# Spatial variation in king scallop *Pecten maximus* maturation state around Isle of Man

Mandy Chi-yan Lo

MSc Marine Biology

School of Ocean Science, Bangor University

Abstract

King scallop fisheries have become one of the most important fisheries in Europe, the United Kingdom and Isle of Man. Much effort has spent to investigate this species' reproduction in order to achieve sustainable fisheries and avoid stock collapse. The aim of this study is to find out if there is any spatial variation in king scallop gonad maturation in order to help predict recruitment and avoid its fishery to collapse. Hypothesis of this study is there is scallop gonad maturation state are significantly different in 9 different sites around Isle of Man and environmental factors such as seawater temperature and chlorohphyll a concentration are contributing to such variation. Four objectives were set: to find out which sites' scallop maturation state were significantly different from each other and to investigate whether there is a significant different of gonad index between 3 age groups; major contributing factors affecting gonad maturation; comparing present study results with previous study. 1085 scallops were collected in June 2009 within 9 sites around Isle of Man. Scallop gonad condition index were used to compare between sites. This study has shown significant spatial variation in gonad maturation state between 9 different sites around Isle of Man. Individual sites have different gonad maturation state owing to variation of environmental and biological factors. There is no significant different of scallop maturation state between age 3 and 4, age 4 and 5; but significant different was found between age 3 and 5. Average chlorophyll a concentration in June from 2004 to 2008 was found to be significantly related to gonad maturation state. A significant positive linear regression was fitted with the correlation. Sea bottom temperature data and PEA was also found significantly related to scallop maturation state. Stepwise regression test confirmed that chlorohphyll a was the most contributing factors to the spatial variation. It has proven efficient and essential to use both GOI and RGH to determine scallop maturation.

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# Abbreviation

| | |
|---|---|
| ANOSIM | Analysis of similarity |
| ANOVA | Analysis of variance |
| Chla | Chlorophyll a |
| DAFF | Department of Agriculture, Fisheries and forestry |
| DN | Digital number |
| GEBCO | |
| GOI | Gonad observation index |
| GSI | Gonad somatic index |
| IoM | Isle of Man |
| LSD | |
| MLL | Minimal length limit |
| MDS | |
| NEODASS | |
| Pea | Potential energy anormaly |
| RGH | Relative gonad weight shell height index |
| SCUBA | |
| SST | Sea surface temperature |

# Chapter 1

## Introduction

King scallop *Pecten maximus* (also known as Great Scallop or Scallop) belongs to the family Pectinidae. It is one of the commercial species that support important fisheries in Europe (Shumway *et al*, 2006). It has been consistently regards as one of five most valuable fishery species in the United Kingdom (Beukers-Stewards *et al*, 2009). Isle of Man king scallop fisheries has begun since 1937 and became significant in 1960s with an increase in number and size of boat joined after the Second World War. By 1969, Queen Scallop *Aequipecten* (*Chlamys*) *opercularis* fisheries have also developed (Beukers-Stewart *et al*, 2003; Shumway *et al*, 2006).

King and Queen scallops fisheries are currently two of the most important fisheries in Isle of Man (Murray *et* al, 2009). King scallop fisheries are usually inshore and mostly done by dredges, only small percentages of scallops are hand captured by SCUBA diving (Beukers-Stewards *et al*, 2009). The current fishing/dredging area in Isle of Man for King and Queen scallop overlapped each other and occupied most of the surrounding waters (Queen Scallop fisheries restricted to the North East and South) (Shumway *et al*, 2006).

King scallop holds a higher commercial value relative to other scallops due to its larger size. Both muscle and gonad tissues are of market value (Alison, 1994). The sales of fresh scallop in-shell also achieve a higher market price than frozen processed product (Bongan *et al*, 2007). Demand of scallop in Europe and United Kingdom itself has increased in past decades. Consequently, both scallop fisheries and aquaculture in Europe has increased (Bourne, 2000). It has been suggested by DAFF to develop aquaculture in IoM which is considered to be more sustainable and profitable with reduced dredge area and recent increasing fuel cost (Murray *et al*, 2009)

The key to success for scallop fisheries and aquaculture is the availability of spat and recruitment success (Slater, 2005). Recent scallop fisheries management regimes has focused on identifying and protecting scallop nursery and breeding areas that have shown positive effect on its fisheries (Beukers-Stewards *et al*, 2009). Therefore research and study of reproduction

physiology in scallop species is essential and beneficial for Isle of Man fisheries (Shumway *et al*, 2006).

## 1.1 Aim and rationale

The aim of this research is to find out whether there is a spatial variation of king scallop maturation state around the Isle of Man waters in order to predict recruitment, increase fisheries landings and prevent collapsed of the fishery. Like most marine species, scallops develop unique physiological properties between different populations that occupied very diverse environments within their geographical range (Sastry, 1970). Reproductive behaviour of scallops is seasonal, which is a characteristic of marine bivalve (Pazos *et al*, 1996). Spawning period, growth and maturation rate of scallop varies between species and population, mostly depending on their geographic/oceanographic location and genetic variation (Pazos *et al*, 1996).

King scallops live on a wide range of sediment types from sand to gravel around Isle of Man and scallop fisheries occur in most of the areas where they are found (only with the exception of the southern limit in the 12nm zone). Scallops were found aggregate in rocky area and areas that cannot be fished. The main fishing locations for king scallop are Targets, Ramsey Bay, Bradda Inshore, Chickens, outside Laxey Bay, and immediately south of Port St. Mary(Kaiser *et al*, 2008; Murray *et al*, 2009).

These fishing grounds surround Isle of Man contains a range of oceanographic characteristic and different degree of stratifications. These geographically separated populations can exhibit distinct reproductive variation due to environmental differences such as temperature and food availability (Pazos, *et al* 1996). Scallop somatic and gonad growth and development are regulated by both internal (pre-mature hormonal regulation) and external environmental change (Mason, 1958; Shumway *et al*, 2006). With different oceanographic characteristics around the Isle of Man, it is therefore expected to stimulate gonad growth (maturation rate) in different time and possibly to different degree.

Isle of Man king scallop fisheries landings, like many other bivalve fisheries, fluctuate significantly through years affecting annual success of its fishery. It has risen to the highest landing in 1980 (4000t/year), dropped to less than 3000t/year by 1993 and rose again similar to the highest landing in 2001 (Shumway *et al*, 2006). Recently landings of scallops has increased

and suggested possibility of continuous increase in response to increasing seawater temperature (Murray *et al*, 2009).

Fishing activities certainly contribute to some degree of damage towards landings as improvement of fishing fleets and technology allow fisher to exploit wider and rougher area (Kaiser *et al*, 2005; Shumway *et al*, 2006). Dredging activities has also been found to have damaging effect on the benthic ecology (Jenkins *et al*, 2001) and reduce scallop escape response to predators (Jenkins and Brand, 2001). However, scallop population is also highly dependent on the percentage of recruitment success. It has always been a desire for fishery management to assess and predict stock levels and recruitment. In order to achieve it, basic biology and continuous substantial data are required.

Department of Agriculture, Fisheries and Forestry, Isle of Man Government (DAFF) has imposed some management plans such as scallop no take zone (in Douglas Bay since 2008 and Port Erin since 1989) and no fishing periods during spawning season for scallop fishery. This study is a part of fishery research helping to understand basic reproductive biology for king scallop. Reproductive/recruitment success of scallop is highly variable, depending on local population density, development of gonad and timing of spawning in respect to availability of food source. Most of the studies on variation of scallop gonad maturation rates are done for temporal/seasonal change. Study on spatial and temporal variation of scallop gonad maturation rate in Isle of Man has not been done before. In this study, by determining the factors affecting scallop gonad maturation rates, basic background knowledge for fishery management is expected to be obtained.

DAFF has contracted out scientific researches to various marine laboratories such as Port Erin Marine Laboratory, University of Liverpool and, recently, School of Ocean Science, Bangor University to investigate, manage and encourage scallop and other fisheries sustainably (Murray *et al*, 2009). The sea near Port Erin area has closed from scallop fisheries to allow scientist to assess scallop cultivation and populations (Shumway *et al*, 2006). Scallop fisheries and its dredging effects towards the benthic community are one of the main researches (Kaiser *et al*, 2008; Murray *et al*, 2009). Management plans such as no fishing area, no fishing period and time were drawn upon these researches.

Currently, fisheries policies in Isle of Man consist of scallop fishing restriction period between November and May (to allow spawning during warm season); no dredging between GMT 1800-0600 and Minimum Length Limits (MLLs) is set at shell length 110mm (Shumway *et al*, 2006).This research provides basic underpinning information on scallop biology. It can assist scallop fisheries management, such as to determine whether these sites and other fishing grounds should be regulated or become closed area for strictly no-fishing area or just seasonal no-fishing area.

## 1.2 Objectives and hypothesis

There are four main objectives for this study: comparing gonad maturation state of king scallops around Isle of Man; comparing gonad maturation state of king scallop in different age groups; finding out factors that affects scallop gonad maturation and comparing king scallop gonad maturation state in Isle of Man to different scallop species or same species but different location.

To compare different gonad maturation rates spatially and between age groups, gonad index were compared using scallop samples obtained during two Isle of Man fishery surveys in June. To find out factors affecting the gonad maturation rate, gonad index was compared towards environmental and biological data from remote sensing data and a habitat survey done in August 2008. The linear regression results were then compared with meta-analysis results from literature review. This comparison can help to achieve last objective to look at how gonad maturation is affected by different environmental and biological parameters.

*HYPOTHESIS:*

H1– There is spatial variation of king scallop maturation state around Isle of Man during early summer month (June).

H2– Variation in oceanography features of habitats affect gonad maturation state in king scallop differently.

## 1.3 King scallop reproduction

Scallop reproductive physiology has been widely studied in various populations around the world. The most studied scallop species on reproductive biology is Bay Scallop *Argopecten irradians,* an important commercial species in the United States (Sastry, 1966; Bricelj and Krause, 1992). King Scallop *P.maximus* population has also been studied in various places: Isle of Man, UK (Mason 1958), Clyde Sea Area, (Comely, 1974), Fosen, Norway (Strand and Nylund, 1991), Ria de Arosa, Spain (Pazos, 1996), St Brieuc, France (Paulet *et al*, 1998), Bergen, Norway (Duinker and Nylund, 2002) and Malaga, Spain (Pazos *et al*, 2003).

*Age at maturity*

Age at maturity and longevity of a species is important for reproduction and fishery management. It usually explains the reproductive strategies of a species/population (Campbell *et al*, 2002). The period between age at maturity and maximum lifespan of a species control the amount of times for a species to reproduce which also related to chance of recruitment success. Hence, it also determines the degree of importance of gonad development in respect to somatic growth.

There is a general trend of long lived species mature later than short lived species. However, actual longevity is highly dependent on individual population and fishing effort. Population maintenance/growth of short lived species are therefore highly dependent on the reproductive strategies and success of the previous generation/year (Shumway, 2006). Vause *et al* (2007) point out that short lived species are more vulnerable to recruitment failure because they have no buffer zone if previous generations are low in fecundity.

Many scallop species are commercially fished; they rarely live up to their maximum lifespan (Shumway *et al*, 2006). Queen (*A.opercularis*) and King Scallop (*P.maximus*) have a relatively long mature state which may be the reason why they were populated around different waters before extensive fishing activities took place (Shumway *et al*, 2006). King Scallop in the Isle of Man start spawning the first time in autumn after the second year shell ring is lied (Mason, 1958).

King scallop fisheries in Isle of Man according to Mason (1958) are relatively sustainable in recruitment sense. King scallop are caught when they are over 100mm in Shell length (after they lay their 3 year ring) giving them chance to spawn at least twice. However, studies has also

suggest that king scallops in Isle of Man are only spawned only once before its fished which means it is vulnerable from fishing (Brand *et al*, 2005 and Murray *et al*, 2009).

*Seasonal and annual growth*

Scallops exhibit indeterminate growth, continuous growth throughout their life. The growth rate changes depending on their life stage and the ambient environmental change (Shumway *et al*, 2006). Throughout their life cycle, energy and resources are used and stored in different tissue/organs (gonad, somatic muscle and shell). Allocation of energy and resource differs through life stage (larval, juvenile and mature adult) and are influenced by environmental factors (Pazos *et al*, 1996). Somatic tissue weight varies throughout their life. After reaching a certain size; weight of somatic tissues decrease to allow energy and nutrients to be retrieved for gonad development (Roman *et al*, 1996, 1999; Heilmayer *et al*, 2003). Consequently, somatic tissue varies throughout a year.

King scallop is functional hermaphrodite and can be protogyny (development of one sex gamete before another one) in birth and in recovery after spawning. Both testis and ovary are present in gonad, testis is white and ovary is orangey-red when ripe (Mason, 1958). King scallop is iteroparous, spawn seasonally and/or annually (Shumway *et al*, 2006). Because of that Gonad sizes fluctuate throughout a year.

Gonad weight increases to maximal in pre-spawning. Gamete production in scallop and other marine bivalves requires large amount of energy (Sauot, 1999). Energy is transferred to the gonad directly from digestive gland when food is plenty (Sastry and Blake, 1971) or from stored energy in adductor muscle when food is not available. During spring and summer months this progress is rapid in order to prepare for spawning (Roman *et al*, 1996).

*Spawning*

Spawning period of marine invertebrates has always suggested being closely related to algal bloom (increase in food availability). Scallop spawning are usually triggered by various environmental cues (temperature, salinity and photoperiod) and internal regulation (genetic variation between population/species) (Beaumont and Gjedrem, 2006; Shumway *et al*, 2006). Most of the scallop species spawn during warm season where algal blooms usually take place.

However, *Pecten novaezelandiae, Amusium japonicum and Chlamys asperima* spawned primarily during the winter (Shumway *et al*, 2006). Sause *et al* (1987) also suggested that pectinid species in the southern hemisphere spawn in the same calendar months as species found in the north hemisphere. In this case, spawning event is more affected by genetic than environmental cue.

Biannual spawning has been recorded in many bivalve species (Campbell *et al*, 2002). This is a typical r-strategy for reproduction (producing numerous offspring) and can be seen in king scallop. Spawning cycle consists of gonad build up, restricted spawning period, emptying of gonad and a recovery period (Campbell *et al*, 2002). King Scallop has shown very few clear reproductive cycle, filled up gonads can be found in many populations throughout the year (Duinker and Nylund, 2002). This suggest multiple or continuous spawning periods. The gonad index varies throughout the seasons. A sharp decrease in gonad index after a peak indicates spawning activities.

During the first 2 years of king scallop, only one major spawning was observed in Isle of Man. In the third year of that generation, two spawning events took place. There seems to be no resting period for King Scallop in Isle of Man as gametogenesis occurs throughout the year (Mason, 1958). Fisheries management policies are highly dependent on the time of scallop spawning in order to set no-fishing period, balancing between maximum meat value and landings (Shumway *et al*, 2006).

## 1.4 Factors affecting gonad maturation

Gonad maturation rate vary temporally as a reproductive cycle. Although there are examples showing same scallop species spawn at similar time even they are geographically separated, most of scallop species mature in various time with different geographic location. It is believed that oceanographic and biological features play a major role in the presence or absence of scallop populations and recruitment (Shumway *et al*, 2006). Different geographic location contain various environmental characteristic that will affect the time and degree of gonad maturate. Gonad development of king scallop starts earlier in Galicia, Spain than in Scotland (Pazos *et al*, 1996).

Many studies have looked at recruitment in scallop affected by abiotic factors such as temperature, salinity, suitability of habitat and biotic facts such as food availability, mortality by

fishing and predator, competition between and within the population (Vause *et al*, 2007). It was found that these factors affect scallop spatially and temporally; and are consider being the reason for inconsistent recruitment for scallop species. Sastry (1963) point out that separated populations of a species breed at different temperature. Suggesting different gonad maturation rate in spatial variation is due to temperature differences.

Studies have suggested temperature and availability of food (nutrition) being the main and greatest factors that affect spatial variation of scallop maturation rate (Sastry and Blake, 1971; Roman *et al*, 1999; Saout *et al*, 1999; Martinez and Perez, 2003).

*Temperature*

Seawater temperature varies spatially, mainly affected by season change, water current, stratification and oceanographic features (Campbell et al, 2002). Gonad maturation rate within annual reproductive cycle of temperate area is correlated with seasonal and temperature changes in the environment (Sastry and Blake, 1971). It has always considered that increase in seawater temperature will increase gonad development and heightened reproductive effort in scallop (Saout et al, 1999, Murray et al, 2009). The growth and spawning period of king scallop increase with increase in seawater temperature (Murray et al, 2009).

Temperature can affect gonad maturation directly (as an environmental cue) or indirectly (affecting metabolic rate). Gonad maturation derived energy from adductive muscle storage but predominantly from digestive gland. Sastry and Blake (1971) described Bay Scallop incubated in higher temperature (15$^{o}$C) for over 15 days have a fluctuating weight in digestive gland with an increase in gonad development. Temperatures determine the speed and efficiency of absorption of digestive gland (Shumway *et al*, 2006).

Increase in temperature increases metabolic rate. However, with solely increase in temperature, gonad maturation rate will not increase. Extraction of food reserve will stop in a certain point, therefore, to encourage increase in gonad development, increase in food supply in needed (Borcherding, 1995). Increase in temperature increase gonad maturation rate is a general pattern. Sastry(1996) combined results Bay Scallop reproduction in USA, found out that with different geographic location, both spawning time and gonad maturation rate change in response to different direction of temperature change. Pazos (1996) found out that in Ria de Arousa,

Spain, spring spawning of king scallop took place with increase in temperature and winter spawning occurred when temperature decrease. An initial increasing and subsequent decreasing of temperature can also stimulate liberation of Bay Scallop gametes and increase gonad development (Sastry, 1996). Fluctuation of temperature will increase or decrease gonad maturation rate depending on different scallop species and geographical location.

*Food availability*

King scallop is sublittoral, epifaunal, active suspension filter feeder. Main food source includes suspended detrital material and phytoplankton, benthic algae has been suggested to be an important component of scallop diet (Shumway *et al*, 2006). Availability of food varies throughout the ocean environment depending largely on water current, salinity and seawater temperature. Microalgae are the main energy source that is required for scallop isomatic tissue, shell and gonad growth (Campbell *et al*, 2002). Scallop larvae are planktontrophic, food availability is important for newly hatched larvae. Phytoplankton together with other environmental parameters act as a cue for favourable condition, subsequently trigger spawning (Pazos *et al*, 1996).

In optimal (usually higher temperature), food availability becomes the main controlling factor. Nutrient from the digestive gland can only act as a supplement for gonad development. External food availability is needed for gonad maturation. There is a positive correlation between the food supply quantity and quality with gonad maturation of bivalve molluscs (Martinez and Perez, 2003). Adult bivalves that were supplemented with extra food in laboratory and hatchery produce healthier broods, as a result the corresponding larvae grew at a more rapid rate and provided greater spat yields (Martinez *et al*, 2000). Fronts are formed when two different water bodies (with different environmental conditions) meet, creating upwelling zone that encourage algal blooms.

Rapid maturation of scallop gonad and gametes in Newfoundland occurs immediately after spring algal bloom (Macdonald and Thompson, 1986). Food availability in local area was found to play a more significant influencing factor for North America mussel *Mytilus edulis* population; mussels were kept in nearly identical thermal environment (Martinez *et al*, 2000). Difference in reproductive cycle of same species of mussel from latitudinal separated

populations on the east coast of USA also found experiences nearly identical temperature cycles but different regimes of food availability (Macdonald and Thompson, 1986). Sea scallop *Placopecten magellanicus* harvest summer phytoplankton bloom for gonad development and gamete release (Pazos *et al*, 1996). Growth and maturation of queen scallop in Spain are more affected by availability of chlorophyll a than temperature change (Roman *et* al, 1999). Decrease in food supply decrease the amount of oocytes present in a gonad, hence decrease in gonad maturation (Boecherding, 1995). Increase in temperature increases metabolic rate and digestive gland absorption rate. This combined with increase in food supply will increase gonad maturation rate. Martinez *et al* (2000) stated that for some pectinids, gonad maturation rate and spawning can only be increased after food reserves are accumulated.

*Other possible factors*

The main factors that affect gonad maturation are temperature and food availability. Both factors interact and regulate nutrient transfer to gonad and subsequently control gonad maturation (Sastry and Blake, 1971). Fluctuation of temperature gives a cue to initiate gonad maturation, sufficient supply of food encourage gonad maturation. Combination of both factors will increase gonad maturation rate. However, many studies have suggested that aside from the influence of temperature and food availability, there are still unpredictable fluctuation possibly cause by other environmental change (Mason, 1958; Roman *et* al, 1996; Martinez *et al*, 2000).

Depth is one of the most arguable factors. Scallops living in different depth showed variation in gonad maturation rate, however, it is consider to be related to different environmental condition (temperature) and food availability (Martinez *et al*, 2000). There are indications of rapid growth and maturation rate of *Hinnites* multirugosus between 8 and 30m in comparison to those live between 60 and 120m (Roman *et al*, 1999). In a study done by Richardson *et al* (1982) on queen scallop living between 10 and 40m has shown no effect of depth on the growth and maturation of gonad and isomatic muscle, when all other environmental conditions were very similar. The change in depth (especially in the first 100m) in a natural marine environment always accompany by changes of other environmental conditions (such as temperature, pressure, light intensity, food availability and salinity) (Campbell *et al*, 2002). Hence, changes in depth itself is already a form of vertical spatial variation, it is dangerous to consider it as a factor.

Salinity can affect survival of marine bivalves (Campbell *et al*, 2002) and therefore bound to have an effect on scallop growth and reproduction. Flat tree oyster *Isognomon alatus* show a massive spawning after high rain which the seawater is diluted (Siung, 1980). Decrease in salinity in the surface layer is likely to reduce queen scallop growth. Salinity below 16 to 28‰ is lethal to queen scallop but at low temperature because of reduced metabolism and growth rate, it will not kill the scallops in that study (Roman *et al*, 1999).

Photoperiod length is another factor that might influence scallop maturation rate; however, it is very difficult to look at the effect of this factor in the natural environment. Pazos *et al* (1996) suggested that photoperiod is recognized as a synchroniser that oscillate the reproduction cycle alone or interact with other factors (temperature in particular). Increase in water temperature encourages gonad development and increases in day length (instead of constant photoperiod) accelerate gametogenesis.

Scallop gonad growth are affected by various environmental change, there is no single parameter to be a definitive factor. The effect of temperature can act as a direct influence on the scallop metabolic rate itself or indirectly affecting algal growth. Roman *et al* (1996) recorded maximum muscle weight (including gonad weight) during the summer months where both sea temperature and food supply is plenty. Gonad growth is maximal when food supply is sufficient and no energy reserve is required from isomatic tissue or digestive gland.

## 1.5 Use of gonad conditional index and different research methods

Gametogenesis occurs simultaneously with gonad development in scallops (Sastry and Blake, 1971) and Spawning events take place dependent on maturation of gonad and external environment stimuli (Sastry, 1966). There are many studies of scallop reproduction especially on spawning event, however, there are only few studies looking at the gonad maturation rate. Studies are done mainly on field based survey (Mason, 1958, Roman *et al*, 1996) on commercially (fisheries) important species, recent years, some studies has been laboratory based to identify different process of gonad development (Saoutt *et al*, 1998; Roman *et al*, 1999) on hatchery species. Study of gonad maturation rate has mainly focus on development of gonad size and gametogenesis through various seasons during the reproduction cycle, very limited study has focus on spatial on bivalve species. Three main methods has been used to look at gonad

maturation rate: Gonad Observation Index, Gonad index (Gonad size in proportion to the rest of the scallop) and histology (gamete development) (Shumway *et al*, 2006).

*Gonad Observation Index*

A detailed and classic gonad observation index was developed by Mason (1958). Gonad Observation Index is an efficient and reliable way to describe gonad maturation rate. Mason's GOI divides scallop into three main stages: Virgins (never spawn), Juveniles (spawn once or twice) and Adults (spawn more than twice). Many studies developed their own gonad observation index based on Mason (1958) (Heaseman *et al*, 1996).

Scallop gonads are separated with the adductor muscle and easy to see. It consists of both female and male reproductive organs (closer to the hinge/white part: testis and orange-red: ovary). The boundary between the testis and ovary is clear but irregular (Mason, 1958). Inside the gonad, folliclese are filled with reproductive products (only one sexual gametes for each sex)

*Gonad Condition Index*

Gonad Condition Index is a mathematical method to study gonad maturation rate. Gonad, isomatic tissue (digestive gland) and shell are weight or measure to calculate the proportion of gonad mass compare to the rest of the body. Both wet and dry weight (g) of the body parts are used in various study. Shell length (mm), shell weight (g) and length (mm) of the disturbance ring are also used.

Three gonad condition indexes are used: Gonad index (GI), Relative gonad height index (RGH) and gonadsomatic index (GSI) (Pazos *et al*, 1996).

$$GI = (\text{gonad dry weight}/\text{shell dry weight}) \times 100$$

$$RGH = (\text{gonad wet weight}/\text{shell height}) \times 100$$

$$GSI = (\text{gonad wet weight}/\text{somatic wet weight}) \times 100$$

Gonad condition index is a very scientific and accurate way to study gonad maturation rate. However, because there are at least 3 different gonad condition indexes, if data is not sufficient in each study, it is very hard to compare.

*Histology*

Histological study of scallop gonad observes the microscopic changes in the gonad. It can detect the slightest changes in gonad maturation and give the most accurate results/data on gonad maturation rate. Comparing to the other two methods, this is more time consuming and require higher level of skill.

Small pieces of scallop gonad (approximately 1-2mm thickness) are removed and fixed in Karnovsky fixative in room temperature. Samples are then observed under the optic microscope (Duinker and Nylund, 2002).

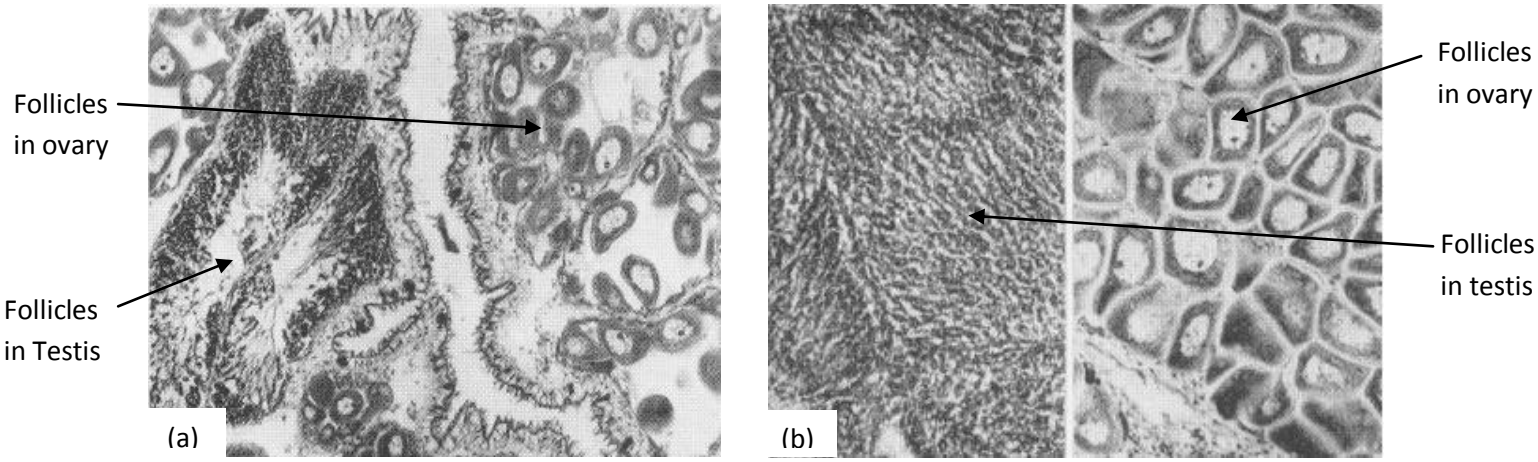



Fig. 1 *Pecten maximus* Manson (1958) photomicrographs of transverse sections through gonads in (a) stage 7, reproductive product spent and (b) stage 6, gonad is fully filled.

Histology shows clearly the follicles within the ovary and testis in the gonad. Measurements and counts can be used to compare different gonad maturation stage. However, it is a very expensive and time consuming process; results from histology are usually similar to using gonad index. It is therefore not used in this study.

Apart from the 3 different method used for gonad maturation rate, some methods using measurement of different type of environmental interaction towards the scallop are used: carbon (y13C) isotope values to reflect primary production within the scallop gonad (Heilmayer *et al*,

2003); feeding rate, oxygen uptake and absorption efficiencies of gonad are measured in the laboratory using artificial diets (Macdonald and Thompson, 1986).

# Chapter 2

Method and materials

Three main sets of data were collected for this study: 1) scallop biology data were collected in June 2009; 2) long term environmental data extracted from satellite images and 3) a short term but more detailed environmental data set collected by Bangor University in August 2008.

## 2.1 Site location

The king scallop *Pecten maximus* used in this study were obtained from natural populations around Isle of Man, United Kingdom. Scallops samples were collected in 9 sites around Isle of Man: Bradda Inshore, Bradda Offshore, Chicken, Peel, Point of Ayre, Port St. Mary, Laxey, South East of Douglas and Target (Appendix 1 and Table 2.1).

**Table 2.1 Co-ordinates of each sites around IoM**

| Site | Latitude | Longtitude |
|---|---|---|
| Bradda inshore | 54.10642 | -4.79853 |
| Bradda offshore | 54.11855 | -4.87243 |
| Chicken | 53.97962 | -4.88167 |
| Laxey | 54.22628 | -4.35638 |
| Peel | 54.20992 | -4.80748 |
| Point of Ayre | 54.51681 | -4.19235 |
| Port St. Mary | 53.83662 | -4.59259 |
| SE Douglas | 53.94851 | -4.24104 |
| Target | 54.31237 | -4.71915 |

Point of Ayre is the northernmost site. All nine sites are regularly fished for both king and queen scallops (Kaiser *et al*, 2008; Murray *et al*, 2009). In the same study, it was found that oceanography features such as sea water temperate (surface and bottom); stratification of water column and currents varies a lot around the Isle of Man. It is no-fishing period for king scallop in the summer around the whole Isle of Man.

Each site contain different population densities, hence in some of the sites, there was not enough samples per age group. In that case, all scallops were taken. Other sites with sufficient amount of scallops, 50 scallops of each age group were randomly picked out.

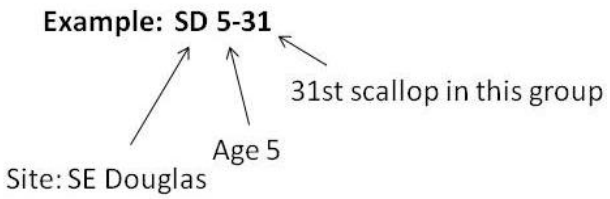
## 2.2Field sampling

A total of 1084 king scallops were collected over 3 weeks($7^{th}$-$15^{th}$ and $20^{th}$ – $25^{th}$June, 2009) during two research cruises around Isle of Man on RV Prince Madog. Four new haven dredges, provided by DAFF, were used. The dredges were towed for 45 minutes at approximately 2.6 knots for 2nm. In each sites, three replicates (tows) were conducted either straight or circular.

Scallops were aged and 50 scallops from each age group were randomly selected. Three different age groups were assigned: 3, 4 and 5 years old. Only scallops without serious shell damaged were used. Most scallops were shelled during cruises to look at their maturation state.

Gonad observation index (GOI) introduced by Mason (1958) were used to assign maturation state of each scallop (Fig 2.1). The height of each scallops were measured to the nearest mm.

All the scallops were frozen on board after initial examination. Each scallop was assigned a label.




They were then transferred and kept frozen in MSc laboratory in University of Wales, Bangor for further analysis.

### 2.2.1 Scallop aging

Scallop in age 3, 4 and 5 were chosen because they were seen to be the three most abundant age groups that are reproductively active scallops around Isle of Man in these two research cruises. Lowestort (1980) suggested king scallop in Isle of Man is fully matured at age 3. Therefore in this study, all scallops were at least 3 years old. The top flat valve was used to age king scallops.

By counting numbers of annual growth rings appears on the valve. With white annual growth rings and red/brown base colour, it allow scientist to count their ring easier than using the concaved valve (Mason, 1957). However, disturbance rings that are usually thinner and more frequent can be falsely recognised as annual growth rings.

In this study, first annual growth rings were assigned for the first complete and clear ring which usually appears approximately 20mm away from the umbone. Mason (1957) has found first annual growth rings of king scallops around Isle of Man are around 19mm to 39mm and only one growth rings is laid each year.

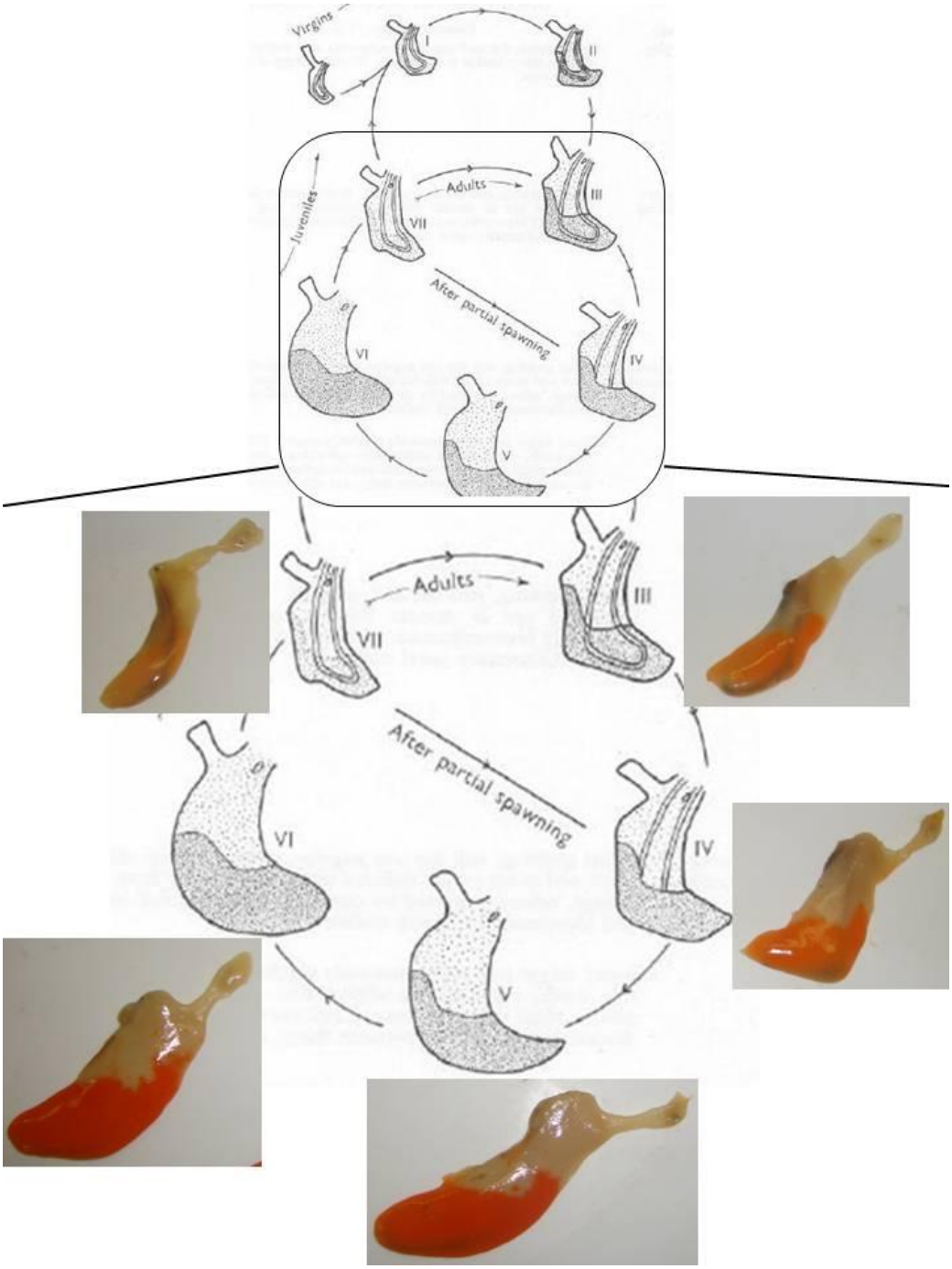
The variation of distance of first growth rings to the umbone is due to different growth rate: autumn spawned scallops has less time to grow their shell than the spring spawned scallop

therefore their first annual growth ring is closer to umbone. Scallops from Isle of Man were found to lie their annual growth rings between April and June (Mason, 1957), the outermost ring (closest to edge of shell) is regarded as their final year.

### 2.2.2 Gonad observation index (GOI)

Mason (1958)'s gonad observation index was used in this study because it is a very detail description and was developed based on king scallop in Isle of Man. GOI is an efficient and reliable way to describe gonad maturation status comparing to other indices which can only describe the gonad ratio towards other parts of body.

Mason's GOI divides scallop into three main stages: Virgins (never spawn), Juveniles (spawn once or twice) and Adults (spawn more than twice). Many studies developed their own gonad observation index based on Mason (1958) (Heaseman *et al*, 1996). Since all scallops that were collected in this study were at least spawned once (age 3 and above), scallop maturation stage starts from III to VII. According to the fullness, colour and shape of the gonad, different GOI was assigned.




Stage III – First stage of recovering. Gonad is flabby and contains free water. Alimentary canal is visible in ovary(yellowish) and testis (creamy). The colour differentiation between two organs is clearer than stage VII.
Stage IV – Gonad is visibly larger and thicker than stage III. Still contain some free water, however it is more fuller. Gonad shape is smoother than stage III but still angular. Alimentary canal is still visible between follicles in testis but not in ovary.
Stage V – Gonad is firmer and thick containing very little free water. Alimentary is no longer visible. Colour becomes more solid. Shape is mostly rounded except at the tip of ovary which is usually still angular. Large follicles can be seen packed together tightly. Gonad can be slightly stretched.
Stage VI – Gonad is at its largest, firmest and thickest. No free water. Shape is rounded to tip. Follicles are closely packed together and highly coloured. Gonad become solid and cannot be stretched.

Stage VII – Gonad is spent or partially spent. Gonad at its smallest: dull in colour, thin, collapsed and angular, contain much free water. Very little colour differentiation between testis and ovary.

Fig.2.1. Mason (1958)'s gonad observation index (GOI) with photographs of different stage of scallop gonad in this study.

Gonad observation index is quick and easy to use; however, it is very subjective and hard to compare results from different studies. Gonad can vary a lot in the same stage (see appendix xx for variation). In this study, only the author assigned GOI and photographs of gonad in different maturate state were taken in early stage of the study and were used as reference to reduce variation and errors.

## 2.3 Further analysis in laboratory

Most scallops were defrosted once only to avoid water lose which may affect wet weight. After shell was removed either on board or in laboratory, gonad, muscle and remaining tissues (including liver, digestive glands and gills) were separated. Shell height was measured to the nearest mm using the standard scallop measuring board.

Most surface moisture on gonad, muscle and tissues were removed for wet weight measurement. They were weight separately and to the nearest 0.01g. A further 20 subsamples from each age group in each sites were dried in oven at 60$^{o}$C for at least 24 hours for dry weight which was also measured to the nearest 0.01g. A preliminary trial was carried out and confirmed that after 24 hours at 60$^{o}$C, constant weight is achieved.

## 2.4 Environmental and biological data extraction

No environmental data were collected during two cruises; therefore two different sets of environmental data were used as reference and were used to correlate with scallop biology data. Depth of different sites was obtained by using GEBCO bathymetry map and extracted using ArcView v.3.3.

Long term data set including sea surface temperature ($^{o}$C) and sea surface chlorophyll concentration was provided by NEODASS in imagery format (.tif). Only last 5 years (2004-2008) of data were used since scallops that were collected were 5 years old or less. Data were monthly average measurements. ArcMap v9.3 was used to extract values for nine sites for 5 years. The

digital number (DN) extracted from image is not the actual measurement; two different formulas was used to extract the real value:

$$\text{Sea surface temperature } (^{o}C) = (DN*0.1)-3$$

$$\text{Chlorophyll a concentration } (mg\ m^{-3}) = (DN*0.015)-2$$

Short term data set was taken during an extensive habitat/environmental survey done by School of Ocean Science, Bangor University in August 2009. Short term data include sea surface and bottom temperature; chlorophyll a concentration on sea surface, in bottom and sediment; sediment grain size and shear strength of sediment.

Fishing effort data within 3nm zone was obtained from Isle of Man fisheries research team in Bangor University through DAFF. King scallop abundance data were collected during the same June 2009 research cruises. Both sets of data were in excel format, no further extraction was required.

## 2.5 Statistic analysis

A total of 1084 scallop gonad observation index and shell height data were recorded for this study (Table 2.2). Out of 1084 scallops, 1081 scallop gonad's dry and wet weights were recorded and were used to calculate RGH.GOI and RGH were used for statistic analysis. SPSS v. 14 and minitab v.15 were used for univariate analysis and Primer v.6 was used for multivariate analysis.

| | **Relative Gonad Height (RGH)** | | | | **Gonad Observation Index (GOI)** | | | |
|---|---|---|---|---|---|---|---|---|
| | Age 3 | Age 4 | Age 5 | Total | Age 3 | Age 4 | Age 5 | Total |
| Bradda inshore | 50 | 50 | 49 | **149** | 50 | 50 | 50 | **150** |
| Bradda offshore | 50 | 50 | 49 | **149** | 50 | 50 | 50 | **150** |
| Chicken | 50 | 50 | 21 | **121** | 50 | 50 | 21 | **121** |
| Laxey | 50 | 14 | 46 | **110** | 50 | 15 | 46 | **111** |
| Peel | 8 | 51 | 26 | **85** | 8 | 51 | 26 | **85** |
| Point of Ayre | 33 | 25 | 22 | **80** | 33 | 25 | 22 | **80** |
| Port St. Mary | 48 | 36 | 28 | **112** | 48 | 36 | 28 | **112** |
| SE Douglas | 50 | 50 | 50 | **150** | 50 | 50 | 50 | **150** |
| Target | 50 | 50 | 25 | **125** | 50 | 50 | 25 | **125** |
| Grand Total | **389** | **376** | **316** | **1081** | **389** | **377** | **318** | **1084** |

Table2.2 shows distribution of scallop recording throughout the nine sites in 3 age groups.

An Anderson-Darling normality test was used for all data to test for normality to determine which statistic test to apply. All results were presented in Appendix 3.

GOI data set was subjected to multivariate analysis using Primer v6. Data was first square root transformed to create a Bray-Curtis similarity matrix. CLUSTER analysis was applied to look at degree of similarity. MDS ordinate plot was drawn to aid visualising results.

An Anderson-Darling test indicated RGH data were not normally distributed so non-parametric Kruskal-Wallis test was used instead of a One-way ANOVA to test for spatial variation significant difference. A Mann-Whitney U test was then applied to find out which sites (groups) were significantly different from each other. Same tests were repeated to look at variation between different age groups.

Further analysis was carried out after spatial variation of RGH was found significant by correlating RGH data to environmental data. Each environmental parameter was tested for normality and a corresponding correlation test was used: if data is normally distributed, Pearson product-moment correlation was used; otherwise, Spearsman rank-order correlation was applied. RGH was then plotted against environmental data on a graph to assess the data's suitability for linear regression and linear regression was calculated. The slope of each linear regression in this study was then plot against each other and against other scallop and bivalve studies to look at possible presence of any relationship.

To look at variation within 3 age groups in different sites, Kruskal-Wallis test was carried out. Age 5 was extracted to see if there is any significant different in one age group within sites. Forth root transformed was applied to Age 5 RGH data and was tested with Anderson-Darling test to be normally distributed. One-way ANOVA was then used to test for significant difference followed by a Post Hoc test (LSD) to detect which sites were significantly different from each other.

Multivariate statistics were used to test for any significant variation in long term environmental data between sites. Environmental data was normalised and resemblance. An analysis of similarity (ANOSIM) was carried out on the resultant resemblance matrix to test between sites. Cluster analysis and MDS plots were drawn to visualise the results.

Linear regression results were compared and collide with meta-analysis results done during literature review. Meta-analysis results include data from various studies (detailed in Chapter 3) in different scallop and bivalve species. Linear regressions of each scallop species

were separated in order to detect any differences. Slopes of linear regression results were then combined with data from present study to detect any significant relationship with environmental parameter ( SST and Chla).

To extend the study in understanding scallop reproduction and energy allocation; ANOVA was applied to shell height, muscle and other remaining tissues to look at any variation between sites. A ratio between gonad, muscle and remaining tissues were calculated assuming the three measurements to be 100% to look at energy allocation. ANOVA was applied to determine any significant differences between sites.

# Chapter 3

Result

## 3.1 Spatial variation in scallop gonad maturation state

Cluster dendogram showed similarity of the sites were from 60% to just above 90%. From MDS plot, GOI stage III, VI and VII indicated two clear groups (Bradda offshore, Chicken and Peel against Laxey, Port St. Mary, Point of Ayre, SE Douglas, Bradda Inshore and Target) (Fig.3.1).

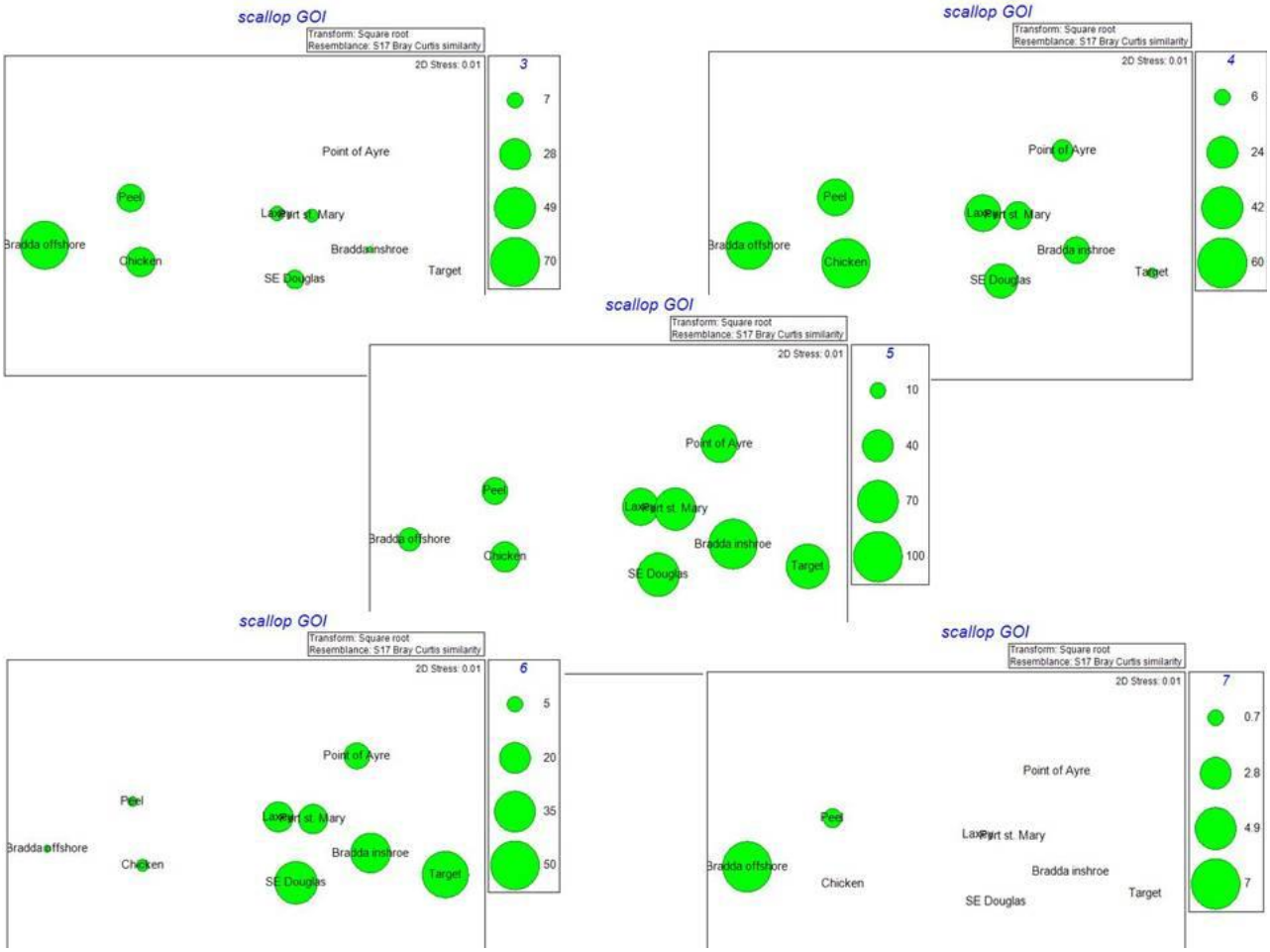



Fig. 3.1 MDS ordination plot for king scallop maturation status, overlaid with a bubble plot of different GOI index.

Combining data from all sites, 12.55% of scallop gonad was in stage III, 23.06% in stage IV, 47.51% in stage V, 15.96% in stage VI and 0.74% in stage VII. SE Douglas has the highest percentage of stage VI gonad consisting 25.33% gonad in this stage and Bradda offshore has the highest percentage of stage III gonad (44.67%). Spent gonad (stage VII) was only found in Bradda offshore (7 scallops) and Peel (1 scallop) (Fig.3.2).

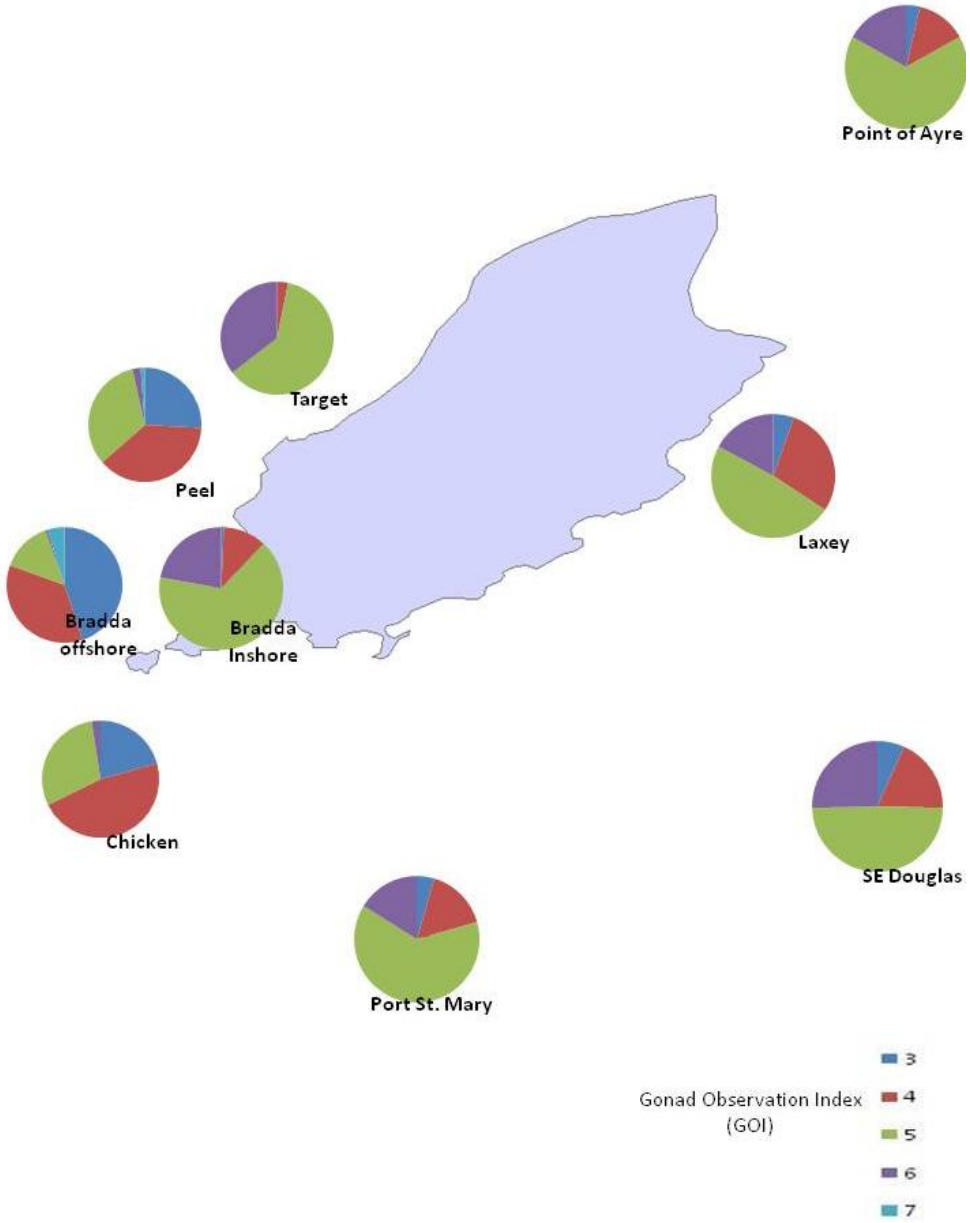



Fig.3.2 Pie charts showing composition of different GOI in 9 sites around Isle of Man

RGH data also showed a significant different in gonad maturate state (Kruskal-Wallis test: Chi-square=529.603, p<0.000). All sites were significantly different from each other (p<0.05) (see appendix 1) but between Bradda Inshore and Port St. Mary (z=-0.128, p=0.898); Chicken and Peel (z=-1.73, p=0.465) and Point of Ayre and SE Douglas (z=-0.838, p=0.402) (Fig 3.3).

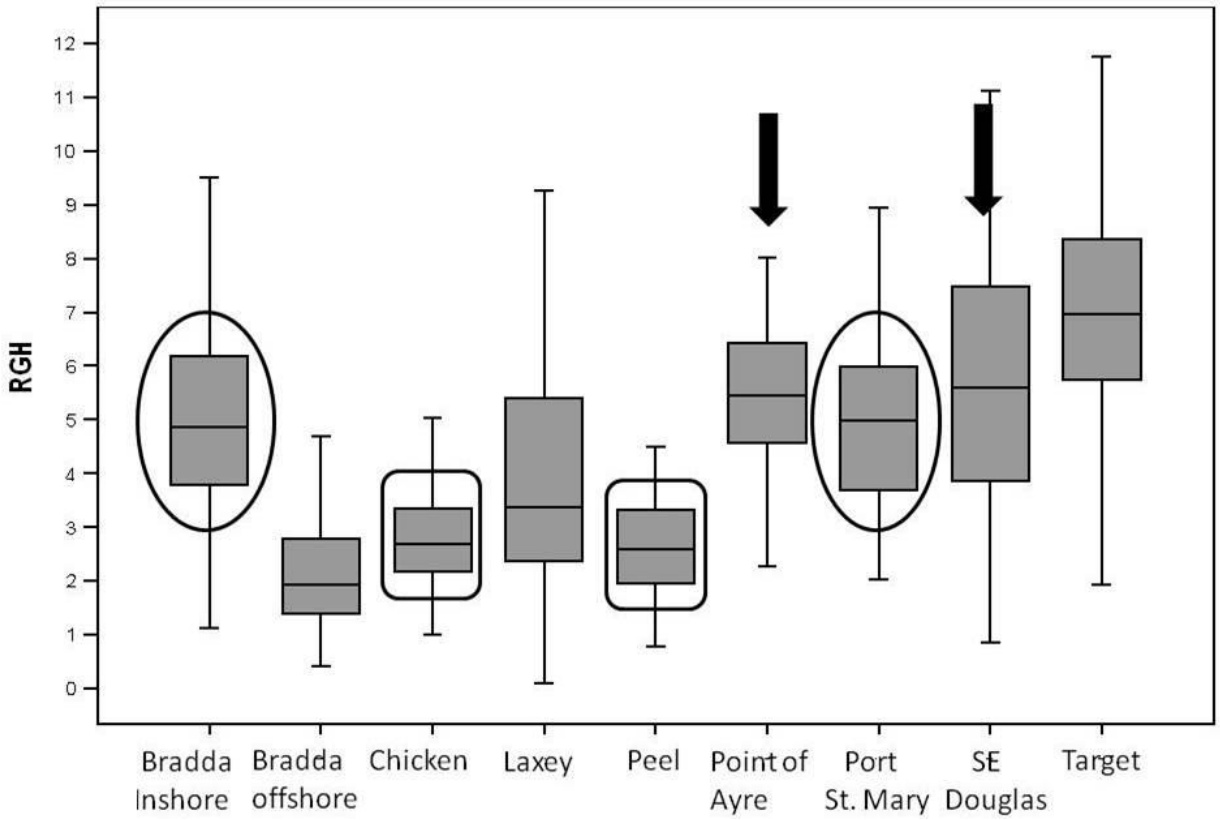



Fig.3.3 Average king scallop relative gonad weight and shell height index (RGH) in 9 sites around Isle of Man with standard deviation (highlight: sites have similar RGH).

There was no significant different in RGH between age groups (Fig.3.4). Age 5 RGH data indicate a significant different between sites (One-way ANOVA: F=41.824, p<0.000). Post hoc test (LSD) revealed similar results as the total RGH data set except there were few more sites including previous mentioned sites have similar RGH (Bradda In – Laxey; Laxey- Peel; Point of Aryre- Port St Mary; SE Douglas – Target).

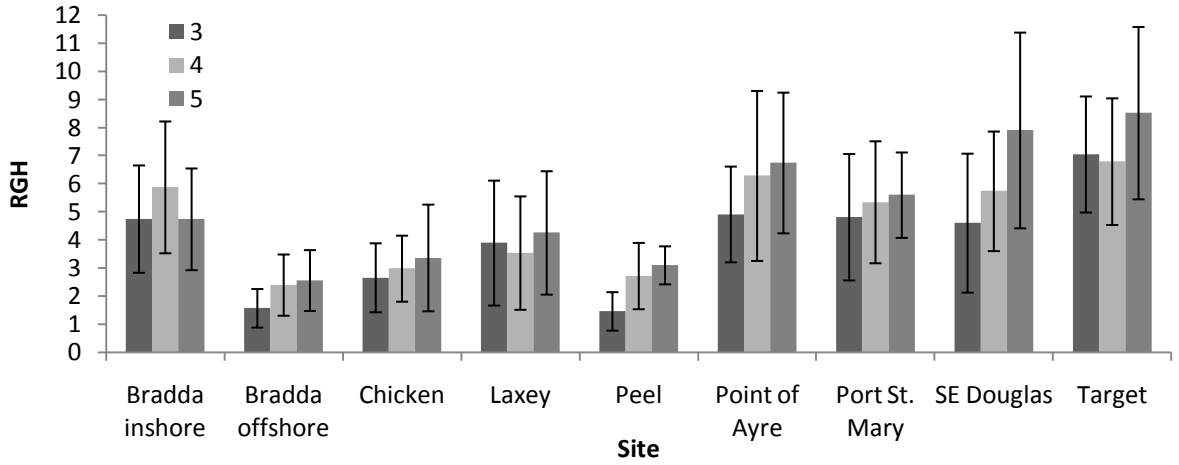



Fig3.4 Average king scallop relative gonad weight and shell height index (RGH) in 9 studied sites around Isle of Man in the 3 age groups.

Out of 1081 scallop samples, eight scallops (found in Laxey age4 and 5, Port St. Mary Age 3, SE Douglas Age 5 and four in Port St. Mary Age 5) were found to have emptied or half emptied male organ but full female organ. It is believed to be either spawning or stress-caused ejaculation (personal communication Dr C. Richardson, 2009). Two scallops (Point of Ayre age 4 and Port St. Mary age 4) were found to have only female organ, it was also seen in Mason (1958)'s study.

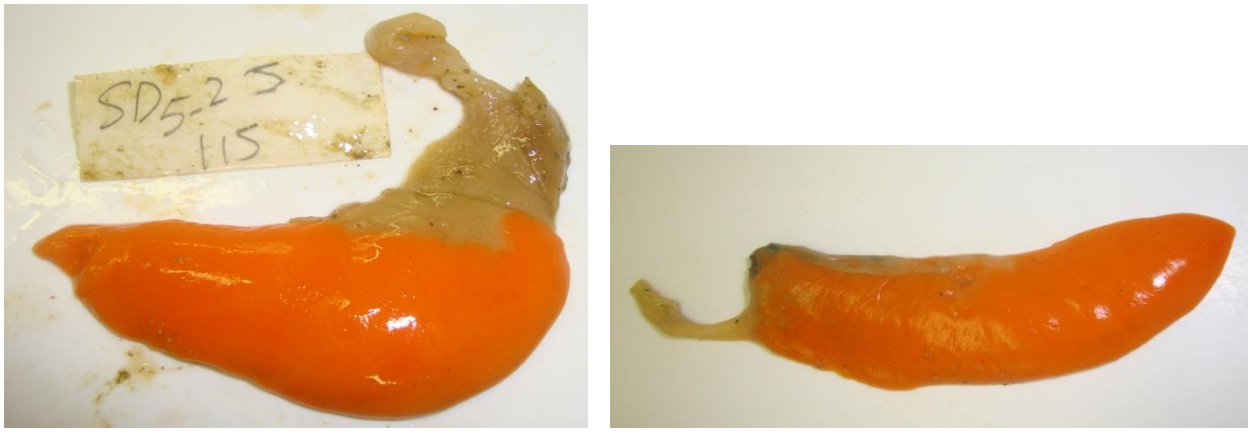


Photo 3.1 Scallop with half emptied male organ (left) and scallop with female only gonad.

## 3.2 Spatial variation in environmental and biological parameters

Summary of environmental data in 9 sites are presented in Appendix 2. There were no short term environmental data for Port St. Mary and SE Douglas. Bathymetry map of Isle of Man

is showed in Appendix 1 with 9sites plotted. Point of Ayre is the shallowest site with average depth of -5.03m and SE Douglas is the deepest site averaging at -49.22m.

No significant difference were found between sites using long term data set including sea surface temperature and chlorophyll a in June from 2004-2008 (ANOSIM, R=0.405, P=0.1). MDS plot indicate possible two groups (Fig 3.5).

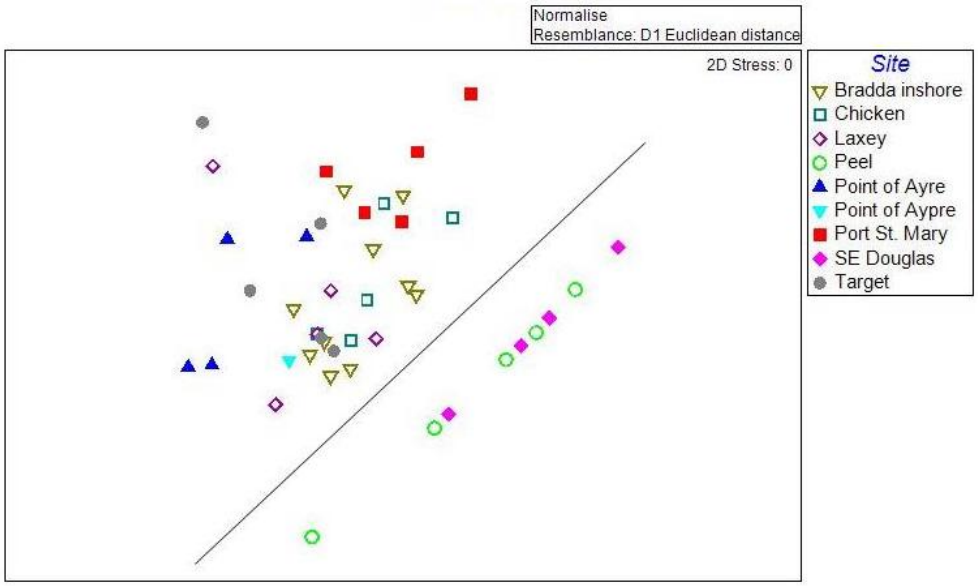



Fig 3.5 MDS ordination plot for sea surface temperature and chlorophyll a concentration in June 2004-2008 in 9 sites.

With the high variability over past 5 years, there is no significant different in sea surface temperature and chlorophyll a concentration between 9 sites. Point of Ayre has the higheset chlorophyll a concentration and SE Douglas appears to have the lowest chlorophyll a, however, it is suspected to be some error in SE Douglas data (Fig.3.6). There seems to be more variation between sites for chlorophyll a concentration than sea surface temperature.

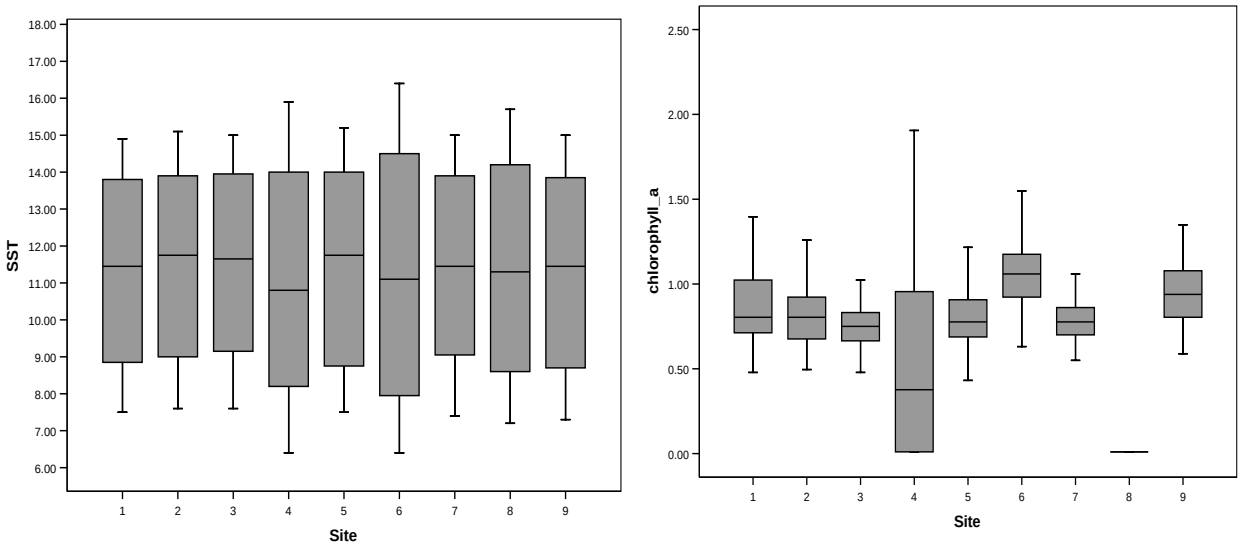



Fig.3.6 Average annual from 2004-2008 sea surface temperature ($^{o}$C) and chlorophyll a concentration in 9 studied sites around Isle of Man (1=Bradda Inshore, 2=Bradda Offshore, 3=Chicken, 4=Laxey, 5=Peel, 6=Point of Ayre, 7=Port St. Mary, 8=SE Douglas and 9=Target)

Since no significant difference was found in the June data for sea surface temperature, plots of annual monthly sea surface temperature and chlorophyll a concentration were drawn to investigate any trends appear that may influence gonad maturation. Most of the sites seem to follow a similar trend except Point of Ayre, which exhibit the lowest winter sea surface temperature and a highest summer sea surface temperature from other sites (Fig. 3.7). It has a high sea surface temperature variation over a year's time. It could be due to it being the shallowest site. Point of Ayre is also has a longest warm period. Port St. Mary has the lowest summer temperature and does not reach maximum temperature until September where all other sites reach maximum temperature in August.

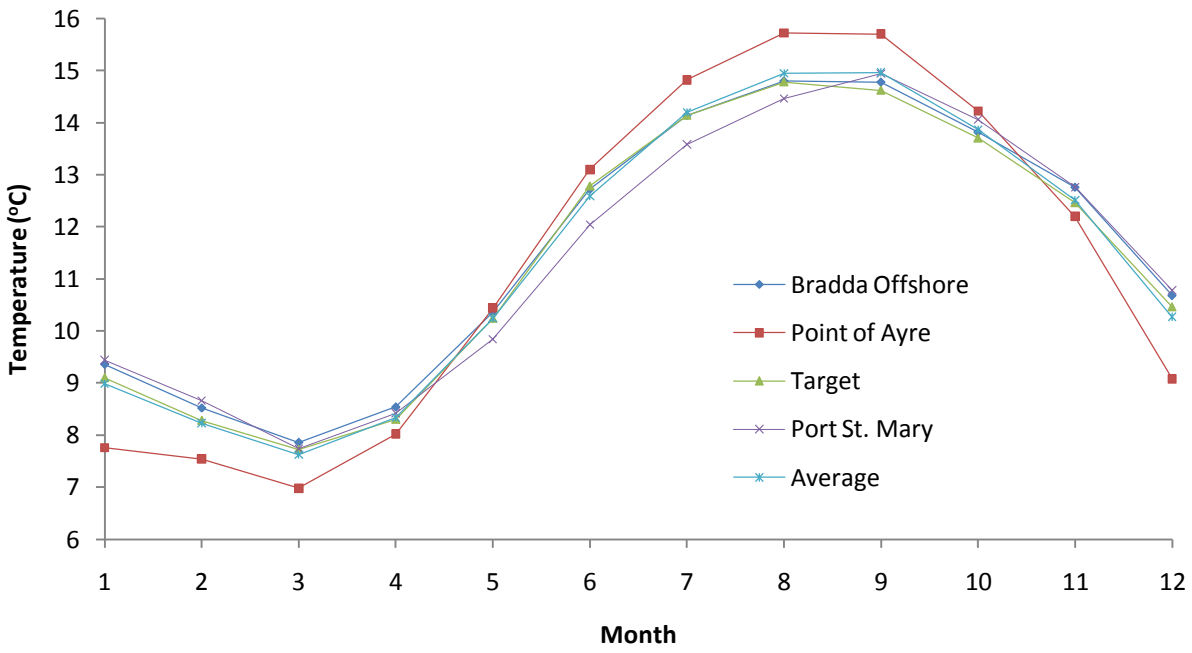



Fig. 3.7 Average monthly sea surface temperature ($^{o}$C) in 4 sites and an average of all 9 sites.

No particular trends were found from annual chlorophyll a plot (Fig.3.8). However, most sites (but SE Douglas and Port St. Mary) seems to reach maximum concentration in May. Port St. Mary reach maximum one month later in June. Similar to sea surface temperature, this site seems to have a slightly delayed trend; it might be due to it being one of the deepest sites (Appendix 2). Peel has the most variation throughout a year's period for chlorophyll a concentration (highest concentration at peak and generally lower concentration than other sites). Only a single peak was found in most sites except in Laxey where it appears to have another one in September. There is more variability in trends of chlorophyll a concentration than sea surface temperature,

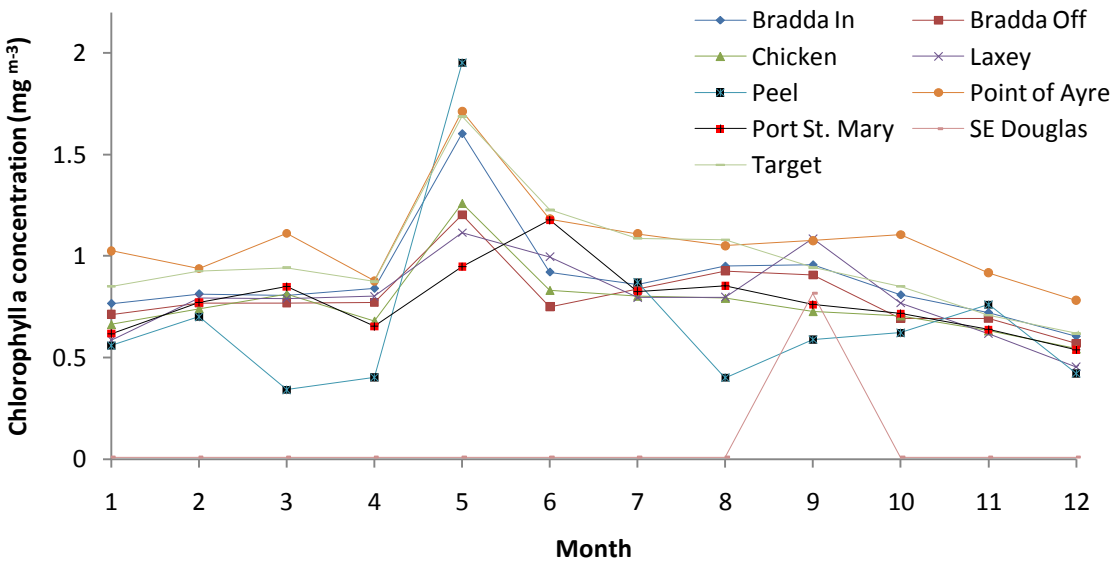



Fig 3.8. Average monthly chlorophyll a concentration (mg $m^{-3}$) in all 9 sites.

From the August 2008 survey, Point of Ayre, Target and Laxey has the lowest variation between sea bottom temperature and sea surface temperature (Fig. 3.9). Bradda offshore has the highest variation between sea bottom temperature and sea surface temperature.

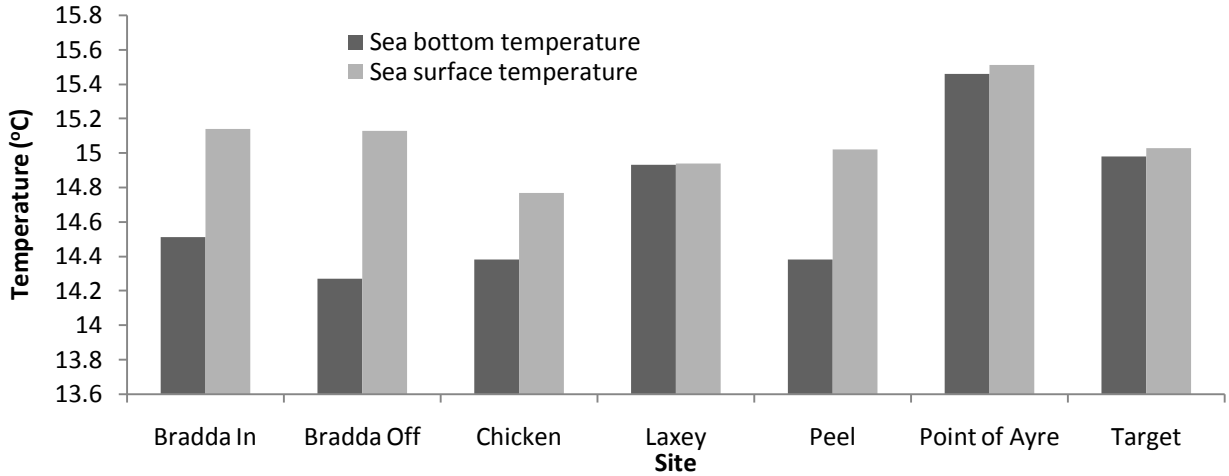



Fig. 3.9 Sea surface temperature (°C) and sea bottom temperature (°C) around the Isle of Man in 7 sites during the survey in August 2008.

## 3.3 Correlation and regression

Both Pearson and Spearsman's correlation tests were applied with different normality nature of data sets. Only chlorophyll a in June and Pea showed significant correlations (Table

3.1). Sea bottom temperature and surface chlorophyll a concentration in August 2008 seems to show near significant correlations (p=0.052 and p=0.069 respectively). Most correlations were positive except depth, bottom chlorophyll a, chlorophyll a concentration in sediment, salinity and Pea. Chlorophyll a in sediment showed the least correlation, followed by sediment grain size, surface salinity, surface temperature in June and depth.

Table 3.1 Correlation of RGH with different environmental and biological parameters.

| | Test | Stats value | significance |
|---|---|---|---|
| Depth | Pearson | -0.365 | 0.335 |
| Sea surface temperature in June | Pearson | 0.31 | 0.417 |
| surface chlorophyll a in June | Pearson | 0.912 | 0.002 |
| Sea surface temperature in August08 | Pearson | 0.403 | 0.37 |
| Sea bottom temperature in August08 | Pearson | 0.749 | 0.052 |
| Bottom chlorophyll a in August08 | Pearson | -0.69 | 0.086 |
| Surface chlorophyll a in August08 | Pearson | 0.719 | 0.069 |
| Chlorophyll a in sediment in August08 | Pearson | -0.011 | 0.981 |
| Bottom salinity | Spearsman | -0.561 | 0.19 |
| Surface salinity | Spearsman | -0.349 | 0.445 |
| Grain size | Pearson | 0.2 | 0.667 |
| Pea | Pearson | -0.769 | 0.043 |
| Abundance | Spearsman | 0.128 | 0.743 |

Li near regression was carried out for some of the more significant correlations and long term data sets. Depth and sea surface temperature in June continue to show insignificance. Surface chlorophyll a concentration in June once again showed highly significant, it was later confirmed to be the most significant regression (stepwise regression, step 1: t=5.13,p=0.007, r-sq=86.49;step 2:t=7.95,p=0.004, r-sq=93.82). Pea and sea bottom temperature also show significance (Table 3.2).

| Regression: | $R^2$ Value | Significance | y=mx+c |
|---|---|---|---|
| Depth | 0.1943 | 0.186 | y=-0.0498x-3.333 |
| Sea surface temperature in June | 0.0164 | 0.978 | y=0.6642x-3.7626 |
| surface chlorophyll a in June | 0.8172 | 0.007 | y=0.3777x-3.8409 |
| Sea surface temperature in August08 | 0.1626 | 0.37 | y=3.2832x-45.214 |

| | | | |
|---|---|---|---|
| Sea bottom temperature in August08 | 0.5617 | 0.052 | y=3.2039x-42.815 |
| Bottom chlorophyll a in August08 | 0.5169 | 0.69 | y=7.5902x-1.4016 |
| Surface chlorophyll a in August08 | 0.4761 | 0.86 | y=-3.5814x-7.8574 |
| Chlorophyll a in sediment in August08 | 0.0001 | 0.981 | y=-0.0006x-4.3324 |
| Pea | 0.5918 | 0.043 | y = -0.1943x + 6.3269 |
| Abundance | 0.0163 | 0.743 | y = 0.0323x + 4.4104 |

Table 3.2 Linear regression relationship between RGH and different environmental and biological parameters.

Depth, surface chlorophyll a concentration and Pea continue to show a negative regression relationship towards RGH where the rest showed a positive regression relationship (Table 3.2 and Fig. 3.10). Slopes and intercepts of all the parameters were different in each linear regression.

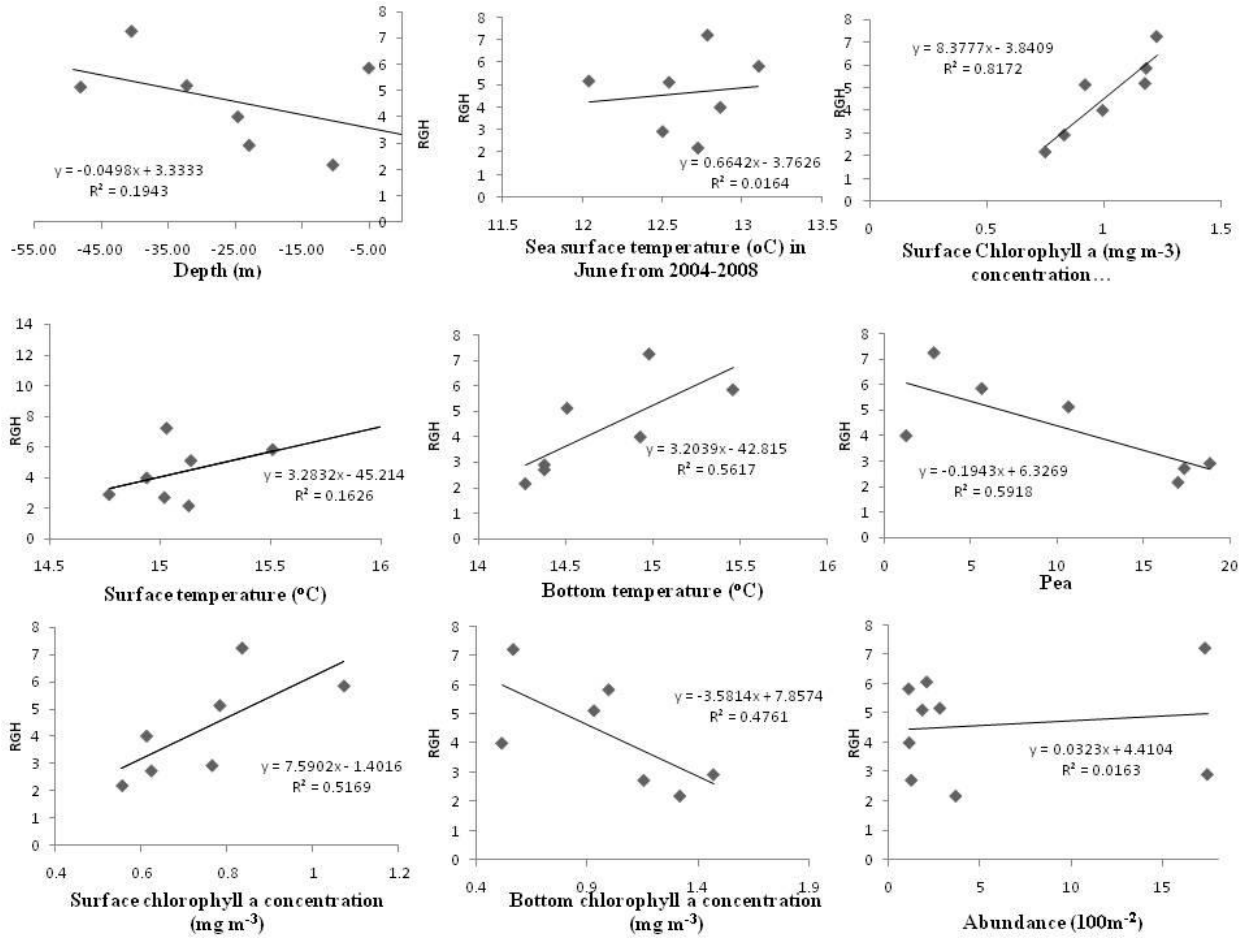



Fig. 3.10 Linear regression relationship between RGH and different environmental and biological parameter.

## 3.4 Meta-analysis

Linear regression was drawn for all bivalve data with sea surface temperature. Due to massive variation, no relationship was found. Scallop species were separated out from data and

linear regression was drawn to detect for any significance. $R^2$ values remain relatively low, only bay scallop and *Argopecten purpuratus* is showing some relationship (Fig.3.11). Data were then put through statistic analysis, however, no significant results were found (Table 3.3).

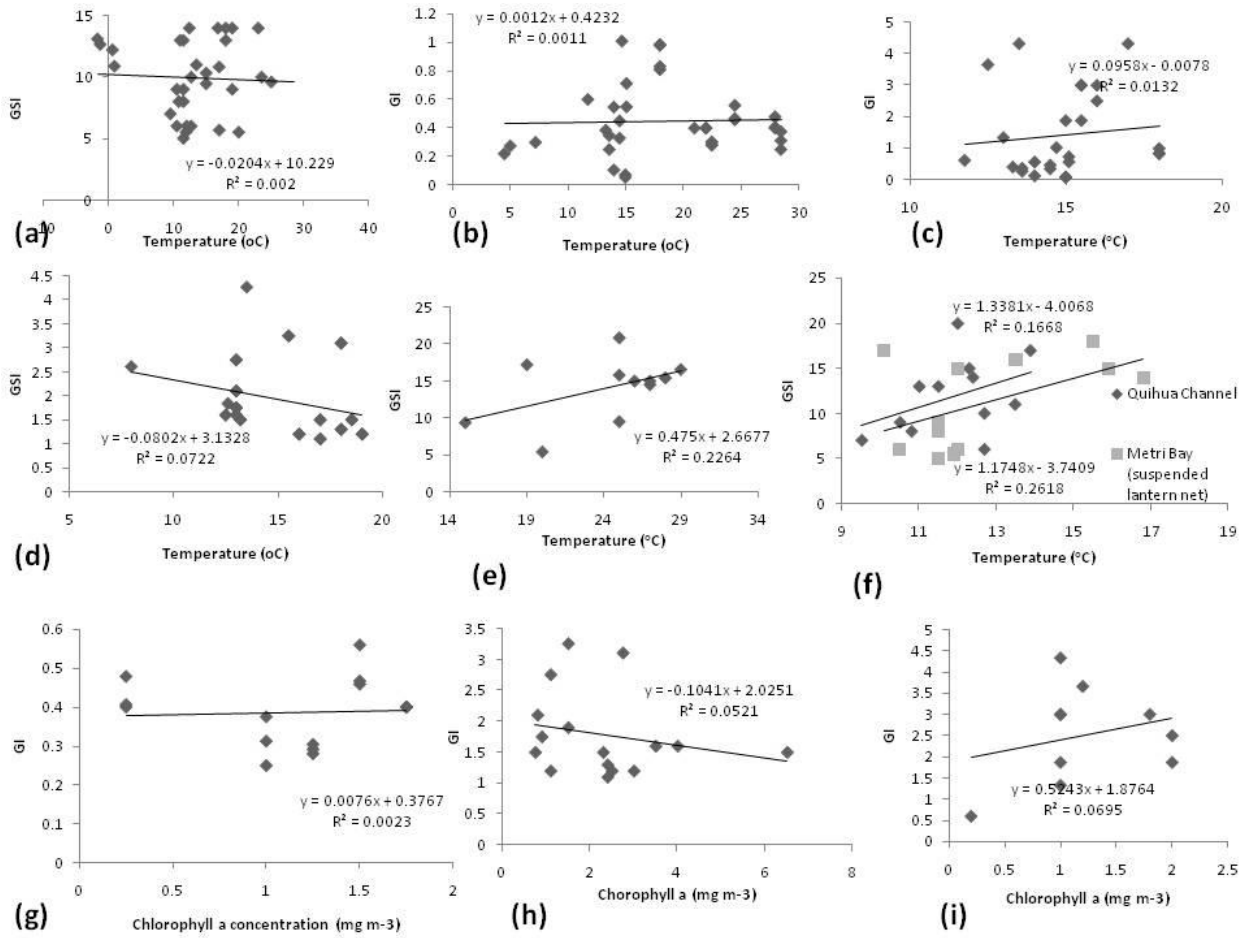



Fig. 3.11 Linear regression of (a) all bivalve meta-analysis data GSI and temperature; (b) GI and temperature; (c) GI and temperature of queen scallop *Aequipecten opercularis* in Ria de Arosa, Galicia, Spain (Roman *et al*, 1996 and 1999); (d)GSI king scallop in Ria de Rousa, Galicia, Spain (Pazos *et al*, 1996); (e) GSI and temperature of Bay scallop *Aquipecten irradians* in Beaufort, North Carolina, USA (Sastry, 1966); (f) *Argopecten purpuratus* in Southern Chile (Gonzalez *et al*, 2002); (g) GI and Chlorophyll a of *Lyropecten nodosus;* (h) *Pecten maximus* in Ria de Rousa, Galicia, Spain (Pazos *et al*, 1996); and (i) *A.opercularis* in Ria de Arosa, Galicia, Spain (Roman *et al*, 1996).

| | $R^2$ Value | Significance | Slope | Intercept |
|---|---|---|---|---|
| SST: | | | | |
| queen scallop (GI) | 0.0132 | 0.577 | 0.0958 | -0.0078 |
| king scallop (GI) | 0.0722 | 0.144 | -0.0802 | 3.1328 |
| bay scallop (GSI) | 0.2264 | 0.139 | 0.475 | 2.6677 |
| *A.purpuratus* in Quihua chanal | 0.1668 | 0.187 | 1.3381 | -4.0068 |

| | | | | |
|---|---|---|---|---|
| *A.purpuratus* in Metri Bay | 0.2618 | 0.089 | 1.1748 | -3.7409 |
| Chlorophyll a: | | | | |
| *L.nodosus* | 0.0023 | 0.867 | 0.0076 | 0.3767 |
| king scallop (GI) | -0.1041 | 0.395 | 2.0251 | 0.0521 |
| *queen scallop (GI)* | 0.5243 | 0.462 | 1.8764 | 0.0695 |

Table 3.3 Statistic analysis of linear regression results.

Combining present study and meta-analysis data for sea surface temperature and chlorophyll a, no significant relationship were found (SST:p=0.693; Chla:p=0.317). The $R^2$ for sea surface temperature was lower than chlorophyll a concentration, however relationship is not as significant as chlorophyll a (Fig. 3.12).

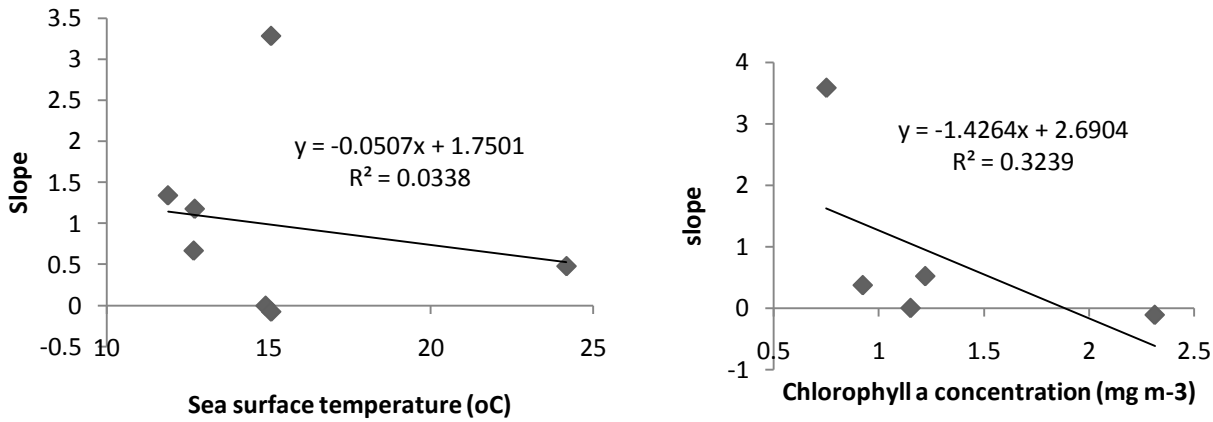



Fig. 3.12 Linear relationship of slope from present study and meta-analysis data with sea surface temperature and chlorophyll a concentration.

## 3.5 Energy allocation

Shell height was found significantly different between sites (ANOVA, F=42.32, p<0.000). Looking at Fig. 3.13, Peel has the smallest shell overall in age 3 scallops. Point of Ayre has the largest shell overall. Shell height was significantly different between age group 3 and age group 5 (ANOVA, F=40.31, p<0.000).

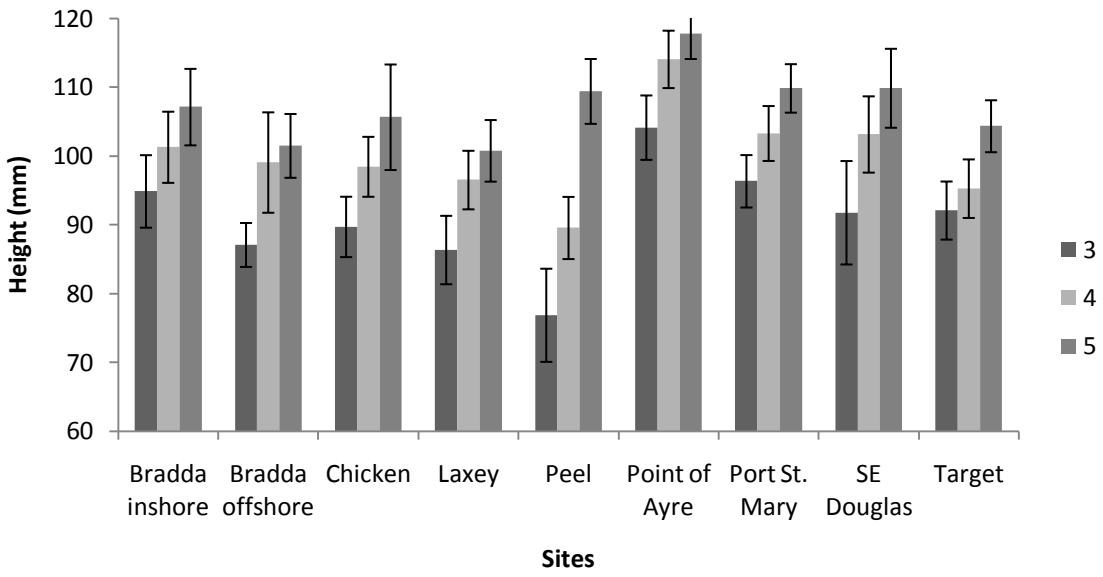



Fig. 3.13 Average shell height (mm) of scallop in 3 age groups in 9 studied sites

Muscle wet weight were significantly different between sites (ANOVA, F=52.9, p<0.000). Using ratio of three tissues, significant different ratio were found between sites (gonad: F=25.40, p<0.000; muscle, F=28.87, p<0.000; remaining tissue, F=20.53, p<0.000). Pie charts revealing the differences in tissue compositions (Fig. 3.14).

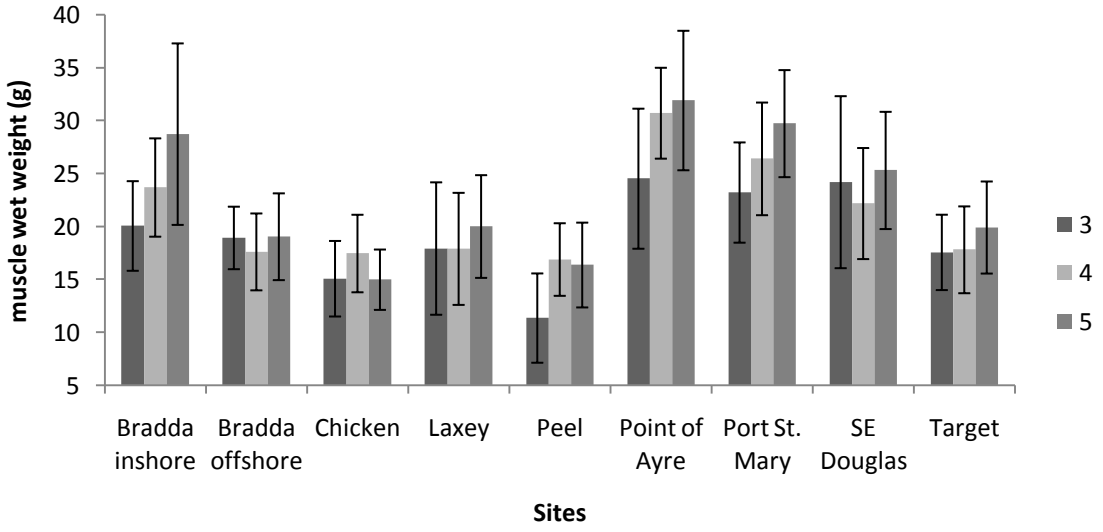



Fig. 3.14 Average muscle wet weight (g) of scallop in 3 age groups in 9 studied sites.

Correlation were found significant of three tissue using all scallop data (gonad and mucle: Pearson correlation: -0.453, p<0.000; gonad and remaining tissue: Pearson correlation: -0.355,p<0.000; muscle and remaining tissue: Pearson correlation: -0.673, p<0.000).

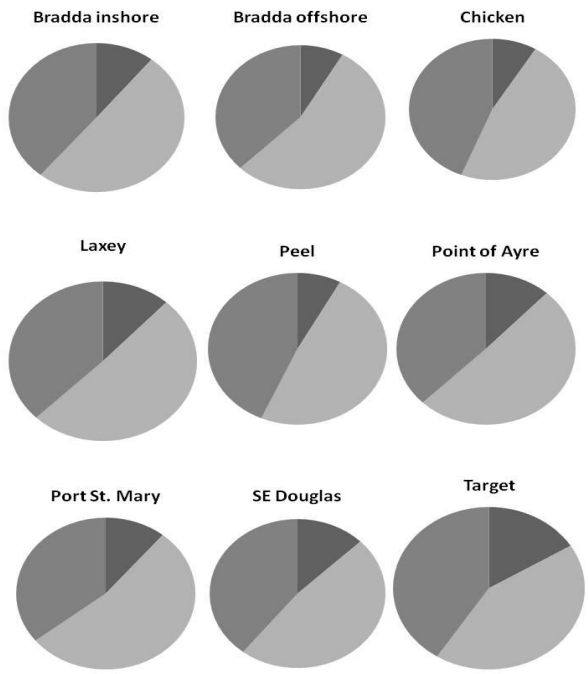



Fig. 3.15 Pie chart showing ratio between three different parts (gonad : darkest grey; muscle: intermediate; and remaining tissue: light grey).

Linear regression were drawn for muscle and gonad and with gonad weight and shell height, $R^2$ values were high and they were both showing significance ($p<0.05$).

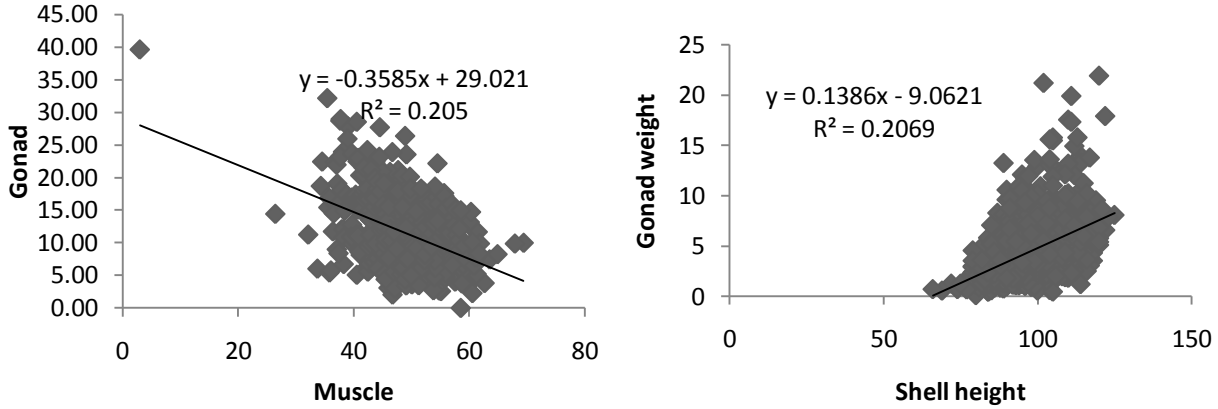



Fig 3.16 Linear regression between gonad ration and muscle ration; gonad weight (g) and shell height (mm).

Variation between dry and wet weight in all the sites were not significant (Fig 3.17). The least different was found in Target. The variability of dry gonad weight within each sites were

high. Both dry and wet gonad showed significant differences between sites.

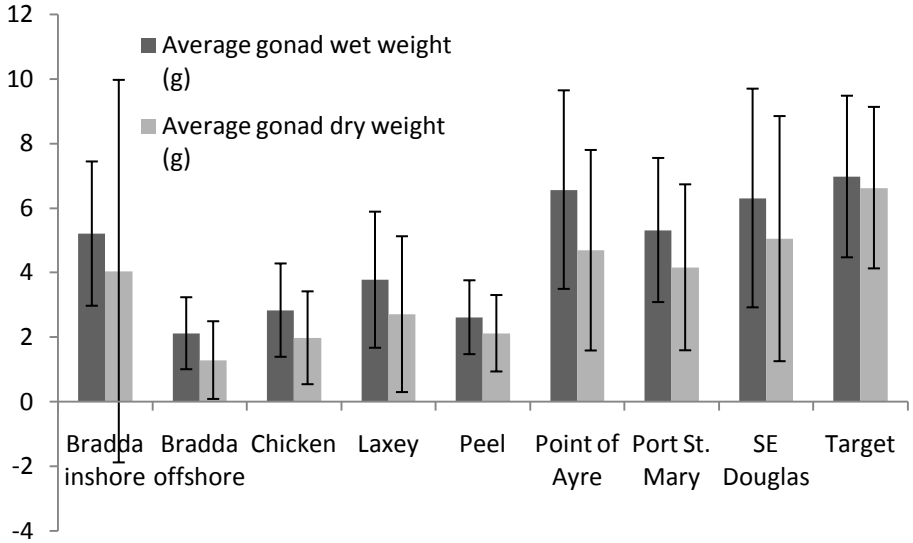



Fig. 3.17 Average gonad dry weight (g) and wet weight (g) of scallop in 9 studied sites with SD.

# Chapter 4

# Discussion

## 4.1 Spatial variation in gonad maturation state

Significant spatial variation in king scallop gonad maturation state were found around Isle of Man in present study. It has suggested that scallop around Isle of Man have various maturation state hence indicating different spawning time. In some sites (Bradda offshore), scallops were found to be spent or recovering whereas Target has the highest gonad index suggesting spawning is due soon. GOI results also indicated king scallops were in various maturation states. Different number of scallop gonad at stage V was affecting the results most significantly. Four sites (Point of Ayre, Port St. Mary, Bradda inshore and Target) were composed of mostly stage V where Bradda offshore, Chicken and Peel consist of gonads in earlier stage or spent gonad were found.

RGH revealed that scallop gonads found in Target are more matured on average. GOI indicate a high percentage of Stage V and VI scallops (ready to spawn) were present in Target. This site is also found to be the most populated and fished area. Mean relative abundance of king scallop in Target increased from <2 individuals per 100m-3 to 27.2 individuals from 2004-2007 (Murray *et al*, 2009). Slater (2005) found that gonad size prior spawning does not relate to spatfall intensity. Therefore instead of amount of gamete produced, recruitment success may be more affected by spawning time.

With present study, it cannot confirmed that decrease in gonad index indicate spawning activities. A decrease in gonad index can result from resorption, not only from spawning (Roman *et al*, 1996). However, because this study is done in June which is their spawning season and chlorophyll a is plenty, therefore a decrease in gonad index can suggest spawning fairly confidently.

No general trends can be drawn geographically (North, East, South and West). Scallop gonad maturation state does not seem to be influenced by sites direction. Bradda inshore and Bradda offshore which were closest together geographically found to have significant different gonad maturation state. Bradda inshore on the other hand was similar to Port St. Mary which is

the southernmost sites of the whole survey. Chicken and Peel were grouped as having similar gonad maturation state, however, they were geographically separated by two sites (Bradda offshore and Bradda Inshore). Point of Ayre and Southeast Douglas were havie similar gonad maturation state but located far away from each other. This results is similar to Roman (1994) and Bonardelli (1985)'s results. Roman (1994) found king scallop in Ria de Arosa has similar spawning time from two far apart location where Bonardellin (1985) showed that sea scallop *Placopecten magellanicus* has very different spawning time from two close population. This suggests that instead of affected by geographic location, scallop maturation state or spawning time may be affected by oceanography features in that particular location.

Gonad index were found to be able to recover after one week in king scallop in Mulroy Bay by Slater (2005). Present study has not considered temporal variation, therefore recovery time and time needed for scallop to build up gonad mass is unknown. Consequently, spatial variation of reproductive strength cannot be drawn using present study.

4.2 Factors contributing to variation

Different environmental and biological parameters were used to correlate with gonad maturation state. Chlorophyll a was showing the most significant linear regression towards gonad maturation state followed by PEA and sea bottom temperature. Stepwise regression has confirmed Cholorophyll a being the most significant effect on gonad maturation. Many studies have also showed chlorophyll a being major factor affecting gonad maturation (Macdonald and Thompson, 1986; Martinez and Perez, 2003 and Roman *et al*, 1999). It has confirmed by this study that scallop maturation is affected by oceanography features instead of location.

Chlorophyll a concentration has shown a positive linear regression relationship with gonad maturation state. Increase food availability allow scallop to build up gametes resulting increased gonad size, it also allow newly hatched larvae to feed on. Therefore an increase in food available usually encourages spawning and speed up gonad maturation. Some studies have suggested that when chlorophyll a concentration increases to a certain level, a negative effect will have on gonad maturation (Lorrain *et al*, 2000; Shumway *et al*, 2005). However, in natural environment, unless eutrophication or toxic algal bloom took place, there is rarely sufficient

chlorophyll a to give a negative effect on scallop gonad growth. Meta-analysis did not show any significant relationship for chlorophyll a.

Potential energy anomally has sown a negative linear regression relationship with gonad maturation state. PEA describes the degree of stratification of seawater within an area; higher than PEA value indicate more stratified sea water. Transition zone that are between stratified and un-stratified zone are important area for primary and secondary production (Murray *et al*, 2009). According to the habitat survey done in August 2008, transition zones are mainly in the south and southwest of IoM. In this study, less stratified sites contained higher concentration of Chlorophyll a which result an increase in gonad maturation state. King scallops are bottom suspension feeding, less stratified sites enable scallop to filter feed re-suspended benthic algae. King scallops are found to re-suspend benthic algae by clapping their shells. As benthic algae were found to be major diet component of king scallop, combination of less stratified water, increase in chlorophyll a in water column and/or sediment will increase king scallop consumption hence increase gonad maturation.

Seawater temperature is another environmental factor that has shown influence towards gonad maturation. Increase in seawater temperature lead to increase in gonad maturation state. This result agrees with Boecherding (1995), Sastry and Blake (1997) and Murray *et al* (2009) that seawater temperature plays an important role in gonad maturation. However, for each species of scallop there's an optimal range of temperature. If temperature has exceeded the range, metabolism, growth and even survival will reduced. Meta-analysis also showed similar results from different species. All but king scallops in Spain were found to have positive relationship towards temperature. The ranges of temperature used in king scallops were between $16^{o}$C-$20^{o}$C. Temperature range in present study is between $12^{o}$C-$15^{o}$C. King scallops' optimal temperature are between $10^{o}$C-$17^{o}$C (Shumway *et al*, 2005), therefore in that particular experiment, temperature has exceeded optimal temperature for king scallop. Present study suggested temperature affect gametogenesis hence gonad maturation, however, survival of larvae and size of gametes are affected by quantity and quality of food (Martinez *et al*, 2000).

Depth of sites around IoM has found significantly different from each other, however, no relationship has been found with gonad maturation state. Change in depth itself is a spatial variation already. By altering depth, many environmental parameters such as pressure has

changed significantly. Although gonad maturation state were not found different with depth, king scallops were found increasing population density with increasing depth in IoM (Murray *et al*, 2009).

Using gonad maturation state to correlate abundance was not significant. Gonad maturation state in June cannot represent recruitment success. Although using statistical analysis it has suggest chlorophyll a to be the main factor affecting scallop gonad maturation. But it is dangerous to assume that with just an increase in chlorophyll a lead to scallop gonad maturation. A multivariate approach of assessing factors affecting scallop growth and reproduction is essential (Tettelbach and Rhodes, 1981). Interaction between environmental, anthropogenic (fishing) and biological factors (internal regulation) act together to alter living condition for organisms.

Sastry (1970) suggested that latitudinal different are most likely to affect the breeding of marine invertebrates, in present study, scallop gonad maturation state varies both latitudinal and longitudinal due to the various oceanography features present in IoM.

## 4.3 Age group variation and energy allocation

Spatial variation in each part of scallops: gonad, muscle, remaining tissue and shell height were found in this study. From this, it suggest that size at maturity of king scallop in IoM is likely to vary spatially and Peel has appeared to have smaller scallops on average. Target has been suggested to have higher number of smaller scallops than other sites possible due to high density caused competition for food (Murray *et al*, 2009).

Variation of size at maturation can be one of the reasons contributing to variation of local population density. It is common in fishery management and in practice in IoM that fishing minimal size limit is set just greater than size reached at maturity (Williams and Babcock, 2005). An overall MLL was set at 110mm for king scallop in IoM. There is spatial variation of scallop size around IoM, it is therefore important to investigate spatial variation of size at maturity in different fishing sites for fishery management. It is important to allow scallops to spawn at least twice to prevent local population collapse.

Variation in scallop gonad and muscle size as well as abundance can alter fishers' interest as larger scallop hold a higher value. King scallops found in Point of Ayre have the largest muscle size and gonad size is also one of the largest. Many fishing effort has been spent in Target (Murray *et al*, 2009) even though muscle size are relatively small, it is due to high abundance of scallops and location of site.

Energy allocation of scallops varied significantly between sites. It correlates with the RGH results showing more energy were invested in gonad building in certain sites. However, using weight is not a very efficient tool to look at energy allocation. Decrease in gonad size does not necessarily means less energy was invested in it, it may indicate spawning activity. Also in this study shell weight data was missing, therefore energy allocation was restricted to tissues. In reality, large amount of energy will be invested for shell building and repairing shells from damage. This in turn will affect energy allocation; consequently energy invested in gonad might reduced.

Mason (1957) has shown there is high correlation between the length, breadth and thickness of the shell. In present study, high correlation was shown between gonad weight, muscle and shell height. Negative relationship was found between gonad and muscle shows gonad development will lead to reduction in muscle growth. It may be competition for energy and space within scallop itself.

## 4.4 Spatial variation of gonad maturation relation to fishery management

Target has been the most fished area with up to 39.7-53.8 fishing effort between end of 2007 to end of 2008, followed by Chicken, Bradda inshore, Point of Ayre and south of Port St. Mary (Murray *et al*, 2009). According to survey in 2008, Target has the highest population density but this June scallop survey revealed chicken to have the highest density with 17.47 followed closely by Target 17.3. High density of scallop has been a big attraction for fishers to fish around, especially with the increase in fuel price. It is more beneficial to fish in a smaller area for more scallops. Spatial variation of gonad maturation has not been shown to have any relationship with fishing effort, mostly due to lack of data that can be used for present study. However, in order to understand stand fishing effect on scallop maturation, scallops with broken shells has to be considered as well.

Laxey was proposed as closed area in 2008. According Landings fluctuations are due to fishing effort, stock abundance and market demand. Recent review has suggested that recruitment of scallops in IoM was heavily relied on year 2 instead of year 3. Aquaculture has been suggested for this area by DAFF (Murray *et al*, 2009). Spatial variation of maturation state can give an indication of reproduction strength in June.

It is ideal to have different limits for scallop fishery management around Isle of Man with such significant spatial variation in scallop maturation. However, it is not practical to do so, therefore it is sensible to be more conservative with fishery management and set its limits using the least productive sites as reference.

June is ideal period to study scallop reproduction because it is in spawning period. With the spatial variation appears around IoM, different maturation state can be found.

## 4.5 Future study

This study has efficiently point out the significant spatial variation of king scallop gonad maturation state around Isle of Man. However, due to lack of temporal data, it is very hard to compare reproductive strength between sites. Therefore a year round study of scallop maturation will give a better idea of reproductive strength. From present study, it can only conclude in June, Target is the most reproductive strength because of high gonad index and high population density.

Size at maturity has been suggested to vary between sites due to spatial variation of muscle, gonad and shell size. Present fisheries policies in IoM have used Minimal Length Limit and have proven to be an effective way to regulate fisheries. However, since spatial variation of scallop growth were found in IoM, it is very dangerous to use average size at maturity as MLL. This may put some sites with slower growth in the risk of stock collapse due to lack of broodstock population and annual reproduction. Scallops should allow to spawn at least twice before fished to maintain population density.

Gonad maturity has found to be significantly different between age group 3 and 5. Gonad weight has also found significantly smaller in age group 3 than age group 5. Scallop possess interdeterminate growth, gonad and muscle grow through age. Larger and more gametes may be

produced and stored in older age groups. However, age group 4 showed no significant different to age group 5. Scallops are usually fished at age group 3 in most sites. It is therefore worth investigating whether younger scallop has same reproductive strength.

Scallop spawning ability in relation to recruitment success should also be studied spatially because of variation PEA and current present around IoM. Broodstock and survival of larvae and spat require different environmental features. Scallop spawning ability cannot directly relate to recruitment success.

Since queen scallop *Aequipecten opercularis* is also one of the most important fisheries in IoM, it is important to look at spatial variation in maturation state for this species as well. Queen scallop occupies very different habitat with king scallops. Population distribution is also different from king scallop. It has been found that population density increase with depth for queen scallops (Murray *et at*,, 2009). Biology of queen scallop also varies with king scallops. Queen scallops have a shorter lives yet a very similar age at maturity. It is also significantly smaller than king scallops. Environmental factors might affect queen scallop differently hence spatial variation may be different for this species. From meta-anlysis data, it has shown variation of queen scallop response to temperature and chlorophyll a with king scallops.

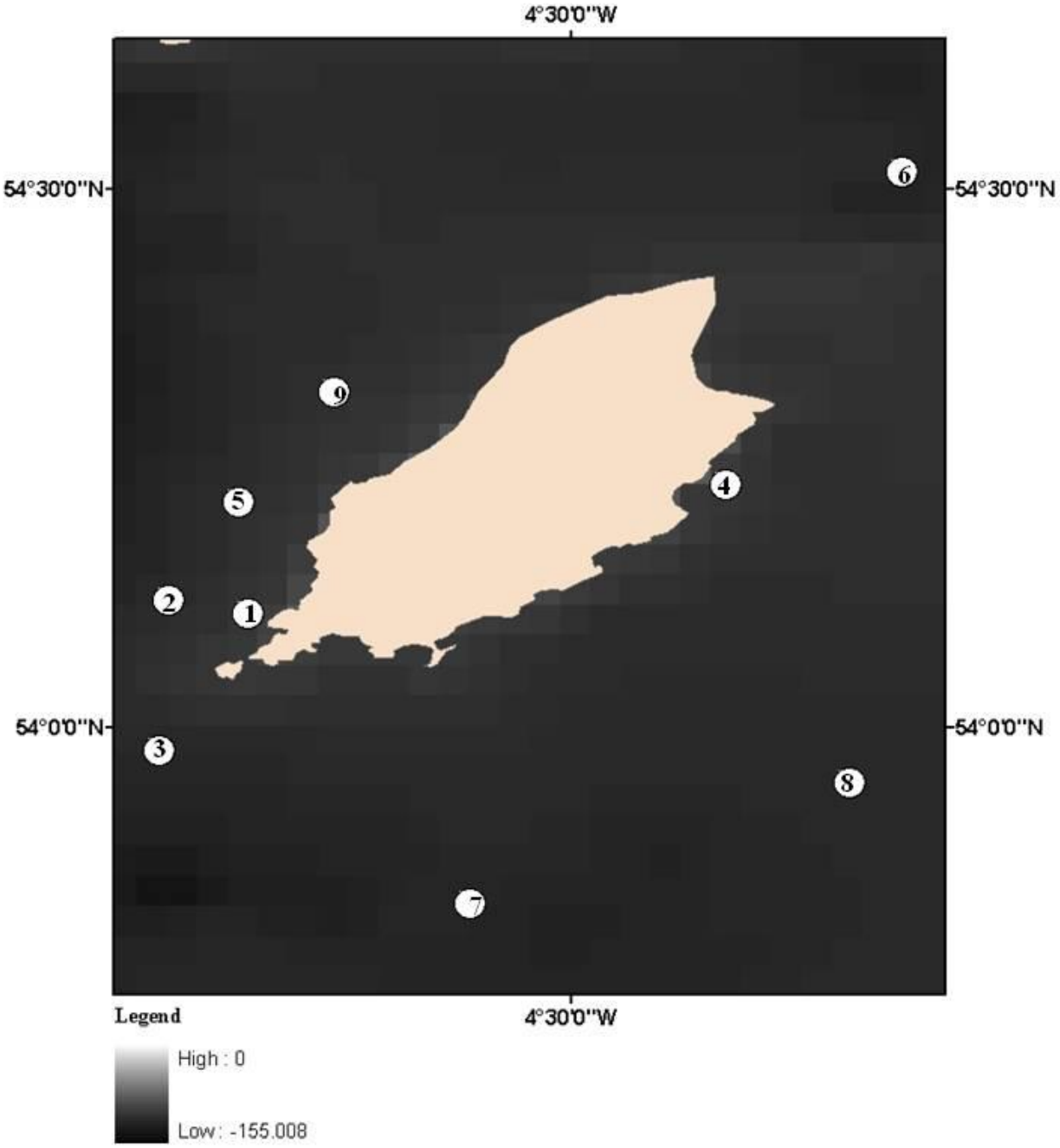
# Chapter 5

## Conclusion

Spatial variation of gonad maturation state was found using both GOI and RGH. Target has the highest RGH and GOI revealed that Target was mostly composed of stage V and VI scallops which were ready to spawn. Bradda offshore has the lowest RGH and GOI revealed that stage III scallops and stage VII scallops were found in this site indicating scallops have been spawned. Gonad maturation state was also found to significantly differ between age group 3 and age group 5, but not between age group 4 and age group 5. Linear regression and correlate results indicate seawater temperature, chlorohphyll a concentration and PEA was the factors affecting spatial variation of gonad maturation. Stepwise regression analysis showed chlorophyll a concentration was the main factor and contributed the most in the gonad variation. Multivariate approach should be used for investigating factors affecting scallop growth, there will not be a sole factor affecting scallop growth and reproduction. Temperature usually indicate harshness of environment, food availability indicate quality of environment. Temperature is the initial factors affecting gonad growth and maturation; food availability is then contributed to the quality of reproductive materials and recruitment success. PEA is an important tool to investigate whether an environment enable scallop feed well. Meta-analysis data from other species and king scallops from Spain did not show any significant relationship; combination with present results, no significant relationship was found with gonad maturation towards temperature and chlorohphyll a. Scallop shell height, gonad, muscle and remaining tissue weights were found significantly different between sites; proportion of gonad, muscle and remaining tissue was also found to be significantly different between sites suggesting different energy allocation between sites. This study has successfully completed the four objectives and aim was achieved. RGH and GOI were good indicators for gonad maturation.

Appendix 1:

Bathymetry map of Isle of Man with 9 studied sites (1=Bradda Inshore, 2=Bradda Offshore, 3=Chicken, 4=Laxey, 5=Peel, 6=Point of Ayre, 7=Port St. Mary, 8=SE Douglas and 9=Target).



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