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Size at maturity and molting probability across latitude in female *Cancer pagurus*

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ABSTRACT

Edible crab, *Cancer pagurus*, is a valuable North Atlantic fishery resource distributed from Morocco to northern Norway, covering a wide range of temperatures and other oceanographic variables. Knowledge on how local environmental conditions affect life history traits like maturity and growth in this species is however lacking, despite its importance in science-based management. Through analyses of field data and fishers' reports from different areas along the west coast of Norway (between 59°N and 69°N), latitudinal differences in size at onset of sexual maturity and molting probabilities of female *C. pagurus* were investigated. The size at which 50% of crabs were found to be mature (CW_{50}) did not differ between areas and was consistent with historical investigations, i.e. overall CW_{50}: 112.3 mm, and CW_{50} for each area/year between 108 and 117 mm. Generalized additive modelling was used to predict probability of molting (occurrence of soft crabs) during late summer/autumn, with 'area' as a categorical variable, and 'day of year' and crab size as continuous non-linear predictors. The predictor variables had low explanatory power (16.4% deviance explained by full model), demonstrating the complexity of the process regulating molting. However, frequency of molting decreases and peak periods of molting occur later at higher latitudes, suggesting that lower temperatures have an impeding effect on growth in northern populations. Overall, our findings suggest that current minimum legal catch sizes for crabs in Norwegian waters are sufficient to restrict the catch of immature females, but that crabs in different geographical regions appear to be variably tolerant to fishing pressure following differences in growth.

1. Introduction

Edible crab, *Cancer pagurus*, is distributed along Northeast Atlantic coasts, from Morocco in the south to the northern part of Norway (FAO, 2015), and represents a valuable fishery resource across most of Europe. The fishery for edible crab is conducted using baited pots, with total annual catches in Europe in the order of 50,000 t (FAO, 2015). In Norway, approximately 5000 t are harvested annually, mainly by small vessels (length < 15 m) fishing along the Norwegian coast between ~59 and 69°N. The fishery is managed, with minimum landing size limit (MLS) applied as a primary tool to preserve the reproductive potential, but there are no quota or effort regulations. The MLS is set at 130 and 110 mm carapace width (CW) for crabs caught north and south of 62°N, respectively. When MLS values were first implemented, the scientific basis for their choice was weak, in part dating back to limited studies by Bjerkan (1927a,b). A later investigation by Woll and Larssen (2004) found that 50% of female crabs were mature (CW_{50}) at around 110 mm CW, with no apparent differences among crabs from various geographical areas, adding support to the current MLS. In a study by Haig et al. (2016), investigating *C. pagurus* in several European countries using the same method as Woll and Larssen (2004), CW_{50} mean values varied between 97 and 117 mm, but with no obvious spatial structure associated with this variation. Also, a CW_{50} of 108 mm was recently reported for female *C. pagurus* from the Isle of Man (Öndes et al., 2017). Thus, these studies indicate that the body size at which the gonads of *C. pagurus* become vitellogenic (i.e. yolk forming) varies little or just randomly across geography. Most historical studies have however been focused around central Europe, with limited knowledge on how size at maturity in this species might vary between areas with distinctly different climatic conditions. In the first part of this study we revisit the question of size at maturity by investigating crabs along a north-south gradient along the Norwegian west coast.

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While size may appear as a general trigger of sexual maturation in female *C. pagurus*, the age at which this size is reached might vary. Slower growth due to lower temperatures at higher latitudes is a general response e.g. in fish (Conover, 1992). In crustaceans, growth is a function of molting frequency (or the duration of the intermoult period) and the growth increment at moult. Although there is evidence of an inverse relationship between moult increment and temperature in crustaceans (see Hartnoll, 2001 for a review), the positive relationship between temperatures and metabolic processes overall results in increased growth at higher temperatures due to shorter intermoult periods (Green et al., 2014; Hartnoll, 2001; Passano, 1960). While the reproductive potential of *C. pagurus* may be conserved by appropriate MLS restrictions, similar across geography, the biomass that can be removed sustainably will depend on growth rate, which, in turn, is likely to vary with temperature and, hence, latitude.

In Norway, *C. pagurus* is distributed along the coast from ~59°N to ~70°N, covering a range of more than 10° latitude and exposed to a wide range of seasonal environmental conditions. The importance of temperature for the complete larval development of *C. pagurus* has been demonstrated by Weiss et al. (2009), but little is known about how growth of adult crabs varies with environmental conditions, such as those experienced at different latitudes. The aim of this study is to provide baseline information on size at maturity and individual growth patterns of *C. pagurus* from climatically different areas along the Norwegian coast. Our hypothesis is that (1) crabs mature at a larger size at higher latitudes (Atkinson, 1994), and that (2) cold temperatures have an impeding effect on the molting process causing lower molting frequency (and hence slower growth) in northern areas. Our results will help to understand how a species life history traits may vary across biogeography, and whether such information needs to be taken into consideration in a management perspective.

2. Material and methods

2.1. Study area

To obtain information on activity of fishing vessels, the species they target and the volumes landed, the Directorate of Fisheries collects data on coastal fisheries from nine different regions (statistical areas) along the coast of Norway (Fig. 1). For studies of size at maturity we collected crabs from Area 05, Area 06 and Area 08, revisiting the same sites as used by Woll and Larssen (2004) eleven years earlier. (The locations are presented as grey, orange and green dots in Fig. 1.) The areas represent (i) the northernmost extent of the commercial crab fishery (Area 05), (ii) the areas with the most intensive fishery in terms of landings (Area 07), and (iii) the southernmost area from where a significant proportion of the commercially harvested crabs are landed (Area 08). For investigations on molting probability we focused on the areas where the registrations by the reference fleet have been most extensive, and which provided sufficient data for statistical modelling (see below). These were Area 05, Area 06, Area 07 and Area 08 (highlighted in Fig. 1 as grey, blue, orange and green, respectively).

2.2. Temperature in different areas

Estimates of the temperature regimes to which crabs are exposed in shallow water were obtained from the Norwegian Institute of Marine Research (IMR) which operates hydrographical stations at different locations along the coast. Stations “Eggum”, “Bud” and “Yttre Utsira” located within Area 05, Area 07 and Area 08, respectively, were used. Data from Area 06 was unfortunately not available as no hydrographical station is located within this region. Temperature measurements at 20 m water depth from 2001 to 2015 were used to calculate mean seasonal temperature for each area by applying a smooth local regression (LOESS) (Cleveland et al., 1992) (Fig. 2).

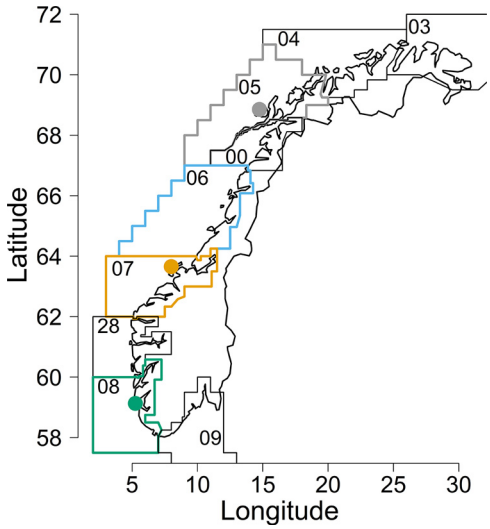

Fig. 1. Map of Norway showing the nine coastal statistical areas used by the Directorate of Fisheries. Areas investigated in our study outlined in grey (Area 05), blue (Area 06), orange (Area 07) and green (Area 08). Dots within each area show locations from where crabs were sampled for size at maturity studies. Polygons for statistical areas represent WMS files obtained from the Directorate of Fisheries online maps services (www.fdir.no/kart). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2.3. Determination of size at maturity

2.3.1. Data collection

In September and October 2014, a total of 621 female crabs were collected (Area 08, n = 181, Area 07, n = 213 and Area 05, n = 227). For each of the three areas, we aimed at collecting a minimum of 20 crabs in each 5 mm size interval from 80 mm to 150 mm carapace width (CW). The crabs were collected from commercial pot catches, at depths of 20–40 m. Fishers in Area 08 are required to have escape gaps on their pots. To increase the likelihood of obtaining small crabs, approval was apprehended from the Directorate of Fisheries to close the escape gaps during the period of collection. The widest part of the carapace was measured in millimetres using a digital calliper. Previous studies on female *C. pagurus* indicate that a change in the width of the abdomen relative to CW occur at onset of maturity (Tallack, 2007; Ungfors, 2007). To investigate if such allometric growth occurred for our crabs, the abdominal width (AW) was also measured to the nearest millimetre. Before dissection, crabs were killed by spiking through one of the eyes (destroying the cerebral ganglia) and through the center of the sternum (destroying the thoracic nerve mass) (Baker, 1955). Individuals were then opened and their gonads stage-determined, following the scale developed by Edwards (1979) and later modified and extended by Larssen et al. (2015) (1 = *Imma*ture, 2 = Early mature, 3 = Mature, 4 = Late mature, 5 = Spawning and 6 = Spent). Stage 2 was set as a threshold for maturity, which is characterized by gonads with district lobes that are extended in the carapace. Histological investigations by Larssen et al. (2015) defined stage 2 as mature based on the presence of primary oocytes covering 50–80% of the lobes, and the presence of secondary oocytes with yolk. Reference data from Woll and Larssen (2004) on the size at maturity of *C. pagurus* females, which were disseminated only in the grey literature, are also included in this paper for comparison. In their study, 524 female *C. pagurus* were collected in September 2003, from the three areas Area 08 (n = 178), Area 07 (n = 181) and Area 05 (n = 166) (Fig. 1). Woll and Larssen (2004) also investigated if crabs had mated, by registering the presence of sperm plugs or sperm in the spermatheca. These data were used to investigate size at onset of behavioural maturity.