequently, we can only compare the relative patterns of catch between the modelled and real data.

Areas 1 and 1a demonstrate much lower catches than Areas 4 and 5, this is reflected in the data gathered from fisher's diaries. This finding shows that the spatial variables that affect crab distribution within the model, namely depth and substrate are recreating a similar catch pattern to the empirical data.

Further, to elucidate the annual pattern of the catch we plotted the average catch per day over a 10 year period of simulation from each vessel and compared this to mean monthly real landings data over a 10 year period from Areas 1, 1a, 4 and 5 (Figure 6.11.).

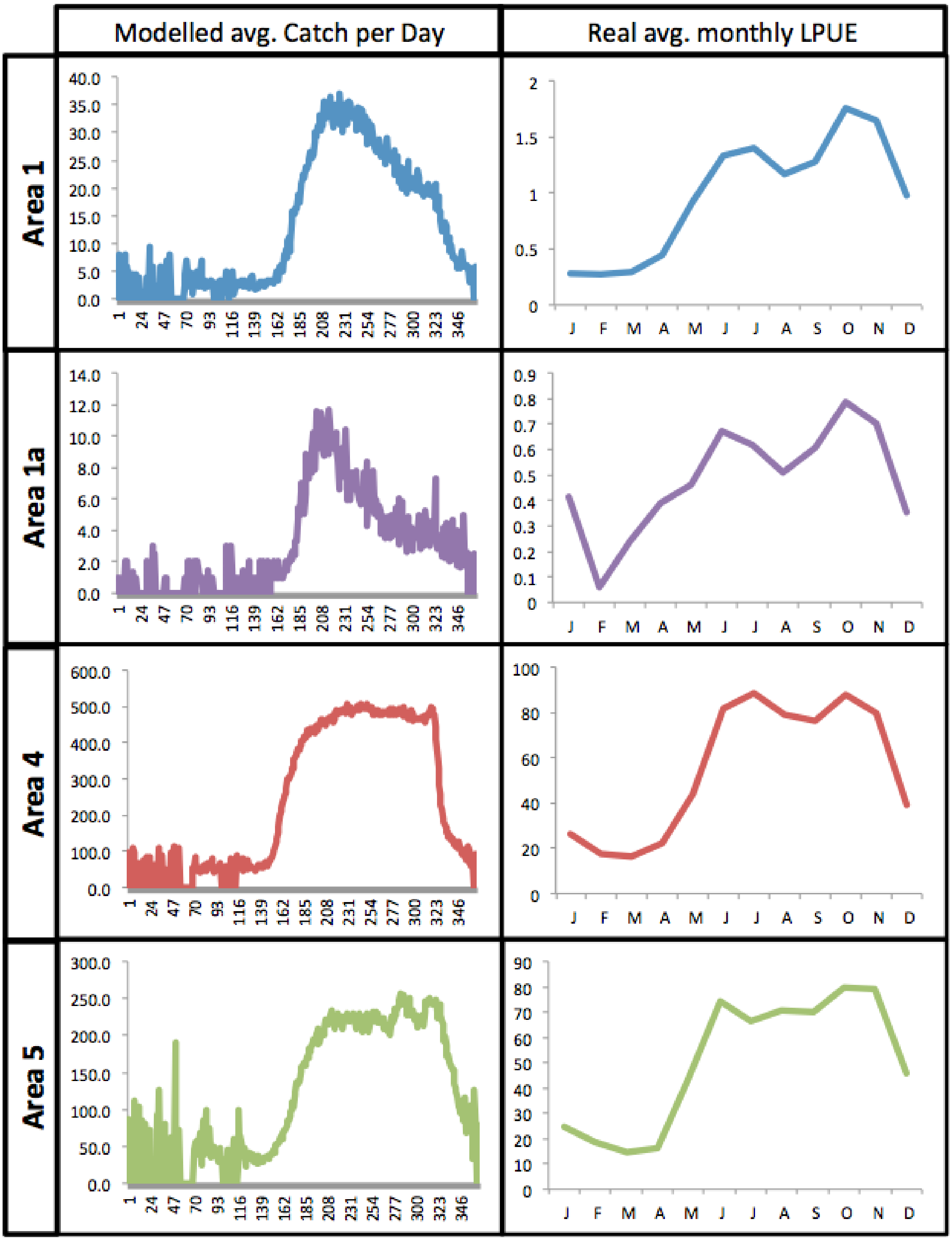

Figure 6.11. The average catch per day over a 10-year period of simulation from each vessel compared against mean real landings data over a 10-year period from Areas 1, 1a, 4 and 5. Left column= Modelled catch, Right column= data from fisher's diaries. X-axis for the modelled data is in days whilst it is in months for the recorded data.

These comparisons indicate that the pattern of average landings in the modelled and real data are similar and therefore we can conclude that the sea temperature is a major driving factor in the modelled simulation as it is in the real data (See Chapter 4). It should be noted that the model outputs do not display a temporary reducing in catches during the summer months (June-July) as seen in the empirical data. In reality this dip is observed due to the onset of a large proportion of the female population becoming soft-shelled and not feeding, consequently reducing their catchability. The model does not simulate this aspect of the crab's life history and as such there is not a reduction in catches over the summer months.

Discussion

We have demonstrated that this model can aggregate the catch and environmental data on depth, substrate type and sea temperature to produce an initial model that produces a satisfactory match between real data and the outcomes produced by the IBM. So far the factors, which have had the most impact on the distribution of females are the movement in a westerly direction and the effect of sea temperature on the instigation of hibernating behaviour of females and the recruitment of new crabs to the fishery.

How could the IBM benefit fishers?

The model we have created will benefit the fishers in a number of ways. Firstly, if the fishers decide to implement the model for its intended purpose of setting seasonal quotas per vessel, this would demonstrate that the fishing mortality rate in the IPA is sustainable. This will be in addition to the sustainable status of the larger western English Channel stock, as assessed by CEFAS (2014). Secondly, some fishers have already stated during semi-structures interviews (Chapter 5) that it is likely that they would not use the model for the purpose of calculating quotas, but would use it to gain credibility with authorities such as CEFAS, MMO, IFCA and DEFRA, to demonstrate that the SDCSA fishers are being proactive in researching the sustainability of their fishery. This type of evidence could also contribute towards fishers gaining a higher price for their catch as they could apply for a number of eco-label certificates or create their own using output from the model as part evidence for sustainability.

Comparison with other studies using an IBM to model crab behaviour

The only study in the literature to utilise an IBM model to research the dynamics of crab behaviour with their environment was that of the South Carolina Blue Crab Regional Abundance Biotic Simulation Project (SCBCRABS). However that project did not publish results and therefore comparisons between the two studies cannot be made.

Criticisms

There are a number of deficiencies of the model's development:

- The overarching aim of the project was to co-operatively develop a model with which fishers could manage their own fishery in a sustainable manner by setting catch quotas. P. J. B. Hart developed the model with input from the lead author. The participation by fishers in the development of the model was as feedback at several stages of the model's development. If all stakeholders designed the model by a truly collaborative method then fishers and scientists would have co-developed the model during all phases of design including the aims, the methods and dynamics of the model. However, the building of the model has been a medium for the improvement of communication between fishers and scientists creating a feeling of unity and comradeship.
- Due to the reasons detailed in Chapter 2 we did not approach the local management authority (Devon and Severn IFCA) at the outset of the project as to whether any model we developed could be incorporated into the future management of the IPA. This was an oversight and all stakeholders should have had equal input into the model from the beginning of the project to give it the most favourable chance of being used in the real management context.
- The model, like all IBM's, is a simplification of the real world and as such does not account for certain elements of the fishery, for example the behaviour of male crabs, predation and other abiotic variables.
- Likewise it is impossible to entirely recreate the marine habitat within the confines of a model, however this paper used the best available data.

Future Work

Currently a robust stock-recruitment relationship needs to be established so that the model can reach its final form and be used to predict sustainable quotas. Until such a relationship is available the model will remain as a tool to test the influence of a variety of factors on the dynamics of the fishery. An example would be a better understanding of the effects of varying sea temperatures on catches. The final iteration of model will eventually be published, peer reviewed and presented to the fishers, who can then decide if they would like to implement the model in its intended state. If fishers do decide to implement the model to set quotas for their future season's catch, we will provide them with the best practices on how to collect catch data for the model and in the future provide the facility to incorporate these data, run the model on a super computer, provide the fishers with the model's outputs and provide a method of facilitating the fisher-directed stock assessment (see Chapter 7).

Wider implications

A wider implication of this study was the change in relationship between fishers and scientist created by working together on the model and the wider project, which included the provision of data, the collection of data at sea and scientists providing detailed results back to fishers. In essence this study has laid the foundations for future truly collaborative research projects based on the ethos of the GAP2 Project in the IPA.

Other crab fisheries incorporating their local data on abiotic environmental factors and catch rates, could with alterations use this model to understand more thoroughly the dynamics and sustainability of their fishery. This would be especially useful in small-scale fisheries where management resources are scarce.

Conclusion

We have demonstrated that by developing an IBM, a relatively inexpensive and relatively fast method of data collection on board fishing boats, it becomes possible to produce a workable method for fisher-directed stock assessments.

The model has enabled the dynamics of the fishery to be visualised and described in a way that could not have been done previously. In particular the modelling process has enabled fishers to get a fishery-wide view of the dynamics of crab movement rather than knowledge of the dynamics of their own 'territory'. The model sets the foundations for future research, which can use the model to explore the effects of environmental, ecological and sociological factors on the dynamics of the fishery. For example, the model could test the impact on the fishery of the currently designated MCZ's areas of the IPA if they were to become No Take Zones. Other investigations could examine the effects of warming sea temperatures on the fishery or the increase of fishing mortality on crab abundance. Even in its current state the model allows scientists and fishermen to share their knowledge of the fishery by using the visual element of the model as a tool, to watch their hypotheses being tested, engaging them in the science and creating further discussions and understanding of the workings of the fishery. For now and in the future the south Devon crab fishery model will remain in active development.

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Chapter 7: General Discussion

The ports of Salcombe and Dartmouth, in Devon, account for 59% (£18.9 million) of the total value of UK crab landings (MMO, 2012) and in the past, the Devon crab fishery has been responsible for the highest catch per unit effort (CPUE) in Europe (Brown and Bennett, 1979). Despite the prominence of the fishery, an overall lack of catch data means that the degree to which commercial exploitation is affecting crab stocks is still difficult to quantify (Bannister, 2009). Further, the IFCA's responsible for the management of local fishery's are grossly under-staffed and under-resourced with an annual budget of just £694,000 for the region at the focus of this thesis (DSIFCA, 2016). The results within this thesis extend the knowledge of catch, landings and discards data in the IPA, initially recorded by Brown and Bennett (1979) and creating possibly the most detailed annual series of crab landings and discards data in the UK. In light of the above information and the increased potting effort in recent years (Bannister, 2009) we have created an approach enabling the exploration of how the crab population and the fishery interact, as well as a tool that can be used to better understand the abiotic factors that affect the fluctuations in the fishery, by using a method of data collection which can be inexpensively and relatively quickly incorporated into daily fishing activity. It is hoped with further work to the model, we could achieve an approach that enables a fisher-directed stock assessment and quota setting system.

We set out to and have successfully set the foundations of a practical demonstration of an approach, which extends from data collection through to how fishers can manipulate the model to understand the outcomes of changes to abiotic factors such as sea temperature and also fishing activity i.e. increase in effort or closing areas. The knowledge and information contained within this thesis could be applied not just to the IPA but also with some adaptation to other small-scale fisheries, especially where resources for research and management are scarce.

In pursuit of our objective to create a self-management system we spatiotemporally mapped the distribution of male and female crabs caught, landed and discarded in the IPA over the annual cycle (Chapter 3 and 4), we interviewed local fishers to comprehensively record their detailed local knowledge of the resource they exploit on a daily basis and compared these observations to empirical data and scientific knowledge in the literature so validating the use of FLEK for local management (Chapter 5). Later, we scrutinised the way we worked with fishers throughout the project to highlight the successes and areas for improvement that we encountered whilst working using a bottom-up collaborative approach (Chapter 2). Lastly, P. J. B. Hart collated the knowledge and data collected throughout the project to develop an Individual Based Model (IBM) of the south Devon fishery with input from the author and SDCSA fishers. This thesis details the information, which was input into the model, why the IBM method was appropriate for this context, and evaluated the strengths and criticisms of the model (Chapter 6). All of these objectives were complimented with the values of the GAP1 and 2 Projects of working collaboratively with fishers.

Seasonal and temporal variation of south Devon fishery

Brown and Bennett (1979) presented an in-depth overview of the spatiotemporal distribution of catch and landings of crab within the IPA in the 1970's. Since this time there has been no research on the catch rates of the crab fishery and therefore despite the crab in the western English Channel currently being exploited at a level to produce MSY (CEFAS, 2014) there has been an increase in fishing effort (Bannister, 2009). To assess the current situation in the IPA we collected, and have presented the results of fine-scale catch, landings and discards data, gathered onboard fishing vessels over the most productive part of an annual cycle (July to November and April to June), with the ultimate aim of using the data to establish the catch rates that the individual based model should reproduce.

This comprehensive data set of catch, landings and discards complimented by fisher diaries allowed the spatiotemporal mapping of the fishery and a much-needed update since the 1970s. The results highlighted areas of high and low catches, landings and discards and the seasonal pattern of catch of both sexes of crab. We established the affects of abiotic variables such as temperature, bathymetry and substrate on CPUE, Landings per Unit Effort (LPUE) and Discards per Unit Effort (DPUE). The value of such results are that they set the foundation of catch rates which the IBM should reproduce, and ensuring that the quotas to be set for fishers relate to the catch levels experienced, thus helping to create a sustainable fishery. Supplementary benefits are that fishers could use these data to demonstrate their catch, landings and discard rates to management authorities when measures such as MPAs and MCZs and other fishing limitations are consulted upon, rather than relying upon NGOs and other non-fisher organisations to carry out their own research.

Comparison of FLEK to empirical data

In the four-year duration of the GAP2 Project we had extensive informal interactions with fishers, and also formally collected their knowledge. Chapter 5 reports the results of a semi-structured interview answered by a subset of fishers to record their FLEK. The results of these interviews compared fishers knowledge with the scientific literature, empirical data collected onboard vessels and 10 years worth of fishers diaries donated by fishers. The results demonstrated that fisher's predictions from years, and often, generations of observations of crab stocks were accurate and correlated with the current scientific understanding of the topics researched (sea temperature, substrate type and wind direction and pot efficiency). The implications of this research was that FLEK can be used as a valid methodology to use in local management to support data collected by scientists or as a stand-alone dataset.

FLEK where relevant was also used develop the IBM. This knowledge was essential, as it was not always possible to gather our own data or long-term datasets on variables, which were required for the model for example sea surface temperature.

This bottom-up method of gathering knowledge is not only cost saving to the regional IFCA but also increases face-to-face communications between fishers and managers and fishers and scientists, which we have demonstrated to led to solid relationships built by the continuity of contact and trust. Additionally the opportunity for fishers to divulge their FLEK led to a feeling of empowerment, as they were able to contribute to a management system regarding the resource they fish and were being 'listen too' for the first time. As stated by Dubois *et al.,* (2015), 'the use of knowledge in this context is not only about the validity of knowledge claims, but increasingly about mobilising knowledge in support of fishers' participation in management discussions'.

Lessons from stakeholder engagement

The main aim of the GAP2 project and this thesis was to bring scientists, fishers and policy makers together to solve common sustainability issues across Europe. An outcome, apart from the data and knowledge gathered, has been the empowerment of fishers, who have come to understand the value of collaborative research, as have the scientists during the course of this work. It is difficult to capture the nature of this empowerment using Traditional Science Communication (TSC), nevertheless, fishers have increased in confidence in communicating with scientists, they offer ideas for new research and openly suggest abiotic or crab behaviour related explanations for the results we have found. After the GAP2 Project some fishers, have become involved in projects such as Fishing into the Future (fishingintothefuture.co.uk), the Secchi Project (secchidisk.org) and research at other universities. This is a major change from their attitude to scientists and managers before the GAP2 Project, when fishers would occasionally offer to collect data or take academics to sea or to assist management authorities. While we concede that this study has not been truly collaborative and in part has been heavily scientist-led it has nevertheless markedly empowered and encouraged fishers to be involved in the management issues that impact upon their fishing activities, rather than just accepting top-down imposed measures.

To aid future researchers wishing to work by a collaborative approach with fishers we analysed the day-to-day mechanics of working collaboratively and extrapolated the reasons for success and areas where engagement could be have improved (Chapter 2). This type of knowledge is not usually concretely described in the literature, as only the scientific results are published in similar participatory studies. This strong relationship led to better access to data (such as fishers diaries data), detailed and reliable FLEK, as fishers were happy to give us this information, because they trusted in our research values and intentions and therefore ultimately a more representative IBM.

Integrating bottom-up approach into IBM model

Chapter 6 evaluated the results of the previous chapters as inputs to an Individual Based Model that is being independently developed by P. J. B. Hart. The model recreates the dynamics of the female fishery to enable the exploration of ideas about how the crab population, the fishing activities and environmental variables interact within the IPA, with empirical data collected as described in Chapter 3 and 4, FLEK from Chapter 5 and information from the literature in Chapter 1.

Built in NetLogo the model recreates the dynamics of the fishery and can alter inputs such as environmental variables values (sea temperature, substrate type and bathymetry), number of crabs, fishing mortality and natural mortality to theoretically test for a sustainable fishing rate per vessel to set quotas. The IBM could be used to establish what the outcomes of other fishery-wide scenarios might be, for example, the model could test the outcome of the implementation of No Take Zones within the IPA or the effect of increased effort by the uptake the of latent capacity within the fishery on catch rates.

The largest implication of the model is that this thesis and the work of P. J. B. Hart in programming the model, with further work, will leave the fishers with a tool for the future, to enable them to demonstrate the sustainability of their fishery. This demonstration could be to the end-consumers so bolstering favourable public perceptions of the south Devon crab fishery i.e. the general public, identify south Devon crab to be a sustainable seafood choice. Further, if fishers desired they could create their own eco-label to secure a potentially higher price for the crab they catch if the data they self-collect and enter into the IBM indicates the fishery is sustainable. The creation of an IPA eco-label might be the motivation and incentive to get all the fishers of the IPA interested in using the model's outputs and decide to use the quota system, once the model is capable of producing these outputs in the future. In the short term the fisher could demonstrate their intentions and proactivity to fish sustainably, and use fishers diaries data to show the level of sustainability the fishery had over the past few years, leading to a higher price when selling their catch as a 'sustainably caught product'. This short-term extrinsic reward could then lead on to a sustainable fishery in the long term.

Future work

In order for the outcomes of this thesis to be implemented and realised we need to outline a robust plan of action. This plan is set out below:

How would fishers collect data?

The initial actions required to instigate the fisher-directed stock assessment would entail the organisation of fishers to collect their own data, via an easy and minimally time-consuming method. There are several viable options to fulfill this requirement, by use of an onboard observer, a smartphone application or an automatic data recording system.

The option that would be most easily installed in the short term would be an onboard observer who is employed by the fisher's association. Data would be recorded by the same method as used in this thesis as described in Chapter 3 under the heading '*Onboard data recording*'. By using a digital spreadsheet on a tablet device, simple catch metrics can be automatically calculated on a per pot, string and trip basis, saving time performing manual calculations on catch metrics and providing fishers with instantaneous feedback on their fishing activities to encourage further participation. The disadvantage of employing this method of data collection is that one observer is needed per vessel, per day. The typical length of time spent at sea per day is approximately 7-15 hours with only a fraction of this time spent by the fishers retrieving the catch from the pots, and the observer recording data. As a result the costs to employ the observer or observers required to collect data on all vessels would be considerable.

If the use of an observer was not applicable then a smartphone application to record the catch or other automatic catch recording facility could be used such as that described by Hold *et al*., (2015). We investigated the cost of collaboratively developing an iPhone application to record catch, landings and discard data per string, which would have been around £10,000 to completion (Appendix F). This method whilst initially expensive to develop, can be run simultaneously on every vessel in the IPA, every day without the time limitations of employing an observer. Fishers would self-report their landings of crab per sex at the end of each string, (as the landed catch is sorted into separate containers (known as 'bongos') as they are hauled) when they enter the wheelhouse to manoeuvre the boat to re-deploy the hauled pots. It is important to note that fishers already record these data for their own records in the form of fisher diaries and for MSAR forms therefore this would not be an extra burden on their activities. A method to record discards would need to be addressed, with discards perhaps retained until the end of the string and counted and discarded *en masse*. The app could theoretically record GPS locations of strings automatically, as well as perform the same simple statistics on catch data as the observer's digital spreadsheet. The limitations of the app method are largely technological, for instance there would need to be a data storage facility for the abundance of data collected with attached cost implications, a facility to overcome 3G internet and GPS blackspots in the IPA would be necessary and those fishers who do not possess an iPhone would need to be purchased (or provided) and possibly guidance given on how to use the phone and application.

A third option to record data would be that developed by Hold *et al*., (2015) at Bangor University. Their system used a video camera attached over the area where fishers empty pots. In this system the fisher holds each crab upside down under the camera for approximately 1 second so that sex and carapace width can later be determined from the video recording. The set up has the ability to allow the sex of crabs to be determined with 100% accuracy, and to allow the measurement of carapace width within ±0.8mm and can record all animals caught not just those landed.

However, the camera system currently only records catch and the recordings have to be manually analysed at a later date. Catch is sexed by visual assessment and carapace width is measured manually using computer software. The system does not have a function in place to distinguish between landings and discards but presumably if an individual were less than MLS it would be discarded. Further, the study does not indicate whether the number of soft discards can be obtained from the video record. A disadvantage of this non-invasive data collection system is that the videos are very time consuming to analyse. The most time consuming element being the 'grabbing' of the still image of each crab under the camera from the continuous video footage. According to Hold *et al.*, (2015) once the still images are collated each image takes approximately 5–10 seconds to measure for carapace width and to sex each crab. The time taken to analyse a vessels sample depends on the time of year due to variation in catch rates with sea temperature. For IPA vessels this could mean up to 6.5 hours analysis per vessel with catches of over 2400 crab, neglecting the time necessary to collect and deliver the camera to each vessel, 'grab' still images and so on. This method of data collection would be most favourable to IPA fisher's once further work to automate still image selection and artificial intelligence and computer learning has been developed to detect the shape of the crab carapace and therefore automatically sex crabs, and automatically measure carapace widths. This method of catch recording 'also mitigates issues surrounding self-sampling, primarily the belief that samples or reporting from fishers may be biased or not collected as rigorously as by onboard observers' (Kraan *et al.*, 2013, cited by Hold *et al.*, 2015).

The three proposed methods of data recording have been evaluated for their strengths and weakness' and it is likely the ultimate factor in the determination of which method will be implemented would be cost. Therefore, full cost-benefit analysis would have to be performed on all the options to determine the most inexpensive but effective method to collect a representative sample of the catch, including fisher's preference to a particular method due to operational/logistical reasons.

Nevertheless, all the proposed methods would require the employment of a 'Data Co-coordinator' for the fishery. Their role would include ensuring that all fishers contributed the minimum catch data requirements for the model to run, solve technical issue relating to data collection and storage, distribute quotas once they are established, compare landing records with quota recommendations to assess whether fishers are complying with their quota share, and if necessary discipline and educate those who fish above their quota.

The SDSCA recently employed an Executive Officer whose role it is to 'fully brief the management committee in matters of interest to them and to ensure that the views of the wider membership are appropriately voiced in marine networks, both local and national, as well as ensuring the smooth running of local matters' (linkedin.com/in/beshlie-pool-43abb024). It would be our suggestion that the Executive Officer could also undertake the roles necessary for the fisher-directed stock assessment system to operate.

What are the logistics of running the model?

Fishers would require assistance to run the model on a supercomputer due to the number of individual crabs within the model and the processing power required to permit the model run, this assistance could be provided by the authors at the University of Leicester.

How is the stock assessment performed within the model?

Once catch data is collected and collated it would be entered into the model to set daily probability of capture per vessel within the IBM to set the removal of crab from the fishery (as fishing mortality), as described in the 'ODD Protocol' in Chapter 6. However, to calculate probability of capture from catch rates we would also need to establish an estimate of crab abundance in the area, which would need to be researched extensively with fisheries independent underwater transect surveys to produce a good estimate for the whole IPA stratified for time of year (sea temperature), depth and substrate (see Chapter 4). Furthermore, moving forward we would also need a method to predict the year class size for incoming immigrants and a stock-recruit relationship.

If the model produced catch rates less than or equal to the inputs of reproduction and immigration rates this would indicate a sustainable fishery. Conversely if the landing rate (plus emigration and natural mortality) is higher than reproduction and immigration rates then the fishery is not sustainable. Depending on the balance of input (reproduction and immigration) rates verses outputs (natural and fishing mortality) catch quotas would be assigned to each vessel to adjust future catches to maintain or create a sustainable fishery.

Current limitations to the model and what needs to be finalised?

There are several aspects of the model yet to be implemented and finalised in the IBM. Most pertinently, a relationship between sea temperature and recruitment, an estimation of crab abundance to set probability of capture rates from fishers landings data and method to predict the year class size for incoming recruits need to be addressed. Additionally, there are currently a number of limitations to the model, for example it does not simulate the dynamics of male crabs, however these comprise a small proportion of the total catch dominated by females. This limitation could be addressed as we have the information necessary on crab behaviour (Chapters 1, 3 and 4) and catch and discard rates (Chapter 3) to model the males. The model does not currently facilitate the input of discard data this could be included by incorporating an additional size of crab that was less than the MLS and adapting its probability of capture, and by having a function which simulated the fluctuation in soft and berried individuals as reflected in the empirical data. Additionally, the model currently does not take into account the fishing mortality generated by other gear types especially trawling and dredging in the seasonally open areas of the IPA. Jenkins *et al*., (2001) estimated that in the Irish Sea around the Isle of Man, these modes of fishing kill approximately 25% of the crabs they encounter, in addition to those caught. As these crabs are not caught in the gear and therefore not observed by fishers or observers, they are not reported as bycatch and not consequently considered by current stock assessment methods. To mitigate this shortfall we should research the catches of the trawlers who fish in the seasonally open areas of the IPA, and around the edge of the IPA (especially the south and eastern sections) and apply a fishing mortality to the model, generated by these vessels using the best available science.

How will the outputs of the model be translated into a quota per vessel?

The fisher directed stock assessment (FDSA) system would require a method to calculate and assign a crab landings quota to each vessel. A suggestion of how to assign this quota would be based on the traditional method of quota assignment by giving a proportional percentage of the total IPA catch quota, based on a historical reference period of landings taken by each vessel. Issues of latent capacity, new entrants and the time frame of the reference period would have to be discussed with fishers and perhaps adjusted after in the future.

Integrating and legitimising the bottom-up approach into local management

The implementation of this quota system would have to be voluntary (at least initially) and would require all fishers in the IPA to subscribe to the quota system. In reality, it is unlikely that all fishers will agree to use this system, as they believe it is already sustainably fished. However, we are optimistic that through word of mouth from other fishers and the successful practical application of the system and a possible increased in the price per kg of crab for being from a sustainable catch, would eventually incentivise most fishers to join the fisher-directed stock assessment system. With the added incentive that it would be more beneficial to be involved in a bottom-up approach than in a potential fixed quota system imposed top-down approach by the MMO in the future. It should also be noted here that as set out in Chapter 1 the establishment of the IPA was fisher-directed, voluntarily adhered to for over 30 years for the mutual benefit of fishers of different gear types, and therefore there is hope that the same attitude could be applied to the fisher-directed stock assessment (FDSA) system suggested in this thesis.

Legitimacy would need to be created for this bottom-up approach, as was developed for the establishment of the IPA to the appropriate management authorities such as the Devon and Severn IFCA, MMO and DEFRA. Without the eventual involvement of these authorities, the bottom-up approach we are recommending will not be absorbed into the established management system and the interest of crab fishers in local management issues developed throughout this project will simply dissipate. The most favourable approach to legitimise the system would be to practically demonstrate that it maintains a sustainable fishery. It would then be possible to work towards persuading the MMO and DEFRA to apply the system to other small-scale fisheries, using the IPA as an applied example. The ultimate aim, perhaps somewhat idealistically would be for this bottom-up approach to the sustainable management of fisheries to become the norm.

It is of paramount importance that the collaborative approach taken in this study by fishers and scientists is disseminated to the wider management, scientific and fishing communities so this nature of working together becomes the norm. Communicating this method could be through scientific publishing, conferences, articles in Fishing News, dissemination to organisation such as Fishing into the Future and the Shellfish Association of Great Britain (SAGB) and through fisher-to-fisher recommendation, which is probably the most effective method of transmission.

Once the model is in its final iteration the NetLogo code should be made freely available to other fisheries, fisheries scientists or managers who want to adapt the model and/or fisher-directed stock assessment method to their own fishery. Further, there should be bi-annual meetings between SDCSA fishers, scientists and local managers to discuss and remedy issues that become apparent when the system is applied. These meetings could also be a platform to invite other fishers, scientist and managers from other fisheries to demonstrate how the fisher-directed stock assessment and quota setting system operates in practice.

The diagram below (Figure 7.1.) shows the application of a fisher-directed stock assessment (FDSA) system to the IPA fishery from data collection to quota setting.

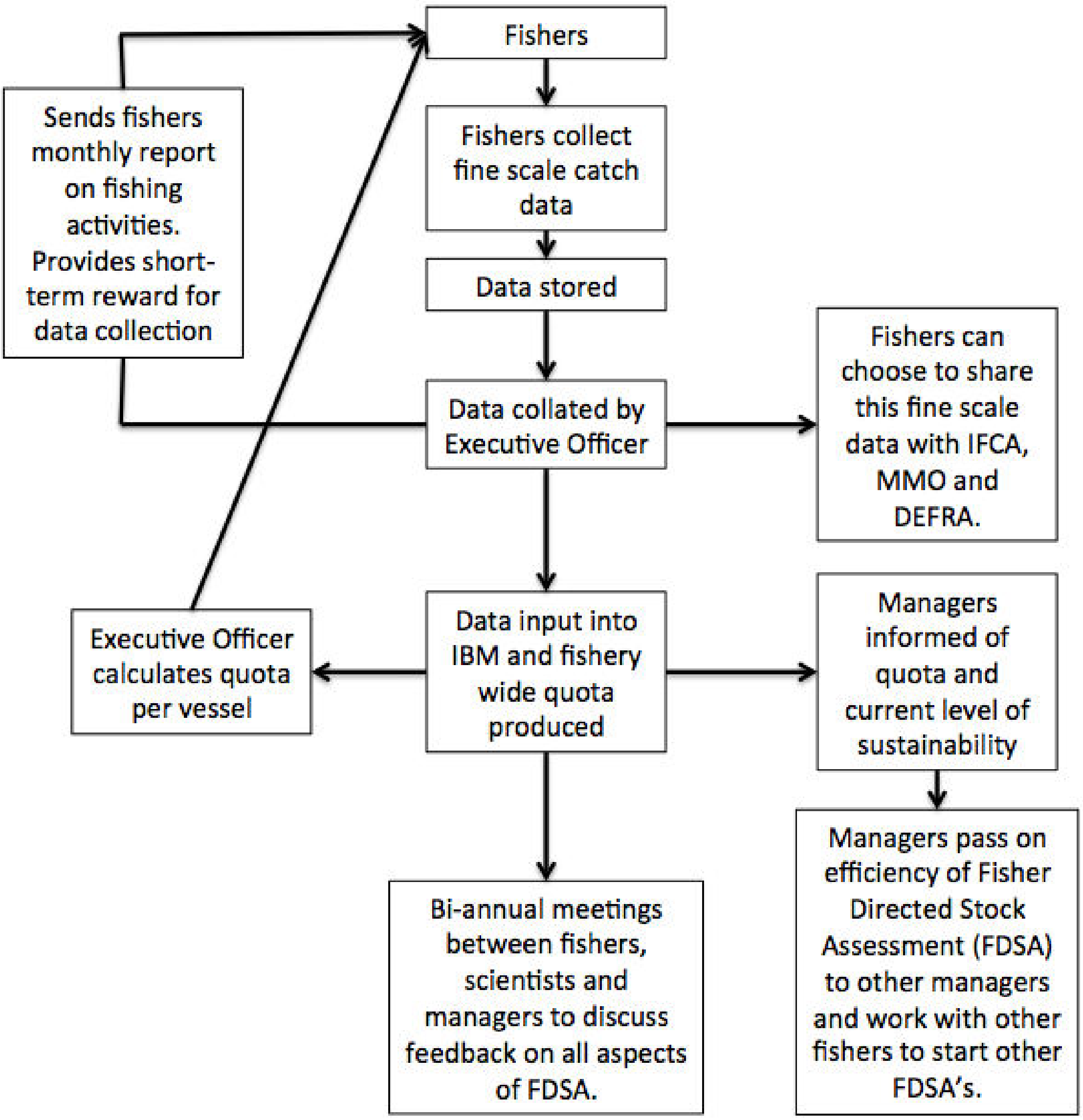

Figure 7.1. Diagram of the practical application of fisher-directed stock assessment system to the IPA.

How could local fishers use data from this study?

Fishers could maximise their fishing efforts in June and then during September to November as the highest KLPUE vs. lowest discards occur in these months (Chapter 3) meaning fishers could fish most economically in these months. Additionally, fishers within the IPA could also aim to align IPA areas closed to trawlers with the months of highest crab landings, and the conversely for the opening of areas to trawling over the months with the lowest crab landings. Our findings on the relationship between landings and sea surface temperature would be useful to fishers because they could choose to target other fish until the sea surface temperature reaches a critical value (9-11°C) and females are caught in large volumes. Fishers could also use this information to fish the deepest parts of their territories to increase landings and decrease discards and therefore using their time at sea more efficiently. As with depth fishers could use our findings on the relationship between substrate type and catch to target a specific sex if they are able to move their pots to a different substrate type within their 'territory'.

How could local IFCA use data from this study?

Local IFCA managers could use the high-resolution data contained within Chapters 3 and 4 to customise their carapace width sampling programme (for stock assessments) around the annual pattern of *Cancer pagurus* landings and discards. They currently sample approximately 3,000 crabs for the western English Channel (WEC) crab stock assessment (CEFAS, 2014) however the data in this study estimates there to be upwards of 2,000,000 crabs in the IPA fishery, therefore the IFCA sample only equates to 0.15% of crabs in the IPA let alone the WEC. Additionally, the local IFCA should use the relationship we have established between landing and discards and bathymetry, and substrate to stratify their stock assessment sampling with the depth and substrate on which vessels fish to reduce confounding variables. Nevertheless, the most pertinent aspect of this study, which managers should utilise, is the collaborative approach to working with fishers.

Conclusion

With the EU setting the aim that all fisheries should be fishing at MSY by 2020 this study enables and empowers fishers to relatively inexpensively and quickly assess the stock they fish and set quotas to achieve sustainability whilst increasing ownership and stewardship by fishers to encourage them to care for the resource they use in the long-term. This method of fisher-directed stock assessment reduces the pressure on local IFCA resources and allows their limited funds to be used elsewhere in the district.

With the uncertainty surrounding the fishing industry in light of the UK leaving the European Union, the use of quotas as a measure for the management of crab fisheries could soon become a reality. If so, this thesis exhibits a practical demonstration of a methodology to collaboratively develop a bottom-up approach to implementing a quota system with engaging all stakeholders.

The ultimate aim of the GAP2 Project and by association, this thesis, was the facilitation of collaboration between fishers, scientists and managers whilst creating a sustainable fishery for the future. This case study provided a demonstration of how we can move from a situation of 'us and them' where data was simply given by fishers and taken by scientists and managers with little or no feedback, to a system in which fishers and scientists work collaboratively. Fishermen of the IPA are now committed to and importantly have the skills and desire to engage with scientists and managers and this thesis has facilitated this pathway.

The IPA was first established for fishers by fishers in an innovative attempt to mitigate the loss of pots to mobile fishing gear, and it continues its pioneering approach to the development of management measures as described in this thesis. The low impact of potting (Eno *et al*., 2001) and seasonally open and closed trawling zones within the IPA fishery (Blythe *et al*., 2002), high MLS and live discards, coupled with the fisher-directed stock assessment methodology outlined in this thesis, along with fishers who actively want to be engaged in research can only benefit the long-term sustainability of the crabs and consequently the crab fishermen's livelihoods in south Devon.

Throughout this thesis we have updated and extended the data for catch, landings and discards of the fishery for the first time since the 1970's (Chapter 3 and 4), captured detailed FLEK (Chapter 5) and integrated this information to a model (Chapter 6) which has the potential to enable fishers to direct their own stock assessments, and specifically considering the impact of environmental variables such as sea temperature, substrate type and depth on the fishery. These data, fishers knowledge and the model culminates to produce a template for fishers to use themselves to fish sustainably in the future, which can only serve to benefit fishers and hopefully sustain local crab stocks.

A list of the key outcomes from this thesis:

- A detailed analysis of the interactions between fishers and scientists working collaboratively. The outcomes of this will enable future researchers to learn from our successes and challenges.

- Spatiotemporal mapping of crab distribution within the IPA.

- Establishment of relationship between sea surface temperature, bathymetry and substrate type and catch.

- The recording of FLEK from local fishermen and validation of this knowledge by comparing it to empirical data, therefore enabling the use of FLEK in local management.

- An IBM programmed by P. J. B. Hart, which allows a deeper understanding of the factors influencing the catch, and can potentially be used to establish sustainability criteria by which the fishery can be classified.

- A detailed approach demonstrating how using a bottom-up method to instigate a fisher-directed stock assessment and quota setting system can be applied to an economically valuable fishery in the UK.

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Appendix F

Initial layout of an iPhone application designed to facilitate the collection of fine-scale catch, landings and discard data within the IPA.