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Environmental drivers of small scale spatial variation in the reproductive schedule of a commercially important bivalve mollusc

Natalie Hold*, Lee G. Murray, Hilmar Hinz, Simon P. Neill, Sarah Lass, Mandy Lo, Michel J. Kaiser

School of Ocean Sciences, Bangor University, Menai Bridge, Isle of Anglesey LL59 5AB, UK

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A B S T R A C T

Understanding variability in reproductive schedules is essential to the management of recruitment limited fisheries such as that of *Pecten maximus*. Small scale (<5 km) variation in gonad condition and the onset of spawning of *P. maximus* were found among commercial scallop grounds in Isle of Man waters. Environmental and fishing drivers of these spatial patterns were investigated using a generalised additive model. Rate of change in temperature over the month prior to sampling was identified as the short term driver of gonad weight associated with the autumn spawning event. Long term drivers were average annual chlorophyll *a* concentration, scallop density, stratification index and shell size. The model explained 42.8% of deviance in gonad weight. Within site variation in gonad condition was high, indicating a "bet hedging" reproductive strategy which may decrease the chance of fertilisation especially at low densities. Therefore, areas protected from fishing, where scallop densities can increase may help buffer against reproductive failure. An increase in shell length from 100 mm to 110 mm equated to an increase of approximately 20% in gonad weight. Protecting scallops from fishing mortality until 110 mm (age four) compared to 100 mm (age three) may lead to an overall increase in lifetime reproductive output by a factor of 3.4.

1. Introduction

The king scallop, *Pecten maximus* is a functional hermaphrodite of commercial importance, found in European waters from Norway to Spain with landings of approximately 60,000 tonnes in 2009 (FAO, 2012). Previous work has demonstrated considerable variability in the timing and synchronisation of spawning over large spatial scales (100s of kms) (Mason, 1958; Paulet et al. 1988; Cochard and Devauchelle, 1993; Mackie and Ansell, 1993). Although one might expect less variation in reproductive schedules at smaller scales, fishers will often target a particular scallop ground with good quality roe until the scallops spawn and then move on to another ground just tens of kms away where scallops are yet to spawn (Personal communication, scallop fishers Isle of Man). If reproductive variation is present on such a small spatial scale this provides challenges for effective management of the stock and understanding this variation and the parameters driving it is essential. Spatially targeted fishing at a time of gonad ripening could also make the fishery more susceptible to collapse.

In the Isle of Man, *P. maximus* first show signs of gametogenic maturation in the second year of growth (Mason, 1958; Devauchelle and Mingant, 1991), although an adult pattern of spawning (spawning in both the spring and the autumn) may not develop until their fourth year of growth (Mason, 1958). *P. maximus* is reported to exhibit several patterns of spawning: continual partial spawning from spring until early autumn; bimodal peaks in spawning (spring and autumn) or a single synchronised spawning event (Mason, 1958; Paulet et al. 1988; Pazos et al. 1996). These strategies seem to be genetically mediated (Cochard and Devauchelle, 1993; Mackie and Ansell, 1993) although environmental conditions appear to alter the timing and onset of maturity and spawning (Magnesen and Christophersen, 2008). Variation in reproductive schedules, driven by climatic variation and hydrographic conditions, can affect the consistency of recruitment (Orensanz et al. 2006) and therefore management of recruitment-limited fisheries, such as *P. maximus* (Beukers-Stewart et al. 2003), requires in-depth knowledge of factors that influence reproductive ecology. In addition this knowledge is of increasing

* Corresponding author. Tel.: +44 (0)1248 382850.
E-mail addresses: n.hold@bangor.ac.uk, oss028@bangor.ac.uk (N. Hold).

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importance in order to understand how reproduction and recruitment may respond to changing climates and water temperatures.

The present study aimed to i) understand the small scale spatial patterns of spawning around the Isle of Man and ii) to explain these observations in terms of key environmental and fishery drivers.

2. Methods and materials

2.1. Study site and sampling

In the present study, ten commercial scallop beds in the waters around the Isle of Man, Irish Sea were sampled (Fig. 1): Bradda Inshore (BRI), Bradda Offshore (BRO), Chickens (CHK), East of Douglas (EDG), Laxey (LAX), Peel (PEL), south of Port St Mary (PSM), Ramsey (RAM), South East Douglas (SED), Targets (TAR). These sites vary in their depths (20 m – 69 m), oceanographic regime (mixed and stratified water columns) and fishing intensity. Table 1 shows the environmental parameters for each site.

Sampling took place in mid-October 2009 and 2010. The timing of the sampling was chosen to coincide with the autumn period of gonad maturation and spawning. Whilst historically spawning has been shown to occur earlier in September, previous surveys by the authors and anecdotal evidence from the fishers indicated that spawning can also occur later. Ramsey was only sampled in 2010. Scallops were sampled as per Murray et al. (2011); For each tow of 20 min duration, the start and end GPS points were recorded, these data, along with the width of the dredges, allowed calculation of the area swept. The total number of scallops from each dredge, in each tow, was weighed and a subsample of 40 scallops were weighed and measured. An estimate of the abundance was made using the subsample weight to extrapolate to the total weight for each dredge. Density was then calculated using the abundance and area swept data (width of dredge × length of tow). A sample of at least 50 scallops was set aside for gonad maturation analysis from each site and where possible 50 scallops from each of the age groups three years, four years and over five years were sampled. Scallops that are two to three years old are considered juvenile and prior to their first "juvenile spawning" event in the spring following the laying down of their second growth ring they are considered virgins (Mason, 1958). Therefore two year olds were not included in our analysis.

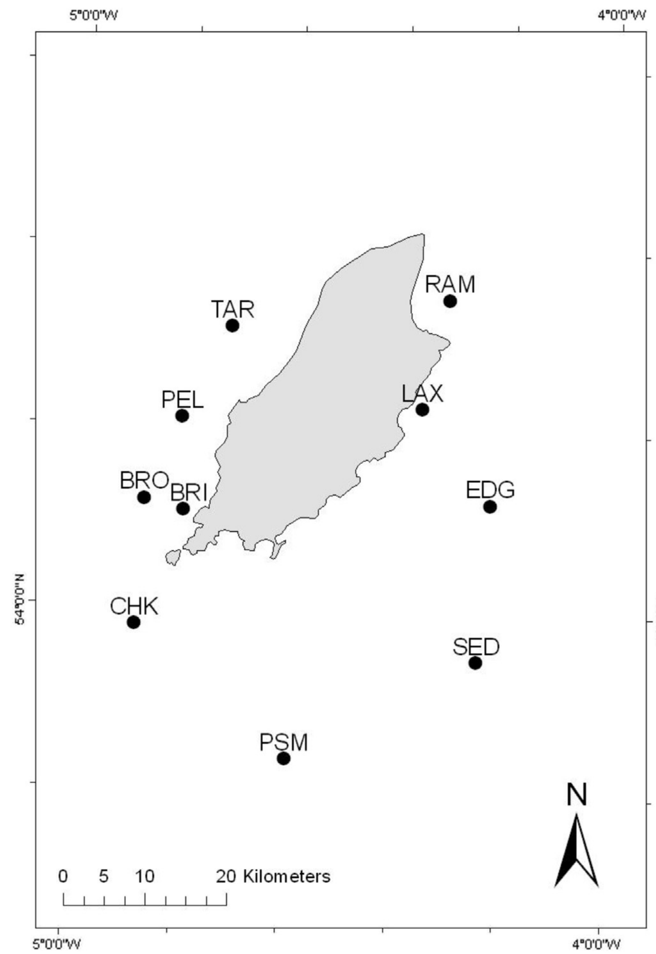

Fig. 1. Survey sites around the Isle of Man in the Irish Sea. Site Codes: Bradda Inshore (BRI), Bradda Offshore (BRO), Chickens (CHK), East of Douglas (EDG), Laxey (LAX), Peel (PEL), South of Port St Mary (PSM), Ramsey (RAM), South East Douglas (SED), Targets (TAR). Ramsey was only sampled in 2010.

2.2. Gonad maturation state

Scallops were sampled from each of the 10 sites. Scallops were dissected on the day of capture and the gonad frozen for wet weight determination back at the laboratory (±0.01 g). Shell height (±1 mm) was recorded on board the research vessel. The Gonad Observation Index (GOI), as described by Mason (1958), was also recorded. This index categorises a scallop gonad into one of seven stages. Stages I and II relate to virgin scallops, stage III is the first stage of recovery following spawning, stage IV and V are filling, stage VI is full and stage VII is a spent gonad. We also calculated the Relative Gonad to shell Height (RGH) index which standardises the gonad weight in relation to the size of the scallop (See Barber and Blake, 2006):

$$\text{RGH} = \frac{\text{gonad weight(g)}}{\text{shell height(mm)}^3} \times 100 \tag{1}$$

2.3. Environmental covariates

Scallops examined for gonad condition were sampled from specific sites around the Isle of Man. The condition and maturity state of the scallops at each site will reflect the circulation history of food availability at that site (Chlorophyll *a* concentration (Chla) was used as a proxy in this study) and exposure to physiological drivers (e.g. water temperature). To understand how spawning may be influenced by these overlying hydrographic conditions, monthly composite sea surface temperature (SST) and Chla data were obtained from NEODAAS for the period of November 2008 to October 2010. The NEODAAS data was in the format of geo-referenced raster files spatially resolved at a scale of 1 km^2 (SST) and 500 m^2 (Chla). As sedentary organisms, scallops will be influenced by a body of overlying water at a scale of a least one tidal excursion. Therefore the value for each environmental variable, in each month, for each site was extracted from the raster layer as the average across an area that corresponded to that of the tidal ellipse at that site. This was carried out using ArcMAP v9.3. The ellipses were drawn as a polygon layer in ArcGIS v10. The depth-averaged, principle lunar semi – diurnal (M2) current vectors (m s^{-1}) (north and east components) were obtained from a model of the Irish Sea (Neill et al. 2008) for the point nearest to each site reference position. These vectors were converted to distances (m) for the semi-major and semi-minor axes of an ellipse using the tidal excursion time of 12 h 26 min and oriented to the angle of the semi-major current axis. Within the area of this ellipse the average