Ecology of the brown crab (Cancer pagurus)

and production potential for passive fisheries in Dutch offshore windfarms

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Summary

It is currently unknown whether low impact brown crab fishery in offshore wind farms in the North Sea is feasible from an ecological point of view. This desk study provides an overview of current knowledge on brown crab ecology and a base document in order to create insight in harvest potential of brown crab (*Cancer pagurus*) within Dutch offshore wind farms.

Brown crab is of substantial commercial importance with an average 50,000 tonnes in landings yearly in Europe. The UK has the largest brown crab fishing industry (approx. 34,000 tonnes) whereas the Netherlands play a much smaller part (approx. 550 tonnes). Stock assessment of brown crab in the central and southern North Sea show that populations of females are increasing and thereby approaching the recommended level for females. Populations of males are low and remain around the minimum recommended level for males. However, the age at which brown crabs become fertile is likely to vary regionally. This has implications for management through appropriate Minimum Conservation Reference Size (MCRS) restrictions (ranging between 130-140 mm) that are set to conserve the reproductive potential of brown crabs. Local estimates of size at first maturity will aid to preserve the production potential.

High densities of brown crab are mainly observed inshore (off the eastern English coast and north of the Dutch coast) with highest densities occurring in the German Bight. Density data from beam trawl surveys in the North sea from 1998 to 2018 fluctuate and do not show a clear trend, partly due to occasional observations of very high local brown crab densities. In the German Bight, the addition of another 5,000 wind turbines in the future is suggested to provide new artificial reef habitat for an estimated 320% increase in the population of brown crabs. In addition, various publications have shown that substantial populations of brown crab can occur near monopiles or other types of artificial substrate such as ship wrecks and oil platforms. Based on the population increase in OWF's in the German Bight combined with the density data in the Dutch part of the North sea an increase in the population density of brown crabs is expected in the Dutch OWF, Prinses Amalia park, which consists of 60 monopiles and covers a total area of 14.2 km^2. These findings along with reproductive and behavioural traits of the brown crab, such as migration patterns of female crabs and burrowing of females with eggs (preventing entrapment of berried females) demonstrate the potential for successful colonisation in offshore windfarms and the development of brown crab exploitation.

The local maximum production capacity and biomass of brown crab that can be fished sustainably will depend on the growth rate, the background population, reproductive success, mortality, colonisation success (including migration patterns and specific interactions between monopiles and different life stages of brown crab) and the local carrying capacity (quality and quantity). Monopiles in the German Bight have been shown to function as nursery grounds and larvae collectors for brown crab. However, little is known about the specific settlement cues for *C. pagurus*. Moreover, the relationships of crabs to artificial structures can be extremely complex and species specific. Therefore extrapolation of the data from the German Bight needs to be interpreted with extreme caution and more accurate densities are needed to provide a better insight. In the TKI project the brown crab (and lobster) population densities will be estimated for OWF Prinses Amalia, delivering first data to confirm these estimates.

Besides reservations concerning extrapolation to more southern parts of the North Sea, uncertainties concerning local carrying capacity and ecosystem interactions exist. Large decapods can play important roles in structuring benthic communities For example as key-stone predators suppressing herbivores. However, it is not clear how general these roles are and to which extent they apply to brown crab. Displacement of soft sediment fauna or less opportunistic hard substrate benthic species are among the scenarios of ecosystem shifts induced by increased brown crab population density.

The collective findings in this report demonstrate the potential for successful colonisation of brown crabs in offshore wind farms and the development of sustainable brown crab exploitation. However, future research is warranted to create insight in the role of brown crab in marine ecosystems, local maximum production capacity and how exploitation (harvesting) or large-scale addition of substrate such as monopiles might change this role.

1 Introduction

With the rapid upscaling of offshore wind farms (OWF's) in the North Sea, pressures are mounting on other users, such as fisheries. Successful increase of OWF development and exploitation requires integration in the environment, in terms of ecology and multi-use. This poses an innovation challenge for multiple parties. OWF operators need to minimise the risks involved in multi-use. Spatial design of OWF's might need to be adapted. Fisheries need knowledge on alternative species with commercial potential and innovation on catch methods. Amongst others the passive low-impact fisheries of European lobster (*Homarus gammarus*) and brown crab (*Cancer pagurus*) have been proposed as excellent opportunities (Linley *et al.*, 2007). To that extent a TKI tender has been awarded and the project Win-Wind on enabling this type of fisheries has commenced. The current research is part of phase 1 "preconditions for a demonstration pilot": generating the essential knowledge to proceed. Subsequent future phases comprise phase 2 "implementation pilot" and phase 3 "business implementation and upscaling". This report on the ecology of brown crabs is a product of phase 1. Here we focus on the ecologic and sustainable feasibility of passive low impact brown crab fisheries by describing the general ecology of brown crabs in the North Sea and around Dutch OWF's in particular.

1.1 Problem definition

It is currently unknown whether low impact brown crab fishery in offshore wind farms in the North Sea is feasible from an ecological point of view. What is the local maximum production capacity and what drives or limits production? In this desk study, the general ecology of brown crab will be described and combined with the most recent data on ecology and catchment to estimate the harvest potential of the North Sea crab.

1.1.1 Target group and knowledge

Target groups: are governments as area manager, aquaculture companies, OWF operators and fishermen being potential users of the knowledge to optimise their business case.
Knowledge: the project will lead to knowledge and tools to manage and optimise multi-use of OWF's aiming at aquaculture in general and lobster and brown crab in particular.

1.2 Objectives of this desk study

The objective of the project is to generate management information on the potential of passive crab and lobster fisheries in wind parks in the North Sea, with a focus on Prinses Amalia wind park where the pilot study of phase 2 will take place. In this desk study the basic question whether it is possible to have a sustainable fishery on brown crab is addressed.

1. This study will describe the general ecology and life history of the North Sea crab (*C. pagurus*) in the North Sea in general and around Dutch OWF locations in particular.
2. The general ecology description combined with the newest data on ecology and catchment will be used to make a first tentative estimate the harvest potential of the North Sea crab.

Figure 1: Brown crabs (*Cancer pagurus*) caught with creels. Image from http://www.dutchcrownseafood.com.

2 Literature review on brown crab

In this section the results of the literature review on brown crab are presented. In its intention it does not aim at being complete on the aspects mentioned but provides sufficient overview for interpretation of future results and further decision making on focus.

2.1 Description

The scientific name of brown crab is *Cancer pagurus*, also known as the North Sea or edible crab (see figure 1). *C. pagurus* is classified within the order decapods and has five pairs of legs or periopods. The frontal periopod on both sides is developed into a strong claw-bearing leg (cheliped) with black tips. The other legs are covered with rows of short stiff hair-like structures (setae) (de Kluijver *et al*., 1999). Like most crabs the abdomen is folded under the thorax and shows clear sexual dimorphism, i.e. the male abdomen is relatively narrow while the female abdomen is wider (Ingle, 1997). The carapace of adult brown crabs is a reddish-orange-brown colour, while in young specimens it is purple-brown (de Kluijver *et al.*, 1999). The carapace is broadly oval with a characteristic "pie-crust" edge and the carapace width is typically 150 mm (Neal & Wilson, 2008) although larger specimens up to 300 mm have been described (Adema, 1991). Length of the male carapace is typically 60 mm and females are typically 100 mm long, although in some cases they can reach up to 150 mm (de Kluijver *et al.*, 1999). Sizes may vary regionally (McKeown *et al*. 2017). Brown crabs can weigh up to 4 kg while size may vary regionally. Large male crabs, up to 267 mm carapace width and 4.2 kg in weight are caught in inshore waters in the United Kingdom, particularly during the spring. Larger crabs are found in deeper water and at the western end of the Channel (Brown & Bennett, 1980). North Sea brown crabs are significantly smaller than English Channel crabs (in McKeown *et al*., 2017). Longevity is typically up to 25-30 years, but individuals can live up to 100 years (Neal & Wilson, 2008).

In crustaceans, growth is a function of moulting frequency and the growth increment at moult. Frequency of moulting decreases and peak periods of moulting occur later at higher latitudes, suggesting that lower temperatures have an impeding effect on growth in northern populations (Bakke *et al.*, 2018). Additionally, the growth rate of brown crabs depends on age, sex and water depth with a range of 1-10 mm per year (Steenbergen *et al.*, 2012). In general the growth rate slows down with age and males grow faster than females (in Steenbergen *et al.,* 2012). The growth rate in males is about 10 mm per year (in carapace width) until the crab is 8 years old. After this the growth rate slows down to 2 mm per year. Female growth rate is less, about 5 mm per year between years 4 and 8, declining to 1 mm per year between years 16 and 20 (Bennett, 1979). Growth rates, however, may vary regionally (Steenbergen *et al*., 2012). In Bennett (1979) moult increments, annual moult frequency and annual growth were determined from tagged brown crabs released and recaptured off south-west England. The lower growth rate in females was suggested to be related to three aspects of sex and reproduction: (1) reduction in moult increments, probably as a result of competition for nutritive resources between egg production and body growth; (2) the interruption of the moulting cycle by successive annual spawnings from a single impregnation at the previous moult; and (3) accentuation of the larger increments in weight at moulting of male crabs due to the allometric growth of their chelae (Bennett 1979). However growth curves of female and male brown crabs in Tallack (2002) are comparable up to 4 years of age. Since growth rates vary between the different regions of the North Sea (Steenbergen *et al*., 2012), it is therefore likely that the age at which female brown crabs reach the adult stage and become fertile varies as well. Sexual maturity has been documented in literature and suggests that male *C. pagurus* in the combined regions Scandinavia, United Kingdom and France become sexually mature at 102-125mm carapace width (CW) whereas females are mature at 100–133mm (review in Haig *et al*., 2016), suggesting that size at sexual maturity overlaps whereas males are younger when they reach sexual maturity Variation in carapace size and sex composition have been detected on small spatial scales along the coast of Norway (Woll *et al.*, 2006). It is therefore plausible that these type of variations may also occur in the North Sea, for example between Kattegat and the German Bight (Steenbergen *et al*., 2012). Moreover, the size at which sexual maturity occurs depends on the definition and method used to determine sexual maturity. Four definitions of maturity are commonly used in fisheries science to determine or infer maturity in crabs. (i) Morphometric: the physical change associated with maturity, typically an increase in claw dimensions in males and abdomen width in females. (ii) Behavioural maturity refers to the physical act of mating. (iii) Physiological maturity infers that females are physiologically mature, and males display both physiological and morphometric traits of maturity. (iv) Functional maturity is the display of mature gonads capable of producing offspring. In the past some of these terms, such as physiological and functional maturity have been used interchangeably as well as various methods used to identify maturity (for example sperm plug present versus gonad development). In a more recent study based on the carapace width (CW) at which 50% of the sampled population was physiologically mature (CW50), estimates of size at first maturity varied between sampled populations from several European countries in the range of 97 – 117 mm CW in females and 59–106 mm CW in males (Haig *et al.*, 2016). No obvious spatial structure was found associated with this variation. These CW50 estimates reported are smaller than previously reported values for *C. pagurus* populations. A decrease in size at maturity can occur in populations where larger individuals are targeted by fisheries, which is common in brown crab fisheries, or naturally when the benefit of maturing early is greater than the benefits of a larger body size (Haig et al., 2016). However, it remains unclear whether the decrease in CW sizes reported in Haig *et al.,* (2016) are real, due to the variety of laboratory and statistical methodologies used in previously published studies that prevent absolute comparisons.

The weight of brown crabs may differ per season and fishing ground (www.fao.org). Approximately one third of the weight is meat, of which two thirds is brown meat and one third white meat. 70% of the crabs total body weight consists of carapace and organs. The white meat is of higher quality for consumption and originates from the male claws. The brown meat is mostly from females which in addition provide less meat then male crabs of equal size. In England the yield per crab is somewhat higher in spring then in autumn. This is due to the higher amount of crabs that have recently shed their carapace. During the shedding the crabs go in hiding, do not feed and potentially subside on their body weight (Slijkerman, 2008).

2.2 Biology and habitat

Brown crabs are benthic and live on a broad range of environments, ranging from soft muds into which it can hide or dig for food to hard, rocky substrata where it exploits and seeks shelter in crevices (Hall *et al.*, 1991, Hall *et al.*, 1993). Hiding spots are preferably created in stony substrate. Young animals that are not yet fertile likely bury themselves in the sand (Verwey, 1978). Activity levels are higher during the night when foraging mainly occurs. Small crabs are more active during both day and night compared to medium and large crabs (Scott *et al.*, 2018, Stensmyr *et al.*, 2005). Antennular flicking rates on the other hand, which are used to sense the environment are lower in small crabs (Stensmyr *et al*., 2005). Female brown crabs have shown a nocturnal activity cycle which may be a response to variation in resources or risk of predation (Skajaa *et al.*, 1998).

Brown crabs have a hard exoskeleton which they must shed in order to grow. This process is called ecdysis (moulting). The relationship between brown crab size and moulting frequency typically has a reverse S shape, with high moulting frequency for small crabs (<~100 mm CW) and very low moulting frequency for crabs above ~170 mm (in Bakke et al 2018). Moulting can take place at various times of the year when factors controlling growth, such as food supply and temperature, vary and may determine the size of moult increments (Bennett, 1995). Moulting generally occurs in the warmer seasons, summer to autumn, and peaks in late summer (Bakke *et al*., 2018). Bakke *et al*. (2018) also show a decrease in frequency and that the peak period of moulting occurs later with increasing latitude. A clear difference in frequency and timing of moulting in different geographical areas, suggests that such differences could be related to variation in temperature at these locations.

Adult brown crabs occur at depths of 6 to 100 m, but usually between 6 and 40 m depth and tolerate current speeds ranging between 0 and 1.5 m s^{-1} (Neal & Wilson, 2008). Small crabs are often numerous in the intertidal zone (Tallack, 2002). Brown crabs are osmoconformers meaning that they are unable to maintain body fluid osmolarity separate from that of the external environment (Whiteley *et al.*, 2018). A benefit to osmoconformation is that organisms don't need to expend as much energy as osmoregulators in order to regulate ion gradients. A disadvantage to osmoconformation is that organisms are subject to changes in the osmolarity of their environment. Adult *Cancer pagurus* cannot tolerate salinities of 17 psu or lower whereas juveniles (50-100 mm CW) can tolerate reduced salinities for extended periods (Wanson *et al.*, 1983). *C. pagurus* predominantly lives in the sub-littoral zone where it experiences a relatively narrow range of temperature, that is consistently below 15°C and usually closer to 5-8°C. The thermal tolerance of brown crab extends to 31.5°C, when the first signs of heat stress occur, with a seasonal range of 21.5-31.5°C results transfer to other species, such as large crabs and clawed lobsters (Cuculescu *et al.*, 1998). In addition, laboratory experiments show that brown crabs are more sensitive to rising temperatures when exposed to very low pH (as a result of high CO_2 concentrations (10,000 ppm)) (Metzger *et al.*, 2007). Although these are extreme conditions, they do warrant that interactions of ambient temperature and ocean acidification (a decrease in the oceans' pH due to the increased uptake of CO_2 from the atmosphere) need to be considered. Moreover, brown crab shows greater species sensitivity to elevated CO_2 since they are poorly equipped for changes in seawater CO_2 and salinity due to the inability to increase ion exchange capacities (Whiteley *et al.*, 2018). An overview of the abiotic parameters *C. pagurus* is encountered in is shown in Table 1.

Table 1. Overview of abiotic parameters *Cancer pagurus* is encountered in.

Environmental parameter	**Response variable**	**Range**	**Optimum**	**Reference**
Temperature (°C)	Survival adults	<31		(Cuculescu *et al.*, 1998)
	Growth adults	4-15		(Bakke *et al.*, 2018, Metzger *et al.*, 2007)
	Survival larvae	11-17	14	(Weiss *et al.*, 2009)
	Spawning and larval development	>7-8		(Lindley, 1987)
Salinity PSU	Survival adults	17-40		(Wanson *et al.*, 1983)
	Survival juveniles	<17*		(Wanson *et al.*, 1983)
Depth (m)	Adults	0-100	6-40	(Neal & Wilson, 2008)
	Juveniles	intertidal		(Tallack, 2002)
Current speed m s^{-1})	Adults	0-1.54		(Neal & Wilson, 2008)

*Adult brown crabs are sensitive to reduced salinities (<17), a sensitivity not shared by juveniles (Wanson *et al*. 1983).

A feasibility study into habitat suitability of potential OWF locations in the North Sea for different types of aquaculture based on observations from different sources (Stichting Duik de Noordzee schoon (DDNZS), Stichting ANEMOON, GBIF and EMODnet Biology) and optimal environmental conditions for brown crab was conducted in order to create qualitative feasibility maps (van den Bogaart *et al.*, 2019). As a result best locations were situated more northern (close to the German Bight) and very good or good locations were scattered offshore along the Dutch coast whereas unsuitable locations were generally found a lot further out to sea (Fig. 2). Due to the qualitative approach of the study direct insight in the factors that determine the feasibility of the locations was not provided.

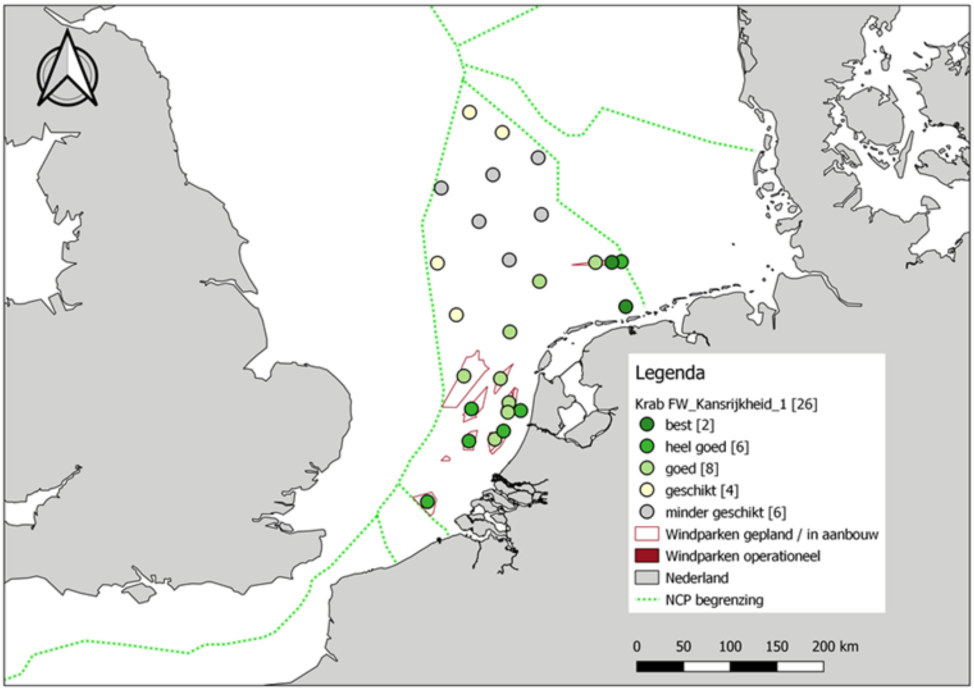

Figure 2: Brown crab fisheries habitat suitability in (potential) OWF's based on occurrence of brown crab on hard substrate (van den Bogaart *et al*., 2019) and correlated to environmental factors (depth, temperature, water movement, zooplankton concentrations, sediment and disturbance such as water movement versus sediment type and depth) by means of Generalised Additive Modelling (GAM) (figure from van den Bogaart *et al*. (2019)).

2.3 Reproduction and juveniles

2.3.1 Mating

The mating season is mainly in July-September (Fig. 14) (Slijkerman, 2008). Mating occurs shortly after the female has moulted, when the female carapace is soft (Brown & Bennett, 1980). Mating predominantly takes place at night-time. After transferring sperm the spermatozoa are kept safe in a special organ (the spermatacae) by means of formation of a plug. In a study into the reproductive cycle of brown crabs from the Shetland Islands (Scotland) peak proportions of plugged females were found in August and October (Fig. 15, Tallack 2002). The plug is visible in the opening of the female which makes it possible to check whether mating has occurred or not. The sperm can be kept (up till 3 years) until fertilization of the eggs. This generally takes place between 1 and 14 months after mating. Fertilised eggs are attached to pleapods in the period November-January (Fig. 14 and 15). Once attached the eggs will take about 7-8 months to develop. During this period while female crabs carry the eggs (berried females), they do not feed, remaining in pits dug in the sediment or under rocks and are therefore unlikely to be caught in a baited pot (Howard, 1982). In fact, in a survey determining catch characteristics in the Irish sea a total of 5795 commercial pots were hauled and only 16 ovigerous females were found in the pots (Ondes *et al.*, 2019). *C. pagurus* appears to use a “capitalist” reproductive strategy[1], relying on previously accumulated energy to use throughout the reproductive season (Haig *et al.*, 2016). Fecundity varies between 0.25 and 3 million eggs per female depending on size (diameter ± 400 µm, in a study of Welsh brown crabs (Haig *et al.*, 2015)) (Bennett, 1995). The mean number of eggs produced per brood of female brown crabs from the Shetland Islands was found to range from 771,485 in crabs of 128mm CW to 2,433,758 in females of 212mm CW (Tallack, 2002). This increase in fecundity with increasing crab size confirms previous fecundity studies of *C. pagurus* (Tallack, 2002). Despite the capacity of this species for long-term storage of sperm and the suspected potential for females to use sperm from multiple males simultaneously paternity, analysis suggests single paternity of broods (McKeown & Shaw, 2008). In the North Sea, berried females migrate offshore to release larvae and then move back inshore to feed (Nichols *et al.*, 1982). The time at which the crabs cease most activity is used as the onset of brooding and occurs from mid-November through to early January (Hunter *et al.*, 2013). In the North Sea, egg development has been observed to cease in late November, at which point the eggs entered a period of diapause (Naylor *et al.*, 1997). Development resumed in late March, with hatching in late June. Hatching depends on the time of moulding and/or the actual timing of fertilisation and can occur from the following spring through to autumn (Tallack 2002) (Slijkerman, 2008) (Fig. 14 and 15).

Reproductive stage	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sept**
Mating	mating														
Fertilisation		probably			if sperm is preserved										
Eggs on pleopods					start development										
Egg development					eggs develop										
Larvae											eggs hatch				

Figure 14: overview of the reproductive cycle of the brown crab in the North Sea.

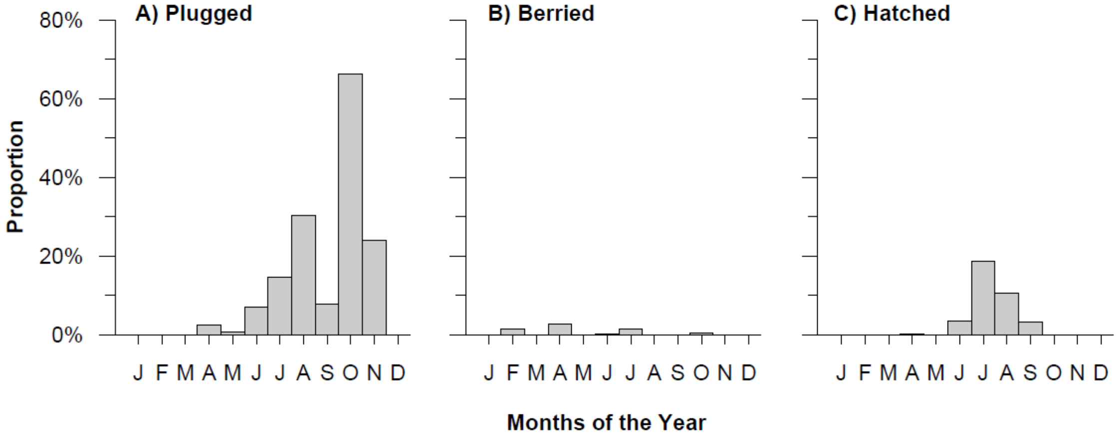

Figure 15: The average monthly proportions of plugged, berried and hatched female *C. pagurus* (Shetland Islands, Scotland) derived from catch samples >100mm CW, during the study period 1999-2001 (n=4155). Figure from Tallack (2002).

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[1] Capital breeders: resources are collected before breeding and are used, they breed once they reach a body-condition threshold, which decreases as the season progresses. Income breeders: breed using resources that are generated concurrently with breeding and time that using the rate of change in body-condition relative to multiple fixed thresholds. This distinction is a spectrum, with pure capital breeding lying on one end, and pure income breeding on the other (Houston *et al.*, 2007).

2.3.2 Pelagic larval stage

The brown crab has planktotrophic larvae that are released in the water column (Fig. 16). Spawning and larval development in *C. pagurus* are both dependent upon temperature and neither are triggered below 7 or 8ºC (Lindley, 1987). The pelagic larval stage lasts for approximately 3 months (Eaton *et al.*, 2003, Hunter *et al*., 2013, Weiss *et al*., 2009) or at least for 60 days at temperatures of 15–20 ºC (Nichols *et al*., 1982). Larvae are detected in coastal waters from May until September. The appearance of crab larvae in the plankton demonstrates a latitudinal gradient (Lindley, 1987), with peak abundance occurring later at higher latitudes. This peak can occur from as early as March off the French Atlantic coast, to as late as August in the northern North Sea (Lindley, 1987). Covered distances by larval drift depend on currents, stratification and the length of the larval stage until settlement. For example Eaton estimated a mean speed of 3.6 cm s^{-1} (~3.1 km day^{-1}) by deploying an instrument in the hatching epicentre off the east coast of the UK during the larvae survey in 1999 (Eaton *et al*., 2003). With a planktonic stage of two months this could theoretically lead to a travelled distance of 234 km.

2.3.3 Early settlement

Little is known about the settlement of juvenile *C. pagurus*. However, there is indication that the young crabs start their benthic life in the intertidal zone on shallow hard substrate areas along the coastline (Bennett, 1995, Ungfors, 2007). They are rarely caught in offshore waters, suggesting that adult crabs only move to deeper water as they grow and reach maturity (McKeown *et al.*, 2017). Other studies indicate that they remain in the intertidal area until they reach a CW of 60-70 mm which takes about 3 years. After this they head off to sea (Nautilus consultants, 2009 in Steenbergen et al., 2012). Structurally complex habitats provide refuge against predation for decapods in their final larval stage (megalopae) and early juveniles. Artificial hard substrate such as wind turbines, shipwrecks and oil platforms are known to provide habitat and attract recruitment of crustaceans (Coolen *et al.*, 2018, Krone *et al.*, 2013, Page *et al.*, 1999). The finding of high amounts of small individuals (CW: 10-60 mm) at wind turbines indicated that the upper construction parts of the WTF may also act as a nursery ground, and thus as an artificial larvae collector for *C. pagurus* (Krone *et al.*, 2017, Krone et al., 2013). Besides structural complexity megalopae in general actively select a habitat suitable for settlement by detecting abiotic and biotic environmental stimuli such as changes in temperature and salinity, and chemical cues derived from conspecific adults and/or nursery areas (Forward *et al.*, 2001). However, little is known about the settlement behaviour and habitat selection of *C. pagurus* larvae.

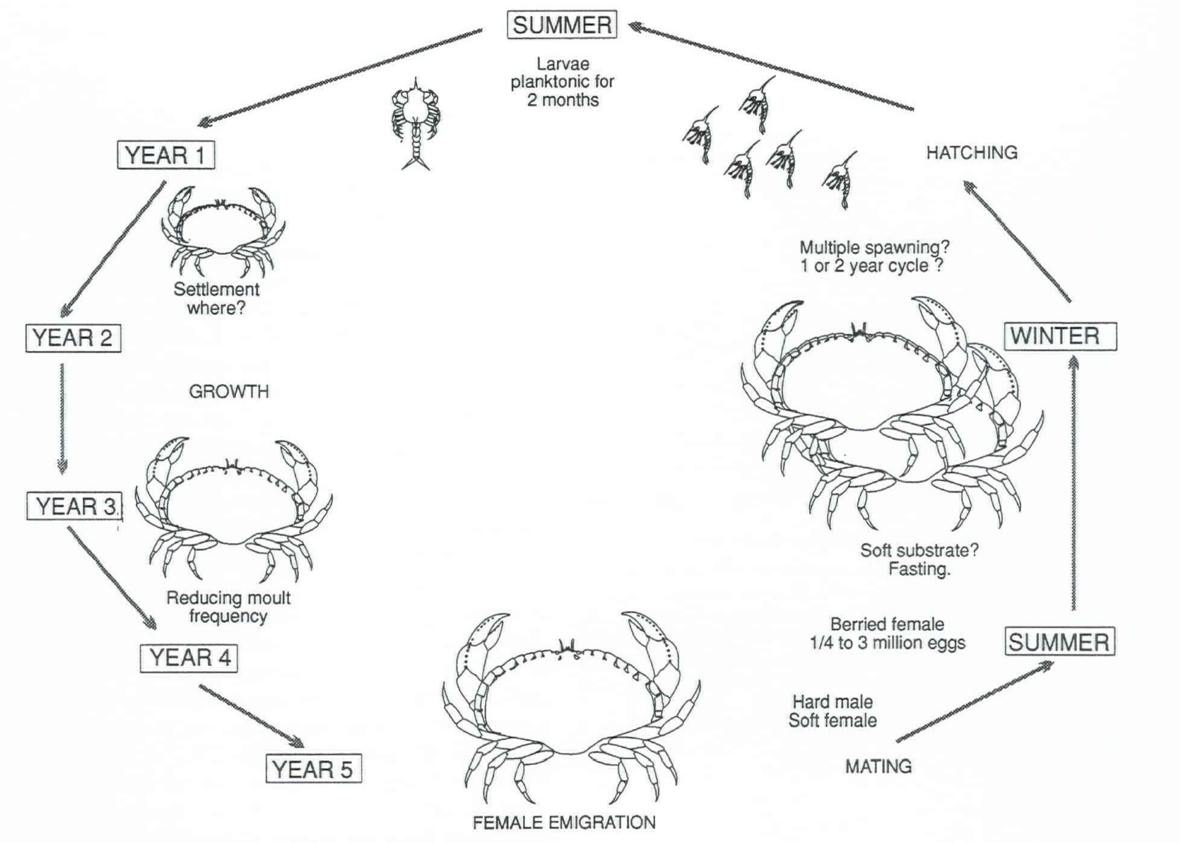

Figure 16: Overview of the reproduction cycle of brown crab (figure from Bennett (1995)).

2.4 Diet

The brown crab is carnivorous. It has large powerful claws with blunt, broad molars and is a specialist on hard-shelled prey (Yamada & Boulding, 1998). Their diet includes molluscs, crustaceans and echinoderms (Lawton, 1989, Lawton & Hughes, 1985). Brown crabs display a wide range of feeding behaviours including picking up molluscs such as mussels and oysters, digging large pits to reach buried molluscs such as razor clams (*Ensis* sp.), chasing, ambushing, grabbing and pouncing for respectively smaller and larger decapod crustaceans (Hall *et al*., 1991, Lawton, 1989). Juvenile brown crabs use their claws to crush prey, usually molluscs and crustaceans, whereas larger individuals use their claws to dig out prey (Mascaro & Seed, 2001). Juvenile brown crabs have also been shown to selectively choose prey with a preference for smaller bivalves (Mascaro & Seed, 2001). Hard substrate in soft bottom environment such as oil platforms, wrecks and monopiles attract benthic biodiversity (Bouma & Lengkeek, 2012, Coolen *et al*., 2018). The blue mussel *Mytilus edulis* for instance is known to colonise offshore substrate and is a common food supply for brown crab (Coolen, 2017, Kamermans *et al.*, 2016).

In a study to increase knowledge on brown crab fisheries in the North Sea different types of bait were tested when fishing with crabbing pots (Steenbergen *et al*., 2012). Results from this study show that most brown crabs were caught using common dab (*Limanda limanda*) as bait. Additionally, Atlantic horse mackerel (*Tracherus tracherus*), Atlantic cod (*Gadus morhua*), small European plaice (*Pleuronectes platessa*) and a combination of European plaice and common dab show a high catch rate. However, common dab was mainly used as bait in week 24, 25 and 26, when numbers of caught crab were highest and not all bait types were tested in an equal amount. Location and date may also confound results on preferred bait type. Herring, a favourite prey species for lobster was not included in the study by Steenbergen *et al*. (2012).

2.5 Mobility

Adult brown crabs are described as benthic and mobile, but there are pronounced dispersal differences between the sexes: males are largely resident, making short random movements within small territories, while females migrate significantly longer distances, and more frequently, than males (Ungfors *et al.*, 2007). Brown crabs migrate to deeper water in autumn because they are sensitive to low temperature. In spring, around May the animals move back to the coastal area. Research has shown that brown crabs can migrate across large distances of 50 to 100 km (Adema, 1991). In the English Channel, female migrations of up to 200 nautical miles (nmi, equals 370 km) have been reported with some crabs achieving a mean speed of 1.98 to 3.00 km d^{-1} (McKeown *et al.*, 2017). From the release of mature female edible crabs tagged with electronic data storage tags (DSTs) from 4 locations in UK waters, a predominantly westward migration in the English Channel was demonstrated (Hunter *et al.*, 2013). Eastern Channel crabs migrated further than western Channel crabs, while crabs released outside the Channel showed little or no migration. Individual migrations were punctuated by a 7-month hiatus, when crabs remained stationary, coincident with the main period of crab spawning and egg incubation. The westward migration has previously been interpreted as an example of counter-current spawning behaviour facilitating the return of settling larvae to their areas of maternal origin (Eaton *et al*., 2003). In a study of male and female crab migration on the west coast of Sweden, facing a northbound current, a predominantly southward migration of female crabs was shown (Ungfors *et al*., 2007). This is consistent with the hypothesis that migration is related to reproduction. By moving up current to release their larvae, females may compensate for larval dispersion (Diamond & Hankin, 1985). Recapture rate of these tagged crabs in the English study was 34% of which 50% was recaptured within 40 days and zero recapture during the winter months (Hunter *et al*., 2013). Tagged crabs were recaptured between 0.7 and 302.4 km from the point of release from 1 to 679 days after release. No information was available of crabs returning to the same location after spring and autumn migration. However, there is a risk of misinterpreting a stock as being “localized” with the mark-release method as the crabs may have moved extensive distances and back during the period until recapture. In the Swedish study, over 40% of the repeated recaptures were towards opposite direction between first and second recapture, which could be interpreted as return movements (Ungfors *et al*., 2007). This is an important finding as understanding of biology and implementation of proper management needs to be aware of possible returns, which theoretically re-establish the stock state. The question is whether this high mobility serve as a source of replenishment when fishing in an OWF and whether local summer migration is sufficient to replenish stocks?

2.6 Population genetics

In general, marine species are expected to show less population structure over large geographic areas because of the fewer barriers to dispersal via larval drift or adult movements compared to species on land (Ward *et al*., 1994). However, genetic analyses of commercial decapods have revealed complex patterns of genetic differentiation at various geographic scales, even over short distances of (40–225km) (Ungfors *et al.*, 2009). For example, the European lobster (*Homarus gammarus*), revealed significant structuring and distinct genetic clusters across its European distribution range (Triantafyllidis *et al.*, 2005). To date, population genetic structure of brown crab has been studied in Scandinavian waters within the Norwegian Sea, Skagerrak and Kattegat (Ungfors *et al*., 2009) and in the NE Atlantic (English channel and North Sea) (McKeown *et al*., 2017). The Scandinavian study reported no significant genetic differentiation among samples spanning 1300 km of waterway distance within the Norwegian Sea, Skagerrak and Kattegat. However, genetic structuring may vary throughout a species’ range. This was partly confirmed by findings from McKeown *et al*. (2017) that revealed patterns of neutral genetic variation in brown crab that indicate local and unstructured genetic differentiation occurring against a background of high gene flow throughout the studied region. Although the majority of comparisons (such as those between geographically different sites) showed no differentiation, some comparisons did exhibit significant differentiation. For example the differentiation of the Gulmarsfjord males from all other samples, including females collected at the same site. This was explained by the intermingling of allochthone females with resident, locally adapted males (McKeown *et al*., 2017). (Selkoe *et al.*, 2010). The study highlights how considerable intraspecific eco-evolutionary diversification can occur despite high levels of dispersal/gene flow. These brown crab data also highlight the fact that genetic structuring may be driven by factors other than dispersal such as specific biological or environmental drivers *(Hunter et al., 2013, McKeown et al*., 2017, Ungfors *et al*., 2007). Comparative studies among taxa with common and contrasting life history strategies will be necessary to elucidate the specific drivers of genetic variation (Selkoe *et al*., 2010). Genetic structuring across a species range has implications for sustainable management since failure to identify local populations may lead to local overfishing of a certain population and ultimately, severe declines.

2.7 Ecological position in the trophic network

Although *C. pagurus* is of substantial commercial importance in fisheries, their role in marine ecosystems is not well understood. More general large crustaceans are seen as key components of marine ecosystems and display multiple ecosystem interactions. Experimental studies have shown that decapods influence the structuring of benthic habitat, occasionally playing a keystone role by suppressing herbivores like sea urchins and snails or space competitors like mussels with strong indirect effects on habitat structure and (likely) primary productivity (Boudreau & Worm, 2012). Indirectly, via trophic cascades, they can contribute to the maintenance of kelp forest, marsh grass, and algal turf habitats (Robles, 1997, Shears *et al.*, 2006, Silliman & Bertness, 2002). Changes in the abundance of their predators can strongly affect decapod population trends (Boudreau & Worm, 2012). Ecosystem interactions of decapods involve in predator–prey interactions as well as non-consumptive interactions by competing with other species for food and habitat, or providing and altering habitat themselves (Fig. 10). Anthropogenic factors such as fishing, marine protected areas, species introductions and the addition of manmade structures such as oil platforms and windfarms are also included as interactions.

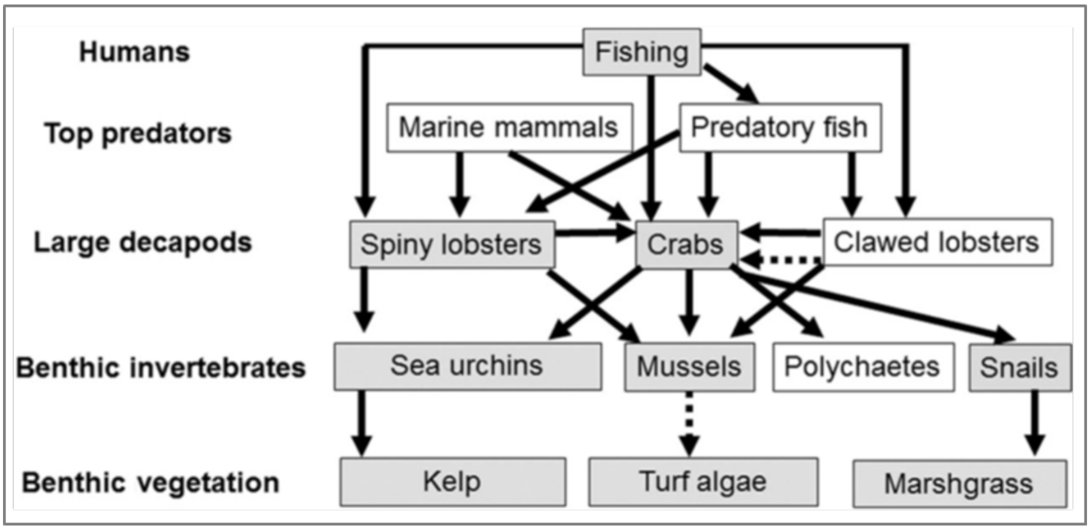

Figure 10: A simplified scheme of ecosystem interactions of large decapods include predatory (solid arrows) and competitive (dotted arrows) interactions. Grey: species that are strongly implicated in trophic cascades (figure from Boudreau *et al*., (2012)).

2.7.1 Brown crabs as prey

The role of brown crab as prey changes throughout its lifecycle. Whereas smaller crabs are preyed on by bottom feeding fish, other crabs and birds (Burton & Burton, 2002) larger crabs have relatively few predators. Known predators of brown crab are octopus, wolf fish, seals and cod. Seals, octopus and large wolf fish or cod are most likely to eat larger crabs. *C. pagurus* is mainly nocturnal, presumably to reduce predation by the latter three (Skajaa *et al.*, 1998). The octopus is known to attack crabs even inside the crab pots that fishermen use to trap them.

2.7.2 Brown crabs as predators

Brown crab feed on a variety of benthic organisms (see 2.4 Diet). Prey selection can influence species composition and abundance. Indeed, crabs in general are suggested to play an important role in structuring benthic communities in this way. For example the predation of crabs on mobile herbivores, such as sea urchins or snails, that graze on algae (kelp, sea grass, turf algae). Therefore, crab fisheries can have indirect effects on benthic community structure by reducing crab predation (Quijon & Snelgrove, 2005b, Quijon & Snelgrove, 2005a). Crabs have occasionally been suggested as keystone species, i.e. having a disproportionally large impact on the community relative to their abundance. For example blue crabs in the NW Atlantic, were described as keystone predators preying on periwinkle, a common gastropod (*Littorina littorea*), and being responsible for the regulation of marsh grass cover through a 3-level trophic cascade (Silliman & Bertness, 2002). However, no existing examples were found for *C. pagurus*.

2.7.3 Other “non-consumptive” interactions

Competition with other species for food and habitat, as well as providing and altering habitat themselves are examples of non-consumptive interactions. Negative, direct interactions between organisms trying to access the same resource such as food or shelter are called interference competition. Two species of Cancer crab (*Cancer borealis* and *Cancer irroratus*) compete with the American lobster for shelter, but are often displaced by lobster when shelter is limited (Richards & Cobb, 1986). Whether similar interactions apply to brown crab, such as competition with European lobster, is not known.

Habitat limitation is less important to crabs (*C. borealis* and *C. irroratus*) since they can burrow and use a wider range of shelters (Richards & Cobb, 1986, Wells *et al.*, 2010). This may also apply for brown crab. Moreover, European lobster prefers to live in holes, protecting its back and sides for predators whereas brown crab is often seen sitting with its back towards a rock or wall. Indeed different habitat enhancement structures in OWF’s have been recommended for both species (concrete blocks with holes or layered reef balls for lobster and shelf-like concrete blocks for brown crab) (Koentjes, 2018).

Most decapods can also provide habitat to for example barnacles, polychaetes, crustaceans and gastropods that live on the outer shell of these decapods and can thereby act as vectors for the spread of invasive species (Boudreau & Worm, 2012).

2.7.4 Anthropogenic factors

Commercial fishing, the creation of marine protected areas, species introductions and the addition of manmade structures such as oil platforms and windfarms influence ecosystem roles by decreasing or increasing decapod densities, often with measurable effects on prey communities (Boudreau & Worm, 2012).

Fisheries may have a range of effects on the ecosystem. Removal of demersal fish or other decapod predators can lead to population increases and shifts in trophic structure. Additionally, fishing operations may also affect species interactions by removing predators of decapods (e.g. Atlantic cod) or prey (e.g. rock crab) species, and by altering habitat (e.g. through dredging or beam trawl) (Boudreau & Worm, 2012, Steneck *et al.*, 2011). These interactions can have important implications for multispecies management. Fishing operations may also have an effect by supplementing decapod diets through bait loss or discards. In Western Australia, stable isotope analysis and gut contents analysis indicated that bait inputs contributed between 30 and 80% of the diet of rock lobster *Panulirus cygnus (Waddington & Meeuwig, 2009)*.

The potentially large effects of fishing on decapods often become most apparent when this influence is removed. Marine protected areas where fishing is excluded can be used to assess ecosystem level effects of fished species at ecologically relevant scales (Shears *et al*., 2006). Reserves have been shown to successfully protect and increase spiny lobster populations which had strong cascading effects throughout the ecosystem (in Boudreau & Worm, 2012). It is unclear whether and how these results transfer to other species, such as large crabs and clawed lobsters.

Introductions and invasions lead to the establishment of a species in a habitat where it was not formerly found. Introduction of invasive species are often irreversible and their impacts can lead to displacement of native species (Bax *et al.*, 2003). Brown crabs are native to the North Sea and are not an invasive species themselves. However, they may facilitate the dispersal of non-indigenous sessile organisms by providing habitat and also indirectly by preying upon bivalves resulting in bare substrate upon which other invasive species may settle (Boudreau & Worm, 2012). In addition, invasive species may act as predators on brown crab.

The introduction of substrate such as oil platforms or the scour protection of monopiles have the potential to act as artificial reefs and can influence decapod populations by providing habitat and food. However, the responses of large decapods such as *C. pagurus* and *H. gammarus* to noise and electromagnetic fields are poorly understood (Hooper & Austen, 2014). As stated earlier, wind turbines have been mentioned to function acting as nursery grounds and as larvae collectors for brown crab (Krone *et al*., 2017).

2.8 Growth modelling

2.8.1 Von Bertalanffy growth model

From a fisheries perspective growth and recruitment influence the sustainable catch (in unit of tonnes) that can be taken from a stock. As mentioned *C. pagurus* will moult numerous times in their lifetime to achieve the larger sizes recorded for this species. Therefore, moult frequency (i.e. the probability of an individual moulting annually or the proportion of the population moulting annually) and moult increment (the absolute or relative increase in size occurring during a moult) are both important and should be incorporated in any method used to estimate crustacean growth. Tagging studies provide useful pre- and post-moult morphometric information on crabs from which growth rates can be estimated by modelling the moulting process using moult frequency and moult increment functions (Spencer, 2013, Tallack, 2002).

The stepwise nature of growth in *C. pagurus* due to moulting, coupled with the variation in intermoult period documented for crabs at different life-stages, results in a discontinuous growth. This means that *C. pagurus* does not conform well to continuous growth curves such as the von Bertalanffy model (see equation 2.3.1) (von Bertalanffy, 1957). However, when a large number of individuals are considered, the von Bertalanffy model is useful for explaining average annual growth rates at the population level (Spencer, 2013, Tallack, 2002).

Equation 2.3.1: The von Bertalanffy growth curve in terms of size:

$$L_t = L_\infty \left(1 - \exp\left[-K\left(t - t_0\right)\right]\right)$$

where L_t is the size at age at t; L_∞ is the theoretical size for the species at ultimate age; K is the growth coefficient or the rate at which L_∞ is attained; and t_0 is the theoretical age at size zero (von Bertalanffy, 1957).

Regression analyses of moult data can be constructed by various methods to produce von Bertalanffy growth function (VBGF) parameters (K, L_∞ and t_0). A summary of known VBGF growth parameters estimated for edible crab stocks in England is provided in Table 2. An alternative approach to modelling growth via the moult process is provided by lipofuscin-based ageing techniques (Sheehy & Prior, 2008). For edible crabs in the Western Channel, Sheehy & Prior (2008) constructed size-at-age data by calibrating lipofuscin concentrations found in the eyestalk to chronological age, from which growth curves and the associated growth parameters were estimated.

Table 2. Summary of known VBGF annual growth parameters estimated for edible crab stocks in England from (Spencer, 2013).

Area	**Authority**	**Data and Method**	**K**	**L_∞ (CW mm)**
Western Channel	Bennett 1974	Tagging data 1968-1971	0.16 (F)0.22 (M)[a, b]	255 (F) 281 (M)[a, b]
	Sheehy & Prior 2008	Lipofuscin-based size-at-age data 2001, via cubic VBGF growth equation	0.46 (F)0.38 (M)	203 (F) 238 (M)
Eastern & Western Channel	Smith 2012b	Tagging data 2007-2011, via Ford-Walford regression method	0.325 (F)	203 (F)
	Eastern & Western Channel	Smith 2012b	Tagging data 2007-2011, via Ford-Walford regression method	0.325 (F)
East & north-east coast	Addison & Bennett 1992	Tagging data 1959-1966 (collected by Hancock & Edwards 1967), via Ford-Walford regression method	0.191 (F)0.196 (M)c	240 (F) 240 (M)c

[a] parameter values cited in Addison & Bennett 1992 b assumed arbitrary starting value for annual growth scale; c assumed value of L_∞ used to estimate K; F represents females and M males.

The universal growth parameters used for ICES crab stock assessments for the 6 main edible crab fisheries in England in 2011 are based on growth parameters estimated by Addison and Bennett (1992) from tagging studies in the fisheries of Yorkshire and Norfolk from 1958 to 1966 (Hancock & Edwards, 1967). Addison and Bennett (1992) acknowledge that growth increment data for large individuals is limited for east coast crab populations due to size selectivity in the capture process and lower moult frequency for larger animals.

Tagging data from 13,000 crabs collected from 2007 to 2011 in the English Channel (unpublished data Smith 2012b in Spencer, 2012) suggested higher growth rates over early years than those estimated by Addison and Bennett (1992) but lower rates over later years (Fig. 3). Note that Addison and

Bennett (1992) artificially fixed the same L∞ value for both sexes to estimate K, while Smith (2012b) used data only to estimate both L∞ and K for female crabs only, due to the scarcity of tag returns for males (Table 2). In a study of growth rates estimated for *C. pagurus* from the Shetland Islands tagging data from 1999 to 2001 was used (estimations of growth were derived using Ford-Walford plots, based on the von Bertalanffy growth equation). Annual growth rate estimations were K=0.188 (year^{-1}) (males) and K=0.224 (year^{-1}) (females) (Tallack, 2002). These are similar to annual growth rates estimated for UK populations by Addison & Bennett (1992), but smaller than estimates for males from French populations (K=0.390 (year^{-1}) for males) and K=0.250 (year^{-1}) females) (Tallack, 2002). Brown crabs (male and female) reach marketable size (130 mm CW) after about 4 years (Tallack, 2002).

Several factors may bias the estimation of moult processes from tagging data, including tag loss, size-selective sampling, higher natural mortality during moulting, differential migration out of the capture area (e.g. to spawning grounds) by mature females post-moult and high potential for measurement errors if reliant on fishermen measuring carapace widths. The majority of these factors may lead to underestimation of moulting rates for large crabs (Spencer, 2013).

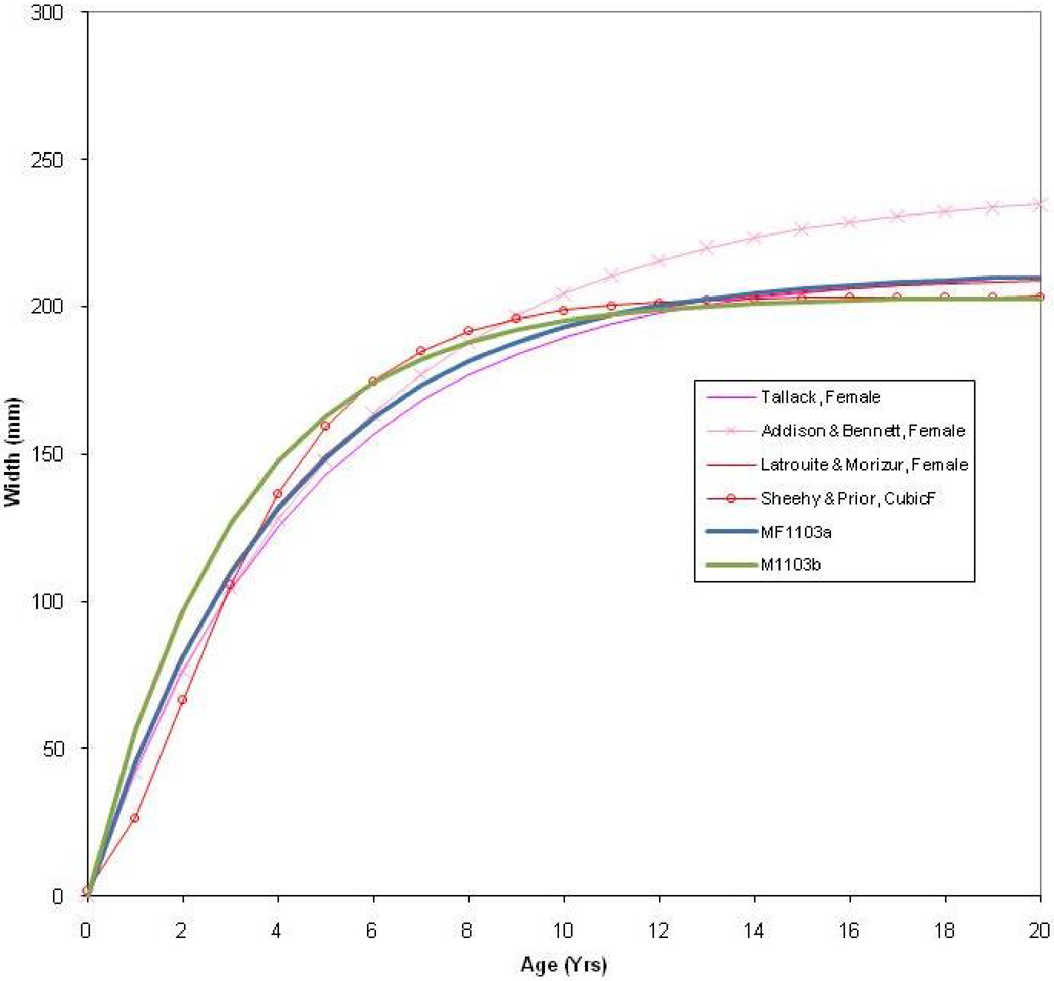

Figure 3: Comparison of von Bertalanffy growth curves for female crabs estimated by several authors (figure from (Spencer, 2013)).

2.8.2 Dynamic energy budget (DEB) model

The dynamic energy budget (DEB) theory describes the aspects of metabolism (energy and mass budgets) of organisms at the individual level, based on assumptions about energy uptake, storage, and utilization of various substances (Kooijman, 2010). It can be used to model individual crab growth under different circumstances, such as different temperature and food regimes to mimic different locations. An example of a DEB model performed for brown crab at a reference temperature of 20°C shows that males grow up to approximately 1500 gram and females to 750 gram in 8 to 11 years (Fig. 4). Model and parameter values were taken from the Add-My-Pet website (Kooijman, 2017). A complete size-structured approach, such as DEB, results in growth curves that can be compared to field data. However this was not within the scope of this desk-study.

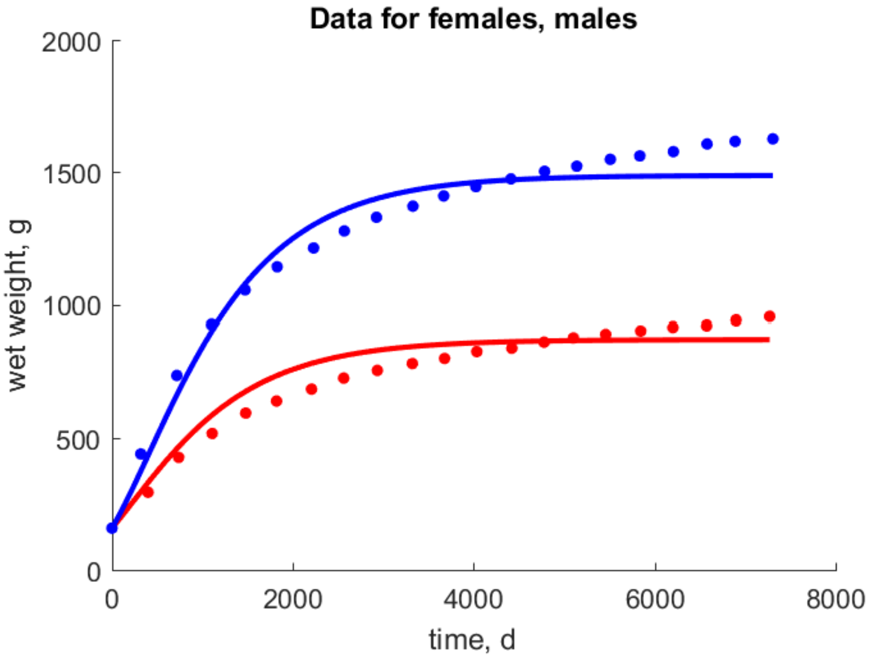

Figure 4: Wet weight (g) in time of male (blue) and female (red) *Cancer pagurus* of south-west England. Data from Bennet (Bennett, 1974) (dots) fitted to the DEB model by Kooijman(Kooijman, 2017) (line).

2.9 Distribution

The brown crab is a temperate-water crab species with a broad distribution throughout the English Channel, the North Sea, the Atlantic ocean from the northern coast of Morocco in the south extending along the Atlantic coast of Europe, to the British Isles and northern Norway in the north (about 70º N); several old recordings from the north coast of the Mediterranean (Marseille, Napoli, Greece) exist (Woll *et al*., 2006, FAO, 2015).

2.9.1 Distribution and trends based on beam trawl surveys

In order to obtain information on brown crab distribution and trends in the North Sea data from two research surveys by Wageningen Marine Research that include brown crab observations from bycatch is used. These surveys, the beam trawl survey (BTS) and the sole net survey (SNS) include crab numbers, carapace width (CW) measurements and gender determination. These data are registered in the database FRISBE. The BTS is conducted every August/September with a 8m beam trawl and a mesh size of 40 mm. The research vessel “Isis” covers the de south-eastern North Sea and conducts 1 to 4 hauls of 30 min per quadrant. The research vessel “Tridens” covers the south-western and central North Sea and performs 1 haul of 30 min per quadrant. The BTS is intended to provide a fishery independent estimate of the age of North Sea sole and plaice. An additional goal is monitoring changes in distribution and/or densities of other fish and aquatic species (specifically macro-epibenthos such as brown crab) (in Steenbergen *et al*., 2012). The Sole Net Survey (SNS) is a flatfish survey that uses a beam trawl of 6m. This survey takes place in September and covers the coast from

Belgium to Denmark (Esbjerg). The goal is to collect information on the age composition of 1 to 4 year old sole and plaice. An additional goal of the SNS is monitoring non-commercial demersal fish stock (in Steenbergen *et al*., 2012).

Brown crabs occur throughout the surveyed area (both BTS and SNS) which mainly comprises of the coastal area of the Netherlands, Denmark and the German Bight. Numbers of brown crabs captured during the survey are higher in 2010 compared to 1998 (Fig. 5, also see section 2.10 Densities) (Steenbergen *et al*., 2012). Data from the last three years show an overall increase in brown crab numbers (Fig. 6, also see section 2.10 Densities). The high density of crabs in the German Bight that is observed in 1998 is still notable in later years but due to increased brown crab numbers in inshore locations in particular (but also extension of brown crab populations further offshore) the contrast in the period 2016-2018 is less pronounced compared to previous decades. Less crabs were encountered in the northerly locations (from approx. 57°N, Fig. 5), potentially due to lower temperatures. Short term dynamics of 2016-2018 however show an increase of the northerly populations inshore of the UK in 2016-2017 (Fig. 6). Inshore locations generally show higher number of brown crabs although in many of the locations closer to the middle part of Dutch coast brown crabs were absent. With increasing distance from the coast where waters are deeper and colder a decrease in brown crab numbers is seen although this decrease is less clear in the last three years where larger populations are seen further offshore from the English coast. The number of brown crabs caught per hectare increase from south to north (near Germany and Denmark, until approx. 50km offshore).

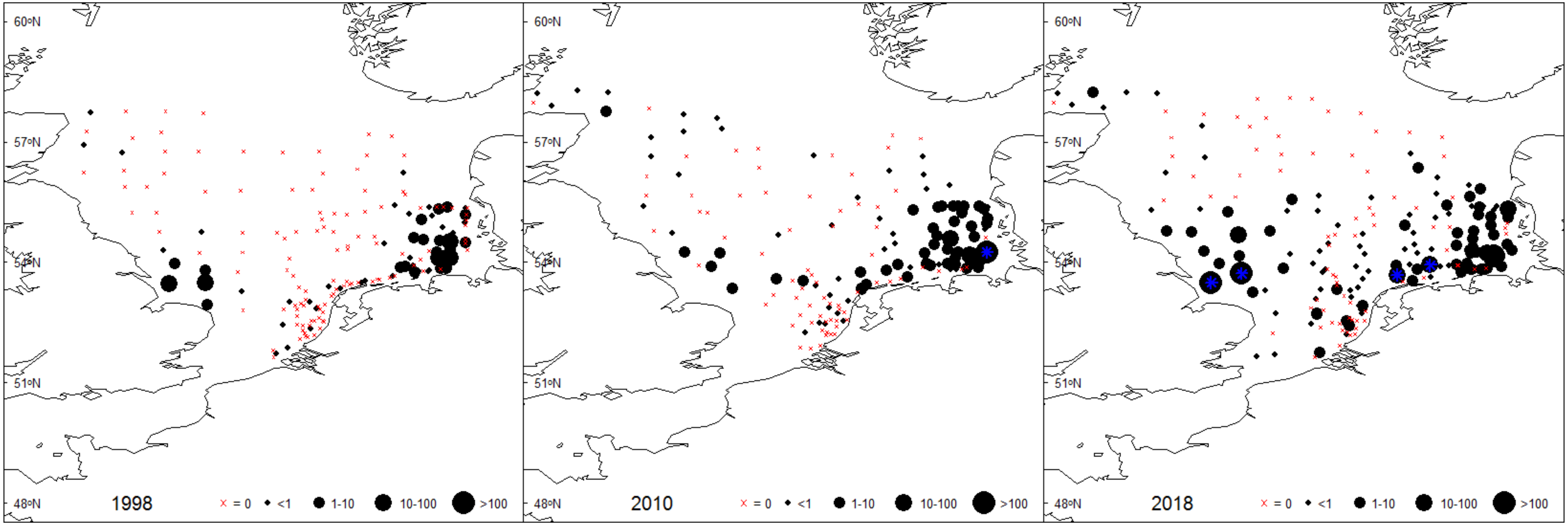

Figure 5: number of brown crabs per hectare based on catchment of two surveys (BTS) and (SNS) in 1998, 2010 and 2018. Red crosses indicate trawled locations where brown crab was not caught. Blue stars indicate locations were more than 200 crabs were caught during a single haul (figure remade from Steenbergen *et al.*, 2012 with the addition of 2018 data).

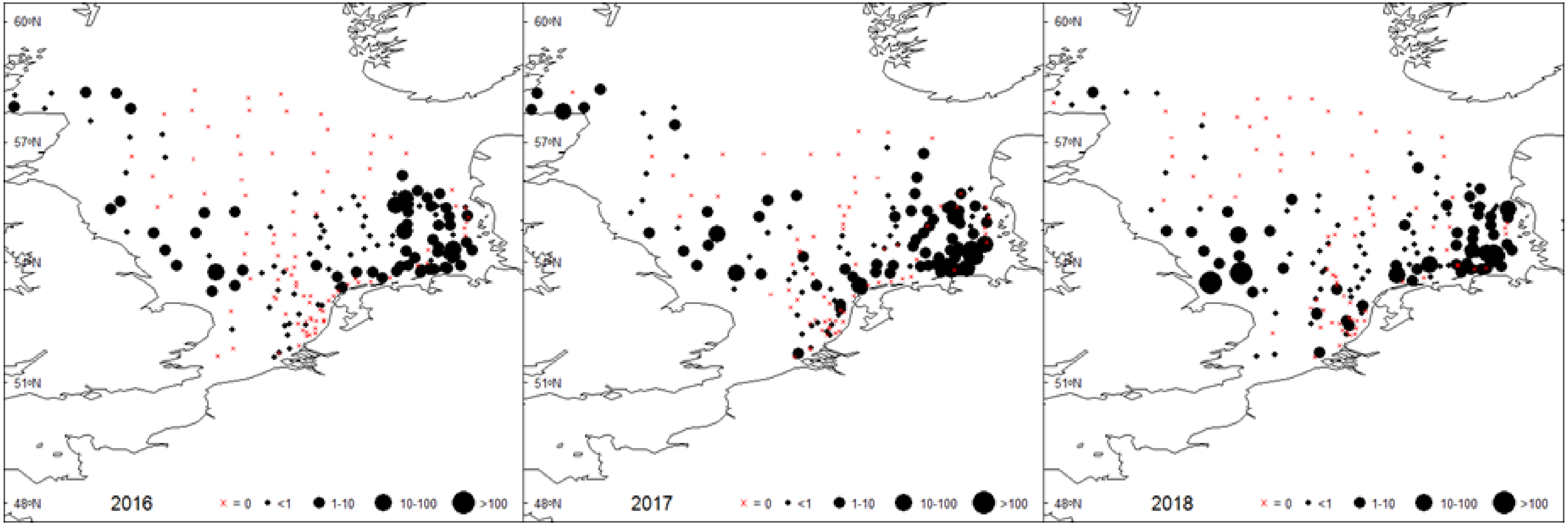

Figure 6: number of brown crabs per hectare based on catchment of two surveys (BTS) and (SNS) in 2016, 2017 and 2018. Red crosses indicate trawled locations where brown crab was not caught (figure remade from Steenbergen *et al.*, 2012 with the addition of 2018 data).

2.9.2 Distribution and trends based on brown crab fisheries

In addition, information is retrieved from brown crab fisheries conducted with 17 inch creels that were deployed west of the islands Texel and Vlieland in the Netherlands. A total of 38 tonnes brown crab was caught over a 7.5 month period (Fig. 7). The average catch success expressed as catch per unit effort (CPUE) varied between 0.1 and 0.8 kg day^{-1} creel^{-1} or between 0.1 and 1.1 crabs day^{-1} creel^{-1} and was highest in the months June/July and decreased hereafter (from week 29). Catch success may have partly been influenced by the number of days creels were left in the water, which increased after week 29. Forty-seven creels were attached to a string (with the exception of two strings that broke and were repaired, in one string of 15 and one of 35 creels). The distance between creels was about 1.6m. When creels are left in the water longer the average catch decreases due to lack of bait. The decrease in catch in week 52 was possibly due to lower water temperature which decreases the activity of crabs (Steenbergen *et al*., 2012).

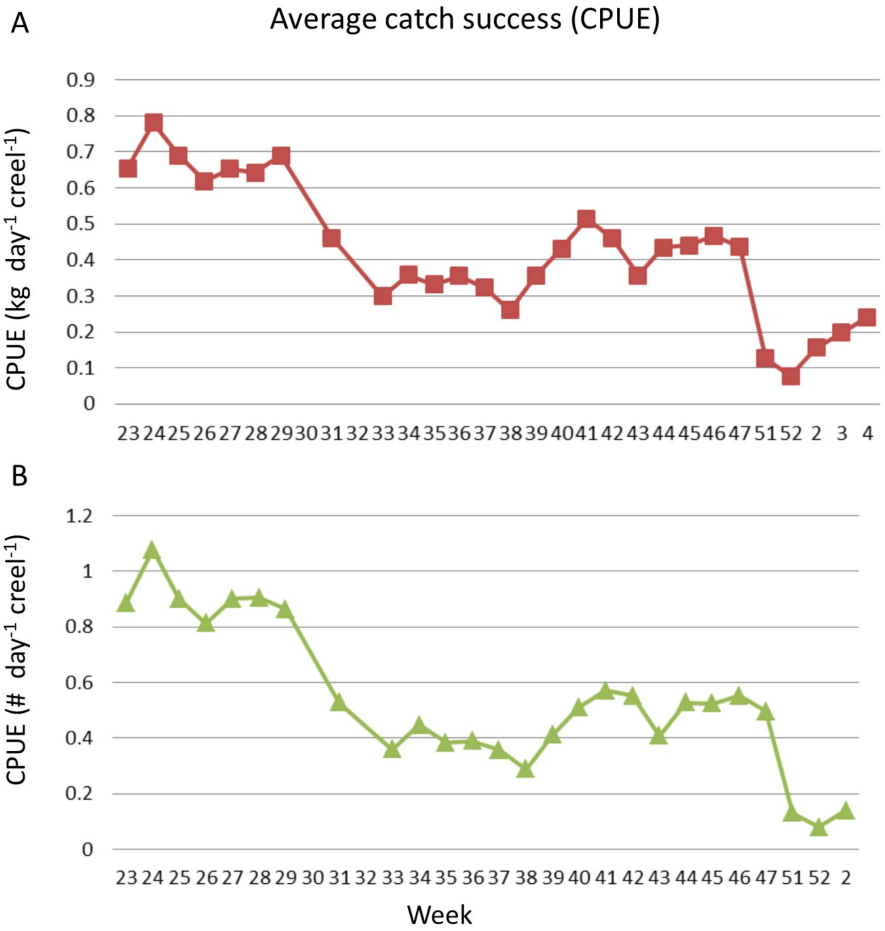

Figure 7: (A) Average CPU brown crab per week in kg per creel per day, measured in 2011 (wk 23-52) and the first weeks of 2012 (wk 2-4). (B) Average CPU brown crab per week in numbers per creel per day, measured in 2011 (wk 23-52) and the first weeks of 2012 (wk 2-4) (figure from Steenbergen *et al*. 2012).

2.10 Densities

The average density of crabs in the North Sea in 2018 was estimated at 5.0 to 6.3 number of crabs per hectare (nha) based on beam trawl surveys throughout the North Sea (Fig. 5 and 6). These are the highest average densities of brown crabs ever recorded in the beam trawl surveys and significantly higher than densities from 2017. The average number of crabs per hectare (nha) caught during the SNS surveys went up from 0.8 (1998) to 1.8 (2010) to 5.0 (2018). The BTS survey showed an increase in nha from 1.75 (1998), 2.9 (2010) to 6.3 (2018) (Fig. 8). Compared to 2010 the average crab densities have more than doubled in 2018 (Fig. 8). However this doubling is mainly due to very high densities found in surveys off the southern English coast in 2018 (see Fig. 5 blue stars from west to east respectively: n=1300 and n=618, n=220 and n=232). Brown crab density appears to fluctuate and do not show a clear pattern. Regression analyses of the average number of crabs caught from 1998 until 2018 was not significant for the SNS data and although regression analysis of the BTS data was significant (p=0.03), excluding the data from 2018 no longer resulted in a significant relation (p=0.11). A clear outlier in the BTS data of 2010 was found in the German Bight (n=618, see Fig. 5) A rough estimate of approximately 100 edible crabs per km^2 (1 per hectare) in the Dutch part of the Netherlands(or 0.01 km^2 per crab) was based on an assessment of the potential for targeted fisheries on edible crab using pots (Coolen *et al.*, 2019) (Steenbergen *et al.*, 2012). These data originated from the SNS and BTS beam trawl surveys of mostly soft substrate along the Dutch coast in 2010.

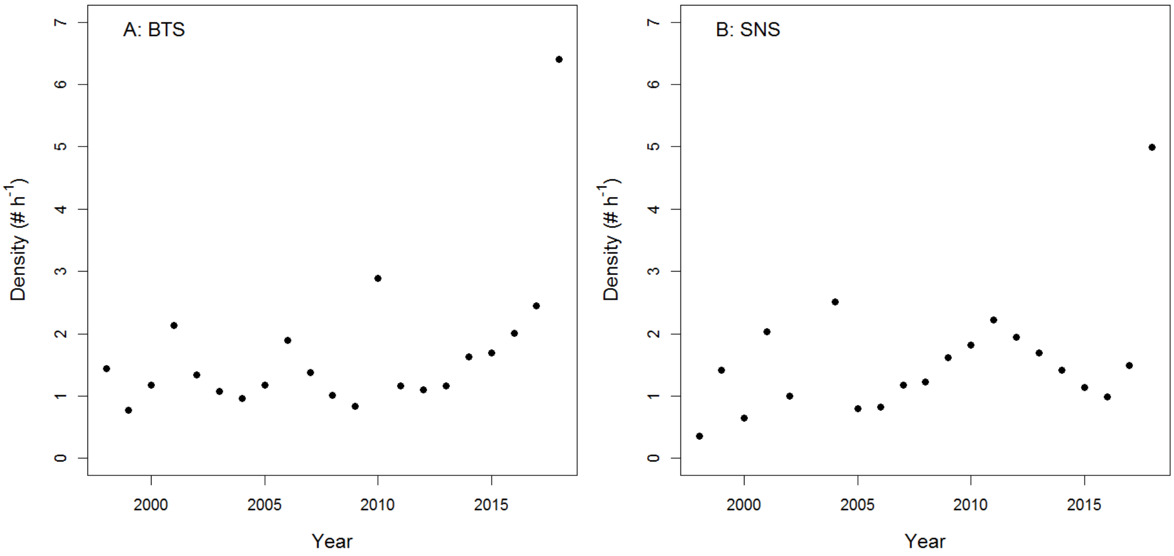

Figure 8: (A) Average number of crabs per hectare of BTS and (B) SNS trawls in the North Sea from 1998 to 2018.

2.10.1 Densities at OWF's

Various publications have shown that substantive populations of brown crab can occur near monopiles or ship wrecks in the North Sea (Bouma & Lengkeek, 2012, Coolen, 2017, Coolen *et al.*, 2018, Didderen *et al.*, 2012, Krone *et al.*, 2017, Krone *et al.*, 2013, Krone & Schroder, 2011). In the OWF Prinses Amalia *C. pagurus* densities have been monitored once, 6 years after the installation of wind turbines (Vanagt & Faasse, 2014). Video transects show maximum densities of 17.9 and 35.7 individuals per m^2 on three out of four turbines (no brown crabs were visible in the monitored sections of the fourth turbine Limited information on monitoring of offshore wind farms is available from the UK (see (Hooper & Austen, 2014, Skerritt *et al.*, 2012)). Overview of monitoring programmes in Hooper & Austen (2014) shows that the monitoring undertaken in OWF Horns Rev in Denmark was the most comprehensive and suggest that adult *C. pagurus* associate with turbine foundations, which may also serve as nursery areas. In a recent study in the German Bight (south of Horns Rev) average densities of 5,080 brown crabs were found per monopile (Krone *et al*., 2017). This was twice as much as the amount of crabs found on other foundations (tripods and jacks) without scour protection in the same study. About 80% of these crabs were found on the sea floor, while 20% was found on the foundation itself. High amounts of small individuals (age class < 2 years corresponding to a size range of 10-60 mm CW) were found on the platform. However, this varied per foundation type. At the section foundation of the jackets and the tripods, the percentage shares of the age class <2 years dominated with 73 ± 21% and 72 ± 21%, respectively. At the monopiles, the section foundation exhibited similar average values for this age class as at the section sea floor (39 ± 5%). Strong evidence was found that the foundation types not only functioned as larvae collectors but also as nursery grounds (Krone *et al*., 2017). Independent of foundation type, the sea floor was always inhabited by larger individuals than the foundation itself.

In a quick scan of the potential to upscale positive effects of scour protection on benthic macrofauna and associated fish species edible crab was used as an example to estimate density (Coolen *et al*., 2019). With an average of 5,080 brown crabs on 1,013 m^2 (equals 5.01 crabs per m^2) around a monopile foundation, Krone *et al*. (2017) extrapolated to 5,000 monopile foundations in the German North Sea (assuming installations identical to the monopile studied) amounting to 25.4 million brown crabs. They estimate that the construction of these installations will allow the edible crab population to increase with 320%. In Coolen *et al*. a background density of 100 edible crabs per km^2 is assumed which is an approximation from beam trawl surveys along the Dutch coast (Steenbergen *et al*., 2012). Extrapolating this background population to the Dutch part of the North Sea, that covers approximately 57,000 km^2, the Dutch population on the natural seabed would be approximately 5.7 million . Coolen *et al*. (2019) calculated that, with the introduction of 5,000 monopile foundations of 1,013 m^2, the population of edible crabs in the Dutch North Sea would increase 4.5 times (approximately 350% additional brown crabs) compared to the background population (25.4 million/5.7 million= 4.46). When assuming scour protections of 2,000 m^2, the estimate may even increase to 50 million, which is 8.8 times that of the background population (Coolen *et al*., 2019). The scour protection around the 60 turbines in Prinses Amalia park cover a total area of approximately 20,790 m^2 (346.5 m^2 x 60 turbines). The Prinses Amalia park in total covers 14.2 km^2. Using a similar approach as Coolen the Prinses Amalia park could provide substrate for approximately 100,000 crabs (346.5 m^2 scour protection x 60 turbines x 5 crabs per m^2 = 103,950 crabs or 7,320 crabs per km^2). Based on a background density of 100 crabs per km^2 this would imply a population of 1,420 crabs and an increase of 73 times that of the background population. It should be emphasized that this is a very rough estimation based on average densities in the Dutch North Sea and examples from a wind park situated in an area with high densities of brown crab. In addition, a large proportion (± 40%) of the brown crabs found in the German Bight OWF were smaller than 60 mm in carapace width (CW) (Krone *et al*., 2017). In the TKI project the brown crab (and lobster) population densities will be estimated for OWF Prinses Amalia, delivering first data to confirm these estimates.

2.11 Landings

2.11.1 Rules and regulations

Dutch regulations regarding fisheries have been described in the “Visserij Jaarboek” (Pronk, 2008). Brown crab is only mentioned in the regulations concerning technical measures (Regeling Technische maatregelen, article 7c). This article states that it is illegal to land or keep brown crabs on board unless this is permitted based on article 18, third or fourth act, regulation no 850/98. Article 18 states that marine organisms are to be measured according to appendix XIII of the fishery yearbook 2008 (Pronk, 2008). Act 4a: Bycatch of brown crab caught in pots may consist of no more than 1% of the amount of total catch of brown crab and parts there off that are kept on board or are landed at the end of the trip, of detached claws. 4b: Bycatch of brown crab caught with other fishery gear then pots may, at any time during the trip, consist of no more than 75 kg in detached claws either on board or landed at the end of the trip. Basically, the fishery is managed with minimum conservation reference size (MCRS) that replace previously used minimum landing size limits (MLS). MCRS is applied as a primary tool to preserve the reproductive potential, but there are no quota or effort regulations. The MCRS of brown crab is determined by measuring the maximum width across the carapace (CW) perpendicular to the median along the front-and back of the carapace. MCRS according to appendix MMO are shown in Table 2. In the Netherlands fishermen are obliged to register brown crab landings (in kg) in logbooks (Steenbergen *et al*., 2012).

To ensure a sustainable way of fishing is maintained standards have been set by the Marine Stewardship Council (MSC). MSC is an international independent non-profit organization founded in 1996 which sets a standard for sustainable fishing by applying a science-based way to measure sustainability. Three main principles are taken into account to acquire MSC certification: 1) maintaining sustainable fish stocks, 2) minimising environmental impacts and 3) effective fisheries management. Fisheries that wish to demonstrate they are well-managed and sustainable according to the MSC standard are assessed by a team of experts who are independent of both the fishery and the MSC. Seafood products can display the blue MSC ecolabel only if that seafood can be traced back through the supply chain to a fishery that has been certified according to the MSC standard. In the United Kingdom MSC certified brown crab is available from Orkney and Shetland (MSC, 2019). To date, no Dutch brown crab fisheries have acquired MSC certified yet.

Table 3. Minimum Conservation Reference Size (MCRS) according to Article 18, appendix VIII per region (the North Sea is divided in regions accompanied with differences in MCRS).

Region	ICES sector	Location	MCRS	Exception
Region 1 and 2		north of 56 °N	140 mm	
Region 2		south of 56 °N	130 mm	ICES-sectors VIId, e and f and IVb and c
Region 2	ICES sectors IVb and c	south of 56 °N	130 mm*	
Region 2	ICES sectors VIId, e and f	south of 56 °N	140 mm	
Region 3			130 mm	

* With the exception of an region bordering a point on the English coast at 53°28’22” norther length and 0°09’24” easterly, the six mile border of the United Kingdom and a straight line between a point at 51°54’06” norther length and 1°30’30” eastern length, with a point on the English coast at 51°55’48”northerlength and 1°17’00” eastern length, where the MCRS is 115 mm.

**Statutory Instrument 2000/ 2029 The Undersized Edible Crabs Order 2000. Applies to UK vessels only

2.11.2 Landings

The brown crab is a commercially important decapod and is exploited throughout Western Europe, from Norway to northern France (Karlsson & Christiansen, 1996). It was worth £13.8 million (€16.1 million) in 2013 in Scotland alone and is the most valuable crab fishery in UK waters (Haig *et al*., 2016). Total annual catches in Europe are in the order of 50,000 tonnes (FAO, Fig. 9A). In the UK, which encompasses the largest brown crab fishery industry, landings have increased by 57% since 1996 to 34,000 tonnes in 2017 (MMO, 2017). Ireland comes second with a brown crab fishery fluctuating around 7000 tonnes and France and Norway approximately 5000 tonnes that are harvested annually (Fig. 9B).

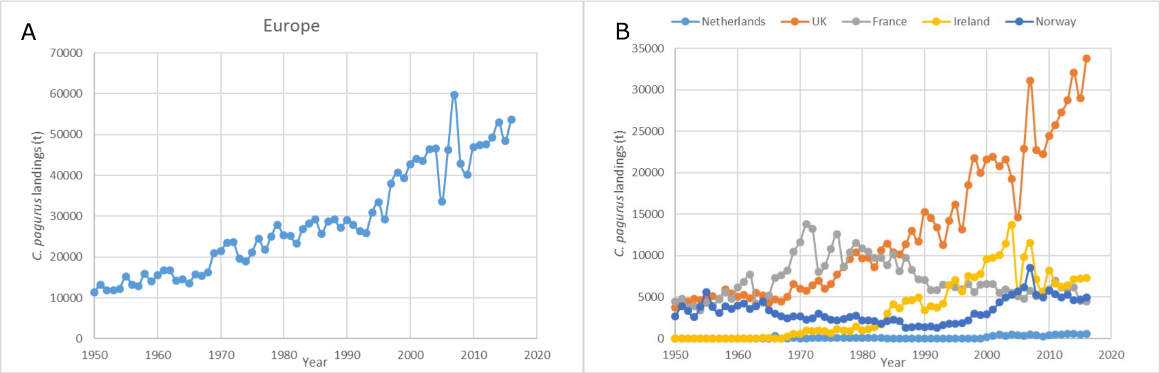

Figure 9. Commercial catch of *Cancer pagurus* in tonnes (t) 1950 – 2016 accumulated for Europe (A) and the four main parties (UK, Ireland, France and Norway) and the Netherlands (B). Data from http://www.fao.org/fishery/statistics/global-capture-production/query/en (access date: 27-02-19).

Landing data from Dutch fisheries is additionally registered in VISSTAT. Steenbergen *et al*. (2012) used information from this database to create an overview of annual brown crab landings between 2000 and 2011, average landings per month between 2000 and 2010 and the origin of landings between 2000 and 2010. In the Netherlands crab landings varied between 130 tonnes (in 2000) to 490 tonnes (2002) from 2000 to 2011. Average landings were highest from August until November (Steenbergen *et al*., 2012). These numbers are derived from the total Dutch fishery efforts and include fisheries directed towards other species than brown crab. Landing data up to 2017 derived from FAO complements this dataset and shows a slightly increasing trend from 2009 to approx. 550 tonnes (Figure 10). Most of the landings in the period from 2000-2010 are from the German Bight. Closer to the Dutch coast most crabs are caught north of Terschelling and near the Zeeland coast (Fig. 10, Steenbergen *et al*., 2012).

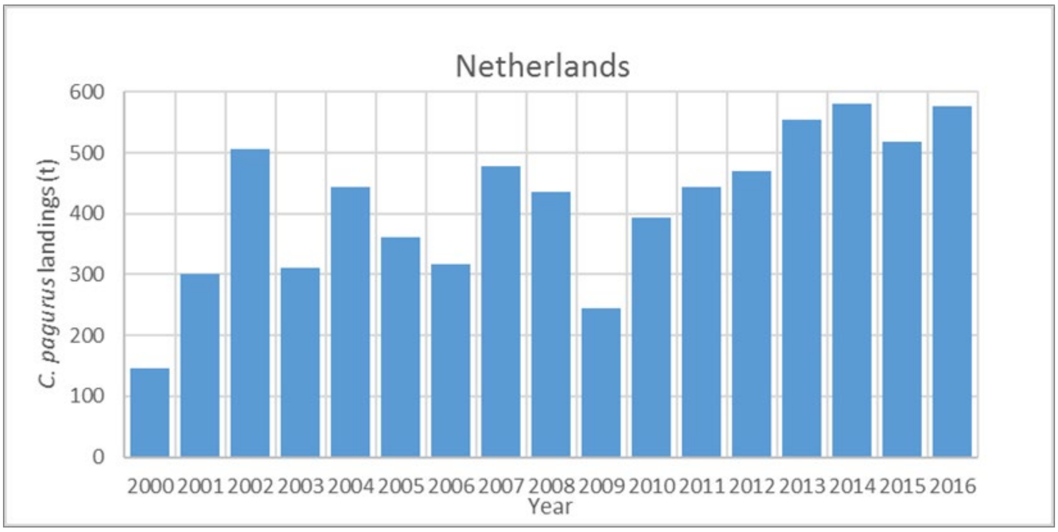

Figure 10. Commercial catch of *Cancer pagurus* in tonnes (t) 2000 – 2016 for the Netherlands. Data from http://www.fao.org/fishery/statistics/global-capture-production/query/en (access date: 27-02-19).

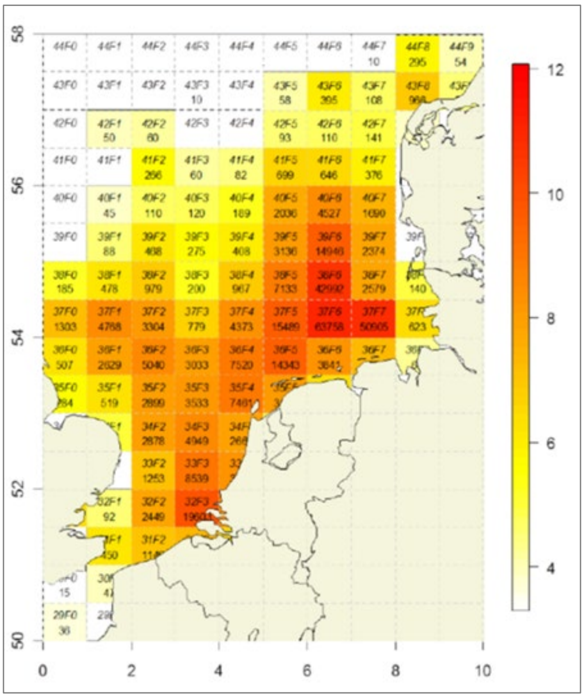

Figure 11: Total brown crab landings per ICES quadrant, average amount in kg per year in the period 2000-2010. The code represents one ICES quadrant (for example: 37F3). The number indicated below the quadrant code represents the average brown crab landings in kg. The legend is in logarithmic scale (figure from Steenbergen *et al.*, (2012)).

2.12 Stock assessment

The Centre For Environment Fisheries And Aquaculture Science (CEFAS) has published reports describing the status of brown crab stocks around the UK, including the central North Sea and the southern North Sea, since 2012 and plans to re-run the assessment every 2 years (CEFAS, 2017). Landings originate from the official Marine Management Organisation (MMO) data records. Between 2006 and 2008, MMO landing data were supplemented by self-reported records of landings from the Monthly Shellfish Activity Return (MSAR) forms. In the 2017 assessment CEFAS combined MSAR data and MMO landings for the <10m fleet. Fishing effort is derived from MSARs for <10m vessels and EU logbooks for >10m vessels. There is no requirement for potting fisheries to record the number of pots being fished, so effort is measured as days fished. The changes to reporting systems over time have predominantly improved the data quality but mean that landings and effort series cannot be viewed as coherent records through time. Within the European Community framework, the current management objective is to achieve fishing rates likely to deliver Maximum Sustainable Yield (MSY) from fisheries. This means the maximum landings that can be regularly taken without causing stock collapse. For crustacean fisheries scientists cannot directly calculate this rate and therefore they rely upon alternative ways to estimate it. This assessment uses 35% of virgin Spawner per Recruit (SpR) as the MSY level proxy, and this is commonly used around the world to estimate the fishing rate likely to deliver MSY. A second point termed a limit reference point has also been calculated and having fisheries operating beyond this level is considered to carry higher risk to the production of further generations. This value is defined as 15% of virgin SpR (CEFAS, 2017).

2.12.1 Central North Sea

There are five Crab Fishery Units (CFU) that have been defined for the UK. These units are based upon the understanding of larval distributions and development, hydrographic conditions and distribution of the fisheries (CEFAS, 2017). The spawning stock biomass of brown crab in the central North Sea is approaching the recommended level for females but remains low and around the minimum recommended level for males (Fig. 12). Exploitation level is moderate on females and, although likely to be sustainable is above the level required for maximum sustainable yield. There has been a trend of increasing exploitation rate on males but this may have dropped slightly in recent years. The status of the stock has not changed since the last assessment in 2014 (CEFAS, 2017).

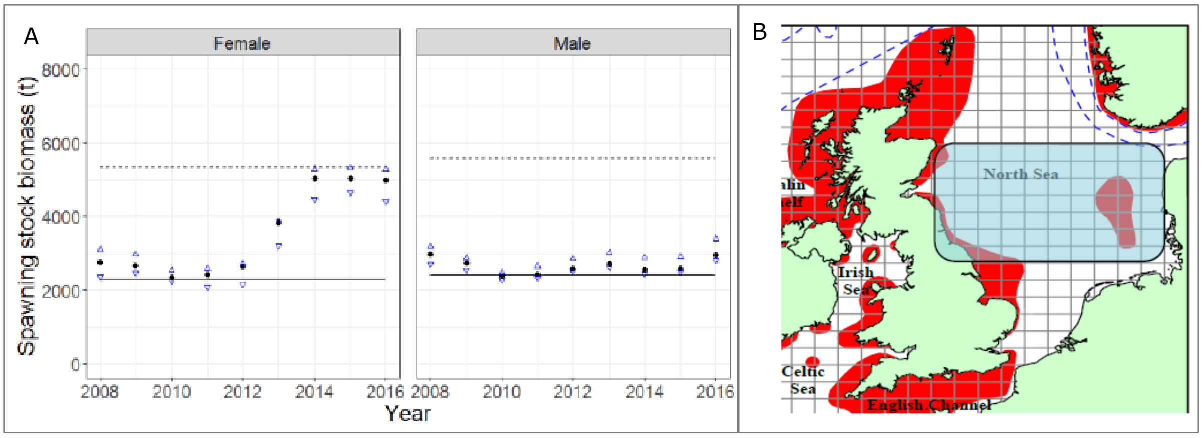

Figure 12: (A) Time series of biomass estimates and MSY target (dashed) and minimum reference point limit (solid). (B) The box indicates the central North Sea crab fishery unit (CFU) assessment region, brown crab distribution is indicated in red (figures from CEFAS, 2017).

2.12.2 Southern North Sea

The spawning stock biomass of brown crab in the Southern North Sea is approaching the recommended level for females but remains low and around the minimum recommended level for males (Figure 8). Changes in the way landings have been recorded in 2006 and 2009 mean the data are inconsistent and unsuitable for assessment. Calculations of fishing mortalities are unaffected by the issues with landings and mortality rates are high, around the maximum reference point limit for both females and males (CEFAS, 2017).

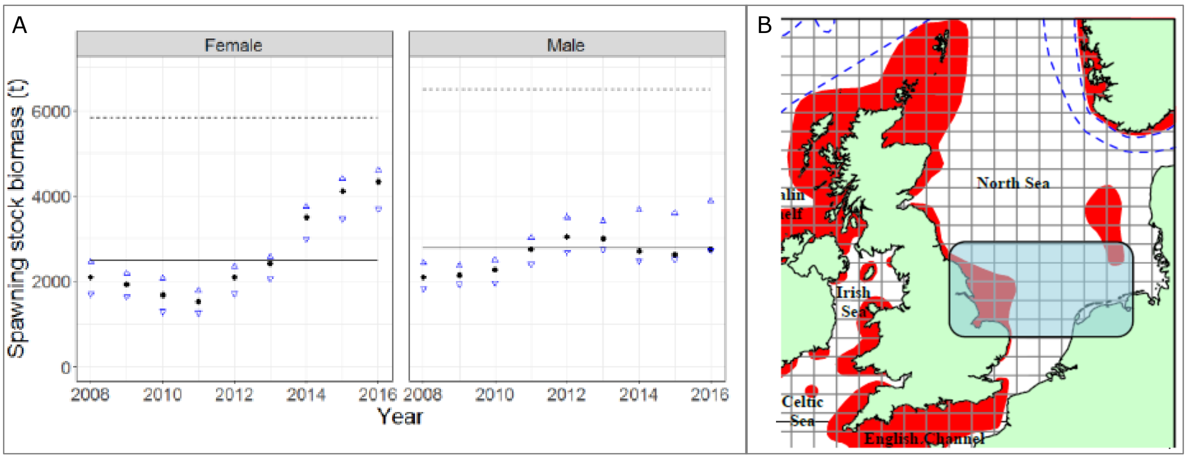

Figure 13: left, time series of biomass estimates and MSY target (dashed) and minimum reference point limit (solid). Right, the southern North Sea crab fishery unit (CFU) assessment region, brown crab distribution is indicated in red (figures from CEFAS, 2017).

3 Discussion, conclusions and recommendations

3.1 Main findings

3.1.1 Description, biology and habitat

The brown crab is a robust predator with a relatively long life expectancy of about 25-30 years. Most vulnerable stages of the brown crab lifecycle are the planktonic and early benthic stage, when they are most susceptible to predation. Unlike lobsters, brown crabs are not obligate reef-dwellers since they can bury themselves in the sandy bottom and are therefore less dependent on shelter such as crevices. Like most marine invertebrates brown crabs are osmoconformers and appear poorly equipped for changes in salinity and seawater CO_2 (Whiteley *et al*., 2018). This potentially makes them susceptible to ocean acidification, the decrease in pH due to the uptake of CO_2 from the atmosphere.

Sizes vary regionally and North Sea brown crabs are generally of smaller size then individuals from the English Channel. Spatially, the biomass that can be removed sustainably will depend on growth rate, which in turn is likely to vary with temperature and hence latitude (Bakke *et al*., 2018), mortality and reproduction but also depends on age, sex and water depth. Recently reported CW50 estimates are smaller than previously reported values for *C. pagurus* populations (Haig *et al.*, 2016). The reason for this remains unclear since the variety of laboratory and statistical methodologies used in previously published studies prevent absolute comparisons results in Haig *et al*. (2016). The age at which brown crabs become fertile is also likely to vary regionally. This has implications for management through appropriate MCRS restrictions (ranging between 130-140 mm) that are set to conserve the reproductive potential of brown crabs. A standardized methodology for size at maturity research along with an open-access data service are suggested to ensure collaborative research and contribute towards more accurate estimates that reflect regional differences in CW50 (Haig *et al*., 2016).

3.1.2 Growth modelling

Growth data to estimate growth rates for brown crab is rather scarce. The studies that have been conducted show a wide variation in estimates making it difficult to draw specific conclusions. Variation in growth rates exist between regions and within regions and the assumed influence of latitude in driving these differences is inconclusive (Tallack, 2002). The problems associated with applying continuous growth models (VBGF or DEB) to discontinuous growth data for crustaceans, due to moult processes, leads to uncertainties in growth estimates. Where possible, local growth rates specific to the population being studied should be estimated and used as input parameters.

A DEB model on lobster production in OWF shows that 1 lobster per monopile can reach marketable size (85 mm carapace length (CL) in Dutch waters) after 3 years when stocked at a length of 50 mm carapace length (Rozemeijer & van de Wolfshaar, 2019). Without restocking it takes about 6 years for lobsters to reach 87 mm CL. It takes about 4 years for brown crabs to reach marketable size (130 mm CW) (Tallack, 2002). Various publications have already shown that substantive populations of brown crab can occur near monopiles or ship wrecks and that lobsters occur to a lesser extent or not at all (Hiscock *et al*., 2002, Krone *et al*., 2011, 2015, 2017, Steenbergen *et al*., 2012, Bouwma & Lengkeek, 2012, Didderen *et al*., 2013, Lengkeek *et al*., 2017, J. Coolen, WMR Pers. Comm.). The local maximum production capacity of brown crab will depend on the background population, the colonisation success (including migration patterns and specific interactions between monopiles and different life stages of brown crab), growth rate and the local carrying capacity. It poses questions about how one lobster needs the entire antiscouring surface of one Prinses Amalia OWF monopile to sustain itself (1 lobster per ± 346 m^2) (Rozemeijer & van de Wolfshaar, 2019), whereas estimated densities of brown crab are much higher, even up to 5 per 1 m2 (Krone *et al.*, 2017). One questions whether the necessary food is available to support such a population. The soft sediments could be a food source but with a typical density of 1 brown crab per 100 m2, as is found in soft sediment surveys, a high carrying capacity of soft sediments for crabs is unlikely.

3.1.3 Reproduction, diet, mobility & genetics

Female crabs with eggs that bury themselves in the sand are less susceptible to be caught in crabbing pots during the berried (oviparous) stage (Ondes *et al.*, 2019), which poses an advantage in terms of keeping stock above recommended levels. The proposed function of monopiles acting as larvae collectors may also benefit local population densities however little is known about the early settlement of juvenile brown crabs and how this interaction takes place. Settlement cues and food supply are possible contributors. The mobility of brown crabs, especially females, show high potential for colonization of the OWF's in the Dutch North Sea.

Genetic studies in the Kattegat-Skagerrak and UK area support this with evidence of large-scale genetic mixing, but also show significant genetic variation at relatively local scales. The more wide-spread area from which larvae may originate demonstrated by the westward migration of female brown crabs, may help explain at least some of the apparent discrepancies in population genetics (Hunter *et al.*, 2013).

The addition of hard substrate and associated mussel settlement on these substrates (Kamermans *et al.*, 2016) may increase the carrying capacity of these areas for brown crab. An assessment of enhancement strategies can assist with the design of innovative OWF scour protection to increase attractiveness of these areas for brown crab. Monitoring of population density is needed to estimate maximum catchment rates to ensure sustainable fisheries.

3.1.4 Ecological position in the trophic network

Although the economic importance of decapods to humans for consumption is well documented and frequently discussed (Steneck *et al.*, 2011), we are only beginning to understand the role that decapods play in marine ecosystems, and how exploitation or large-scale addition of substrate in the form of monopiles might modify this role (Boudreau and Worm 2012). Knowledge of predation behaviour is needed to understand predator–prey interactions as well as consequences for the trophic network. In general, experiments where decapod predators were excluded consistently reported an increase in benthic infaunal or epifaunal density, changes in species composition, and sometimes cascading effects affecting various epifauna and vegetation. The available evidence suggests that large decapods can play important roles in structuring benthic communities. However, it is not clear how general these roles are and to which extent they can be assumed across species (Boudreau & Worm, 2012). The limited information currently available regarding constraints and opportunities of decapod fisheries in OWF's demonstrates the need for further research into the ecological and socio-economic issues surrounding fishery co-location potential (Hooper & Austen, 2014).

3.1.5 Distribution and densities

The German Bight, an important area for brown crabs that provides rich crabbing grounds (Steenbergen *et al.*, 2012) is a good example for the substantive populations that can occur near monopiles (Krone *et al.*, 2017, Krone *et al.*, 2013). The scour protection around monopiles in this region show great potential to enhance certain benthic species. The addition of hard substrate in the form of wind turbine scouring in 2012 acted as larvae collectors and an average of 5,000 brown crabs per monopile were observed (Krone *et al.*, 2017). The addition of another 5,000 monopiles in the future is suggested to provide new artificial reef habitat for another estimated 320% brown crabs. However, it is unclear how the increased amount of crabs at monopiles in the German Bight will affect the carrying capacity and whether the available food supply will sustain sufficient growth of these crabs. Follow up studies including growth rate and survival are needed to provide more insight on how this expansion in crab population will develop and the effect on the carrying capacity of the ecosystem needs to be assessed. In addition, displacement of soft sediment fauna or less opportunistic hard substrate benthic species is to be expected following the steep increase in brown crab population density. The study by Krone *et al*. (2017) illustrates a potential system shift towards a future North Sea fauna, which displays a more important role of certain reef animals than in the current state of the North Sea.

Nonetheless, these findings show huge potential for the envisioned crab fisheries in Dutch OWF's further south in the North Sea. However, it is not known how the extraordinary amounts of brown crab associated to monopiles in the German Bight infer to the OWF's in the more southerly North Sea since natural crab densities in the German Bight are higher, potentially due to the availability of suitable habitat in this area. The seabed substrate in the German Bight is a mix of sand and more course substrate (see Fig. S1). In addition Helgoland and the numerous OWF's in this area (see Fig. S2) provide hard substrate for larvae settlement. Other factors such as food availability and the geographic positioning of the German Bight may also play a role. Relatively little is known about brown crab densities further south in the North Sea. Based on a roughly estimated background density of 100 crabs per km^2 (Steenbergen *et al*., 2012) a quick scan calculation resulted in an estimated increase of 4.5 times, or even 8.8 times in population growth when assuming larger scour protections (Coolen *et al*., 2019). Using a similar approach as Coolen the 60 turbines at the Prinses Amalia park could provide substrate for approximately 100,000 brown crabs which is a 73 times increase assuming a background population of 100 crabs per km^2. This is a very rough estimation based on average densities in the Dutch North Sea and uses examples from a wind park situated in an area with high densities of brown crab. In addition the 5,080 crabs found around the monopile foundations in the German Bight included all size ranges (especially smaller specimens) and these monopiles are suggested to function as larvae collectors. It should be noted that the relationships of crabs to artificial structures can be extremely complex and species specific (Page *et al*., 1999). Therefore extrapolation of this data needs to be treated as a very rough indication and more accurate densities of brown crabs are needed to provide a better insight. In the TKI project the brown crab (and lobster) population densities will be estimated for OWF Prinses Amalia, delivering first data to confirm these estimates.

3.1.6 Landings and stock assessment

Brown crab is of substantial commercial importance with an average 50,000 tonnes in landings yearly. The UK has the largest brown crab fishing industry whereas the Netherlands play a much smaller part (approx. 550 tonnes). Dutch fishery efforts from 2000 to 2011 show that average landings were highest from August until November (Steenbergen *et al*., 2012). In increase in landings is shown from 2009 onwards (Fig. 10). According to the FAO's latest stock assessments the spawning stock biomass of brown crab in the central and southern North Sea is approaching the recommended level for females but remains low and around the minimum recommended level for males.

The fishery is managed, with MCRS applied as a primary tool to preserve the reproductive potential, but there are no quota or effort regulations. The MCRS is set at 130 and 110 mm carapace width (CW) for crabs caught north and south of 62°N, respectively (Bakke *et al*., 2018). As *C. pagurus* is a seasonal synchronous breeder, the operational sex ratio (the ratio which influences mating success) is dependent on the length frequency, density and proportion of available males in the population (Duffy & Thiel, 2007). Males may come under higher fishing pressure as markets desire the larger claws with higher white meat yield. Therefore, it would be important to manage towards a suitable length frequency for both sexes. The variable migratory and behavioural differences between male and female *C. pagurus* (Brown & Bennett, 1980, Hunter *et al*., 2013) make it difficult to determine the functional sex ratio, as bias will be present in fisheries catches (Woll *et al*., 2006) in (Haig *et al*., 2016).

Enhancement strategies in OWF's such as food and habitat provision have been assessed for commercial species such as the European lobster (Rozemeijer & van de Wolfshaar, 2019). This desk study concluded that all enhancement strategies (habitat, stock and food) have potential. However, monitoring in OWF’s is necessary to describe the actual situation in OWF’s. In the TKI project the brown crab (and lobster) population densities will be estimated for OWF Prinses Amalia, these data will be used in an assessment of potential enhancement strategies. In a quick scan approach, reproduction appears to be plentiful and many juvenile crabs can be expected. Although food availability appears to be abundant, for instance such as mussels that are known to colonize hard substrates in OWF’s, it may not be enough to support high densities of adult brown crab. Depending on the sizes of crevices in the scour protection, habitat enhancement through the addition of custom-sized broad crevices for brown crab (and more narrow and deeper crevices for lobsters) may be used to increase the density of adult brown crabs. To address the potential low densities of large males a possible approach could be the designation of closed areas to increase the male stock to the recommended level.

3.2 Conclusions

In this report the available information on brown crab ecology combined with the newest data on catchment was used to make a first tentative to estimate the harvest potential of the North Sea crab in OWF’s. Various publications show that substantive populations of brown crab can occur near monopiles. These findings along with reproductive and behavioural traits of brown crabs demonstrate the potential for successful colonisation of offshore wind farms and the development of sustainable brown crab exploitation. The local maximum production capacity of brown crab will depend on the background population, the colonisation success (including migration patterns and specific interactions between monopiles and different life stages of brown crab) and the local carrying capacity (food and habitat availability). Monopiles have been designated nursery grounds and larvae collectors for brown crab. However, many uncertainties concerning extrapolation to more southern parts of the North Sea, carrying capacity and ecosystem interactions exist. Displacement of soft sediment fauna or less opportunistic hard substrate benthic species are among the scenarios of brown crab population density induced ecosystem shifts. Future research is warranted to create insight in the role of brown crab in marine ecosystems, local maximum production capacity and how exploitation or large-scale addition of substrate such as monopiles might change this role.

3.3 Recommendations

3.3.1 Biology

Little is known about the early life stages of brown crab. Monopiles have been named larvae collectors, however, interactions between the monopiles at different life stages of brown crab, including settlement cues and larvae behaviour need further investigation to create insight in the effect of monopiles on local population density.

The age at which brown crabs become fertile is likely to vary regionally. Moreover, North Sea brown crabs are generally of smaller size then individuals from the English Channel. This has implications for management through appropriate MCRS restrictions (ranging between 130-140 mm) that are set to conserve the reproductive potential of brown crabs. Monitoring the age at which brown crabs become fertile at proposed OWF sites can provide insight whether the regionally set MCRS is sufficient to preserve the local population. In addition escape hatches can be used to allow the escape of undersized crabs.

3.3.2 Growth

DEB can be used to model individual crab growth under different circumstances. A complete size-structured approach, such as DEB, results in growth curves that can be compared to field data. Although this was not within the scope of this desk-study, DEB modelling is recommended in combination with planned monitoring in OWF Prinses Amalia to quantify local production potential.

3.3.3 Density

Although the potential for low impact fisheries on brown crab looks promising more insight is needed in local brown crab densities in Dutch OWF's to estimate production capacity. In the TKI project the brown crab (and lobster) population densities will be estimated for OWF Prinses Amalia, delivering first data to confirm these estimates. Given the high mobility and the summer winter trekking, migration could play an important role in restocking an OWF during the seasons and over the seasons allowing more harvests. Research is needed to assess this mobility.

3.3.4 Landings and stock assessment

According to the latest stock assessments in the UK the spawning stock biomass of brown crab in the southern and central North Sea is approaching the recommended level for females but remains low and around the minimum recommended level for males. As mentioned under 3.3.1 insight in the age at which females and male crabs from local populations become fertile may improve the management of spawning stock biomass. Males may come under higher fishing pressure as markets desire the larger claws with higher white meat yield. It is therefore important to manage towards a suitable length frequency for both sexes.

Enhancement strategies of habitat, stock and food have the potential to increase production capacity and will be assessed in a follow up report. The designation of closed/no take areas is suggested to address the potential low densities of large males in the Dutch OWF's.

3.3.5 Reproduction, diet, mobility & genetics

The mobility of brown crabs, especially females, show high potential for restocking the OWF's in the Dutch North Sea. Innovative design options need to be explored to enhance attractiveness perhaps through the positioning of the monopiles in the park (distance between monopiles, positioning towards the current) or monopile scouring adaptions.

Low impact crab fisheries show high potential in OWF's, follow up questions are 1) to determine whether food supply is sufficient either on the monopiles or the surrounding sediment and 2) when large crabs are caught how long does it take to restock?

3.3.6 Ecological position in the trophic network

In addition, relatively little is known about the role of brown crab in marine ecosystems and how exploitation or large-scale addition of substrate such as monopiles might change this role (for example, ecosystem shifts). Information on interaction of brown crab and European lobster may aid in the design of placing pots and creels to ensure optimal catch success. In addition, extra substrate could be designed towards the specific needs of one or both species (broader crevices for brown crabs or narrow, longer crevices for lobsters).

4 Acknowledgements

We would like to thank TKI and RVO for funding opportunities, Ingeborg de Boois for providing data and Brenda Walles and Jeroen Wijsman for assistance with R.

5 Quality Assurance

Wageningen Marine Research utilises an ISO 9001:2008 certified quality management system (certificate number: 187378-2015-AQ-NLD-RvA). This certificate is valid until 15 September 2018. The organisation has been certified since 27 February 2001. The certification was issued by DNV Certification B.V.

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Justification

Report number C064/19
Project Number: 4316100149

The scientific quality of this report has been peer reviewed by a colleague scientist and a member of the Management Team of Wageningen Marine Research

Approved: Jeroen Wijsman
Researcher

Signature:

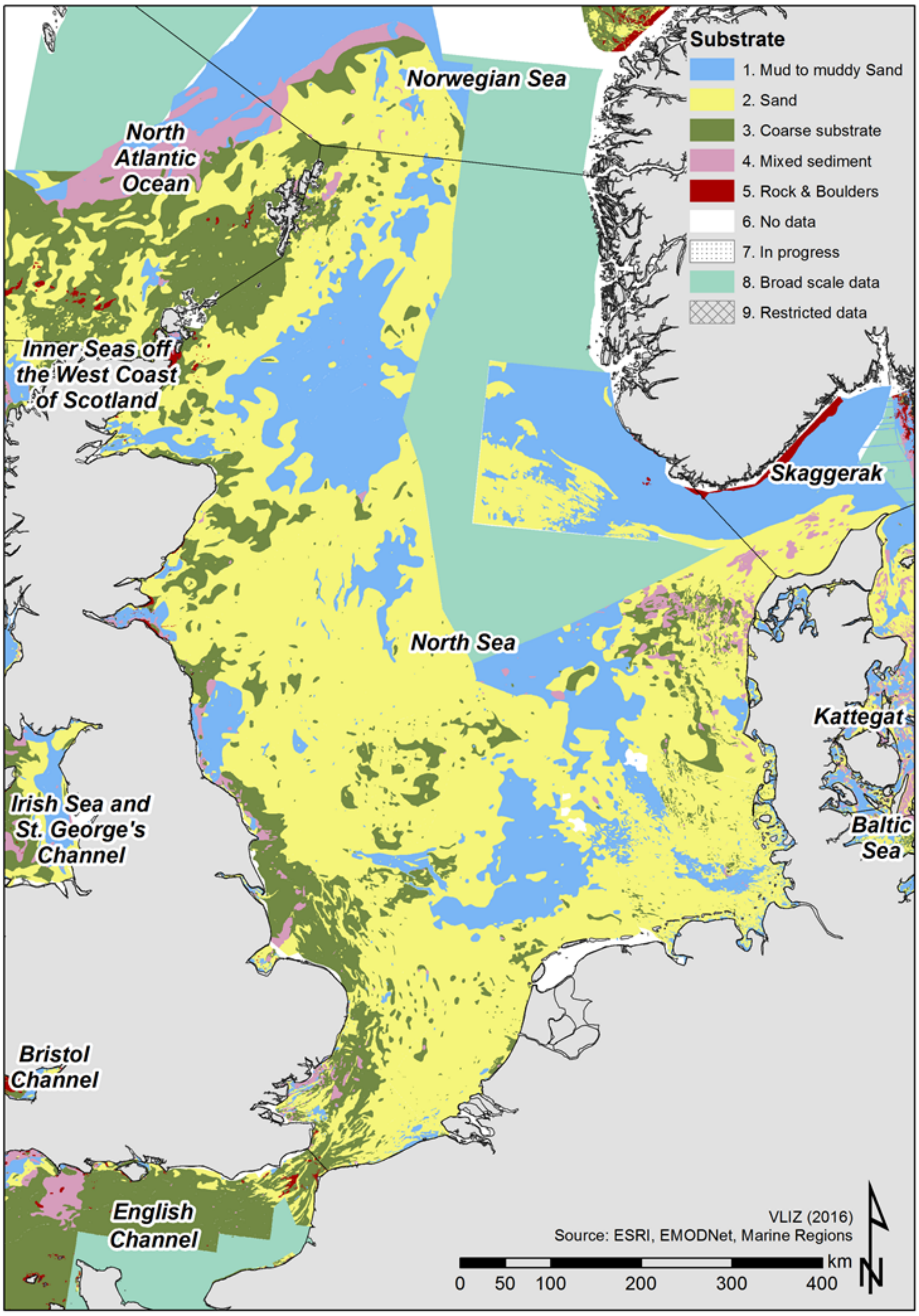
Date: 10 July 2019

Approved: Jakob Asjes
Manager Integration

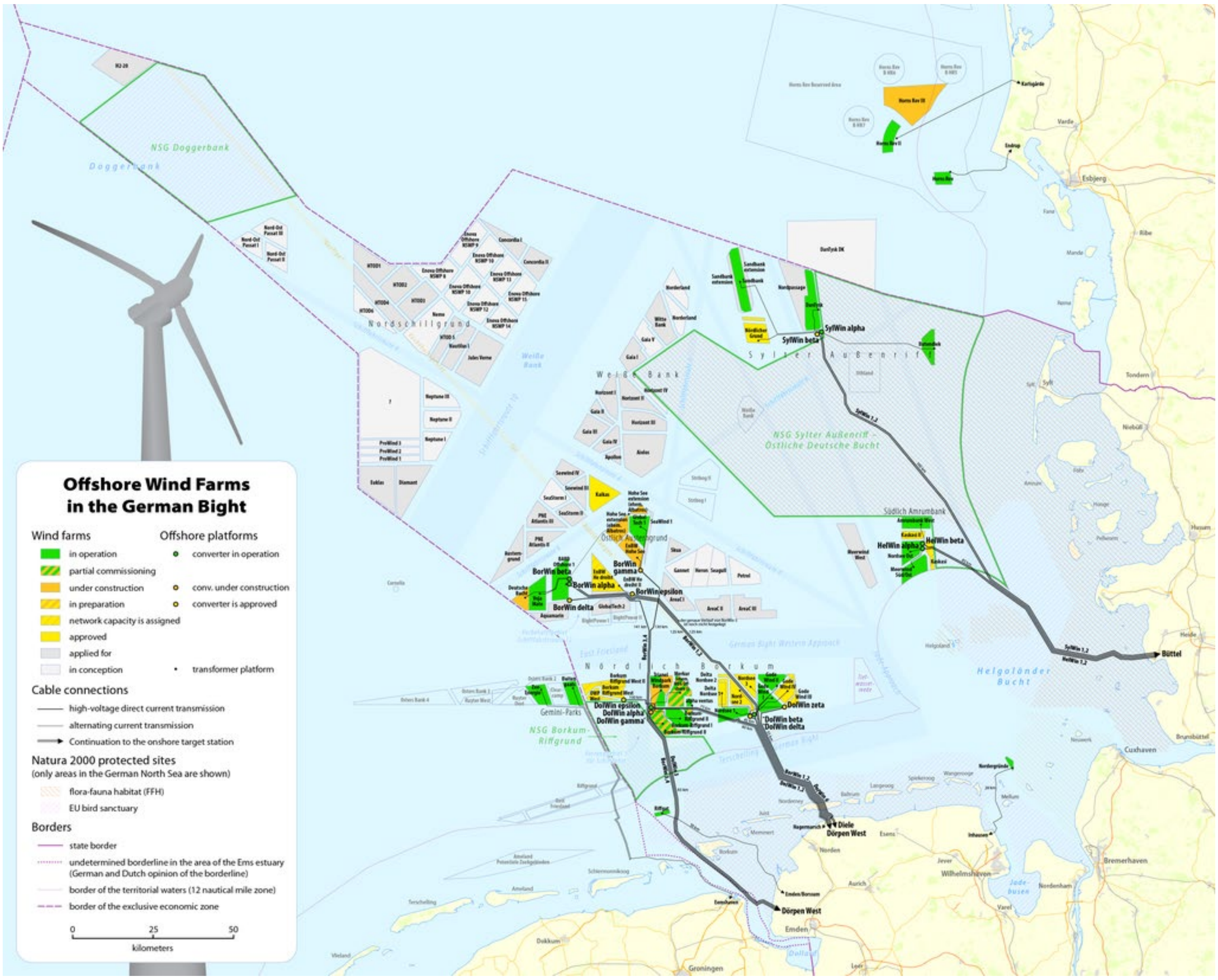
Signature:

Date: 10 July 2019

Annex 1 Supplementary figures



Supplementary figure 1: Seabed substrate types of the North sea (Figure from de Hauwere (2016)).



Supplementary figure 2: OWF’s in the German Bight. Figure by M. Dorrbecker. https://en.wikipedia.org/wiki/List_of_offshore_wind_farms_in_Germany#/media/File:Map_of_the_offshore_wind_power_farms_in_the_German_Bight.png

Supplementary Table 1

Cancer_pagurus (Edible crab):

Predictions & Data for this entry

Model: abj climate: MC migrate: phylum: Arthropoda
COMPLETE = 2.5 ecozone: MANE food: bjP, biD, jiCi, jiS class: Malacostraca
MRE = 0.072 habitat: 0bMb, bjMp, jiMb gender: D order: Decapoda
SMSE = 0.081 embryo: Mbf reprod: O family: Cancridae

Zero-variate data

Data	**Observed**	**Predicted**	**(RE)**	**Unit**	**Description**	**Reference**
ab	244	244	(0.0001338)	d	age at birth	Wiki
tj	331	288.2	(0.1293)	d	time since birth at metam	WeisThat2009
tp	766.5	1122	(0.4637)	d	time since birth at puberty	Benn1974
am	3.65e+04	3.65e+04	(6.076e-05)	d	life span	Wiki
Lp	12.7	12.38	(0.02548)	cm	carapace width at puberty for females	Wiki
Lpm	11	10.97	(0.00249)	cm	carapace width at puberty for males	Wiki
Li	24.2	23.66	(0.02244)	cm	ultimate carapace width for females	Benn1974
Lim	26.7	28.09	(0.05217)	cm	ultimate carapace width for males	Benn1974
Wwb	3.3e-05	3.301e-05	(0.0003)	g	wet weight at birth	HaigRayn2015
Wwp	452	411.8	(0.089)	g	wet weight at puberty for females	Wiki
Wwpm	294	294.2	(0.000579)	g	wet weight at puberty for males	Wiki
Wwi	3100	2876	(0.07232)	g	ultimate wet weight	Benn1974
Wwim	4200	4937	(0.1755)	g	ultimate wet weight	Benn1974
Ri	8219	8222	(0.000362)	#/d	maximum reprod rate	Wiki

Uni-variate data

Dataset Figure (RE) Independent variable Dependent variable Reference

tW_f see Fig. 1 (0.07074) time wet weight Benn1974
tW_m see Fig. 1 (0.04888) time wet weight Benn1974

Pseudo-data at Tref

Data Generalised animal Cancer pagurus Unit Description

v 0.02 0.02047 cm/d energy conductance

kap 0.8 0.9675 - allocation fraction to soma
kap_R 0.95 0.95 - reproduction efficiency
p_M 18 52.39 J/d.cm^3 vol-spec som maint
k_J 0.002 0.002 1/d maturity maint rate coefficient
kap_G 0.8 0.8083 - growth efficiency

Facts

- After a short protozoea stage, five zoea stages occur before metamorphosing into the megalopa, which settles with 24 h (ref: HaigRayn2015)
- No feeding occurs during brooding (ref: HaigRayn2015)

Discussion

- Males are assumed to differ from females by (p_Am) and E_Hp only

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Cancer_pagurus (Edible crab): Results Code Links
DEB CONTEXT COLLECTION APPLICATIONS
Cancer_pagurus Page 1 of 2
https://www.bio.vu.nl/thb/deb/deblab/add_my_pet/entries_web/Cancer_pagurus/Canc... 05/06/2019

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