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THE SEASONAL MOVEMENT AND ABUNDANCE OF THE STARFISH, *ASTERIAS RUBENS* IN RELATION TO MUSSEL FARMING PRACTICE: A CASE STUDY FROM THE MENAI STRAIT, UK

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ABSTRACT Mussel cultivation is the most valuable sector of the bivalve aquaculture industry in the United Kingdom, and the largest mussel fishery in Britain is located in the Menai Strait, North Wales. The common starfish, *Asterias rubens* is highly abundant and widely distributed throughout British waters, affecting the distribution and abundance of prey species such as the common mussel, *Mytilus edulis*. This study investigates the potential influence of the Menai Strait mussel fishery on seasonal patterns of abundance, distribution, and migration of *A. rubens*, and aspects of their reproductive strategy. Starfish and mussel populations were surveyed and sampled monthly over a 2-y period using a visual survey technique and by trawling the seabed during the mussel harvest period. Maximum starfish density (40,586 ± 5,648 starfish·ha^{-1}) and percentage mussel coverage (~40%) were recorded on a commercial subtidal mussel bed. Mussel density and starfish abundance increased seasonally between April and July and declined between September and March, with the loss of 1.7×10^6 starfish attributed directly to the activities of the mussel fishery. Starfish migration onto subtidal mussel beds is deemed to be in response to the transplantation of high densities of mussels and trawling activity, and the reduction in starfish numbers over the winter a direct result of harvesting activities. Estimates of starfish reproductive condition determined from trawl samples collected during the same period suggest that starfish were aggregated and highly abundant at sites without mussel cultivation during their peak reproductive state. *Asterias rubens* migration into deeper water is believed to be in response to increasing seawater temperature where gravid individuals spawn in close proximity to improve fertilization.

KEY WORDS: starfish *Asterias rubens*, Menai Strait, movement, abundance, mussel cultivation, reproductive cycle

INTRODUCTION

The mussel cultivation industry is currently the fastest growing and most valuable sector of the bivalve aquaculture industry in the United Kingdom (Caldow et al. 2003), with Wales the most important mussel producing area. Commercially grown mussels form part of a major managed fishery in the Menai Strait, North Wales, UK, which is now the largest in Britain. The fishery is based on the operation of six defined areas (lays) encompassing some 761 hectares, of which 520 ha is allocated to 4 lay-holders on 7 y licences. In the Menai Strait, mussel spat collected from wild stocks are initially laid onto mud substrata in the intertidal zone for approximately 18 mo, until they are large enough (30–40 mm) to reach a partial predation refuge from crabs *Carcinus maenus* (Linnaeus) (Pillay 1993). They are then relaid onto subtidal lays for a final period of rapid growth and fattening (6–12 mo), until they reach marketable size when shell length is ~45 mm. Mussels are harvested from the beginning of September and throughout the winter until all mussels of marketable size have been collected.

The common starfish, *Asterias rubens* (Linnaeus), is highly abundant and widely distributed in the Northern Hemisphere and throughout European waters (Vevers 1949, Dare 1982, Barker & Nichols 1983) and occurs on a range of substrata from mud to gravel and rock. On British shores, *A. rubens* may occur intertidally as well as subtidally, controlling the distribution and abundance of prey species such as the common mussel, *Mytilus edulis* (Dare 1976, Dare 1982, Sloan 1980, Barker & Nichols 1983). In Northern Europe, *A. rubens* occurs in low densities with occasional aggregations of groups of adult animals or single individuals (e.g., Brun 1968, Sloan & Aldridge 1981). Amenable seawater temperatures and weather conditions (Sloan 1980), optimized feeding, resistance to predators, improvement of fertilization during spawning (Sloan 1980), and more importantly an abundant food supply (Sloan & Aldridge 1981) are believed to be the main causes of starfish migration and aggregation (Feder & Christensen 1966).

The reproductive cycle of *A. rubens* has been the subject of numerous European studies (e.g., Jangoux & Vloeberg 1973, Jangoux & van Impe 1977, Nauen 1978, Nichols & Barker, 1984). *Asterias rubens* generally breeds between April and June (Vevers 1949, Nichols & Barker 1984), and the larvae have a protracted period of planktonic development of ~90–140 days. The majority of marine invertebrate populations are demographically open, and their replenishment is largely dependent on a supply of juveniles from the plankton (Caley et al. 1996). *Asterias rubens* settles exclusively on hard and phytal substrata in shallow water and is able to prolong its planktonic life if a suitable substratum cannot be found (Thorson 1957).

In this paper we present data on the seasonal abundance and distribution of the mussel, *Mytilus edulis*, and investigate the seasonal patterns of movements and abundance of *Asterias rubens* in relation to mussel farming practices and patterns of food availability and reproductive strategies.

MATERIALS AND METHODS

The study was conducted in the Menai Strait, North Wales, United Kingdom (Fig. 1a: 53°14′70″N, 04°06′91″W) on mussel lays leased by the commercial mussel company Extramussel Ltd, and in the surrounding areas (Fig. 1b). Depths within the area ranged from ~19 m below and up to ~4 m above chart datum, along a wide variety of substrata including

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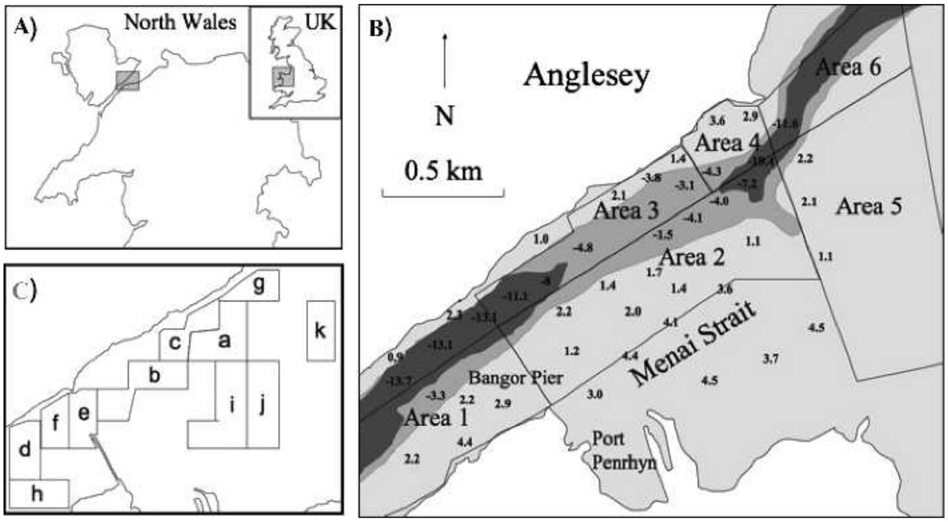

Figure 1. Location of (A) the study area in the Menai Strait, Anglesey, North Wales, (B) details of the Menai Strait mussel lays (Area 1–6) including water depth above (+) and below (–) chart datum and the approximate area of the subtidal zones indicated by the dotted-shaded areas, and (C) Sample sites (SM1–3: a to c, SNM1–3: d to f, IM1–4: g-j, & INM1: k) in areas 1–6.

seed mussel to established mussel beds, sand, shell debris, and rocks and pebbles. The abundance (numbers·m^{-2}) and length frequency distributions at several sample sites (Fig. 1c) of mussels, *Mytilus edulis*, and starfish, *Asterias rubens*, were determined within a sample area of ~4 km^2. The sites were selected based on the presence or absence of mussel cultivation, providing 16 sites in total; 4 subtidal sites with mussel cultivation activity (SM1–4), 4 subtidal sites, the "Bangor pool" area without mussel cultivation activity (SNM1–4), 4 intertidal sites with mussel cultivation activity (IM1–4), and 4 intertidal sites without mussel cultivation activity (INM1–4) (see Fig. 1c). After an initial survey of the areas, three of the intertidal sites (INM2–4) and two subtidal sites (SM4 and SNM4) were not sampled further as no starfish or mussels were observed in these areas.

Starfish and mussels were collected monthly during neap tides between April 2006 and May 2008 using two methods. Using the first method a visual survey of each site was conducted using a Mobitronic RV-2 Marine underwater camera mounted on a steel frame at a height of 0.58 m, giving a 0.25 m^2 field of view. The camera was deployed randomly from the SOS MV "Mya" at each site (located using GPS). The camera was lifted and lowered to the seabed at regular intervals (~5 m) along a transect of ~100 m within the site, while the boat drifted with the current or under power. Images were captured continuously by a Canon MV850i camcorder, and recorded onto mini DV tapes. On return to the laboratory 20 still images were randomly extracted from the video recordings taken at each site, using the computer program video2photo V.1.0. Following size calibration of the images in the camera's field of view using artificial mussel patches of known size, percentage mussel coverage, starfish size (radius – mouth to tip of longest arm) was measured to the nearest 0.1 mm using the program Image J V.1.38. Starfish abundance was estimated by counting the number of starfish in each image and estimating abundance in a known area at each site.

In the second method mussels and starfish were trawled from the seabed in each area using a 2×2 m dredge deployed for a minimum of 5 five minute tows from a commercial mussel boat during the harvest period between September and March 2006 to 2008. The contents of the dredge were emptied onto a conveyor belt on the boat's deck and all the starfish collected. Frequently >700 starfish were trawled and a stratified sampling strategy was adopted; starfish were counted and removed from the conveyor belt during the first 10 seconds out of every 30-second period, and the number collected over a known time period estimated. On return to the laboratory the starfish were counted and measured using vernier callipers to the nearest 0.1 mm. Camera and dredge tow positions and tow lengths were determined by recording the start and finish point of each tow using GPS and the data transferred to MapInfo Pro. V.8 to visualize the distribution of the dredge tows and positions of the camera images at each site in each area.

Reproductive condition of *Asterias rubens* was determined to examine the relationship between the annual reproductive cycle and seasonal abundance of starfish. The gonosomatic index was determined monthly from samples of 20 starfish of between 20 and 150-mm arm length collected from the mussel beds. Starfish were selected either at random from the trawl samples taken by the mussel boat during the harvest period (October to March), or from additional trawl samples collected by MV "Mya" between April and September. Occasionally during inclement weather starfish were collected by hand from a site close to the mussel beds beneath the Telford Suspension Bridge, Menai Bridge. Gonad indices were determined using a variation of the method of Pearse (1965). After measurement of the diameter of a selected starfish to the nearest 0.1 mm it was opened aborally by cutting along the midline of each arm, the gonads were removed and blotted dry and the viscera discarded. Wet gonad weight was determined to the nearest 0.01 g and gonad dry weight determined following drying to constant weight at 50°C. The dry weight of each starfish was not determined each month. Instead dry weight was estimated from the relationship between eviscerated starfish dry weight and arm length using a sample of 30 starfish, (59–284 mm diameter), collected from a trawl sample taken in June 2007. Using the

TABLE 1.

Mean (±SE) densities of the mussel, *Mytilus edulis* (% coverage), and *Asterias rubens* (starfish ha^{-1}), at subtidal and intertidal sites with (SM1-3/IM1-4) and without (SNM1-3/INM1) mussels between April 2006 and May 2008 in the Menai Strait, Anglesey, United Kingdom. n/a denotes not applicable.

Site	Percentage Mussel Coverage (mean ± SE)	Number of starfish·ha^{-1} (mean ± SE)
SM1	39.30 ± 4.80	40,586.56 ± 5,647.88
SM2	2.72 ± 0.60	8,932.50 ± 2,508.57
SM3	21.87 ± 4.39	29,410.00 ± 8,158.62
SNM1	n/a	4,550.00 ± 3,080.00
SNM2	n/a	9,980.44 ± 3,868.00
SNM3	n/a	9,200.00 ± 5,200.00
IM1	20.00 ± 4.84	0.00 ± 0.00
IM2	23.58 ± 2.77	341.78 ± 235.55
IM3	20.30 ± 3.96	0.00 ± 0.00
IM4	25.29 ± 5.07	0.00 ± 0.00
INM1	n/a	0.00 ± 0.00

relationship between starfish dry weight and starfish diameter a regression line was generated, which allowed the dry weight of a starfish of known size to be calculated. The dry weight of each starfish each month was estimated in this way. Monthly gonad somatic index (%) was determined as gonad dry weight as a percentage of total starfish dry weight.

RESULTS

The percentage cover of *Mytilus edulis* (mean ± SE) on the mussel lays between April 2006 and May 2008 ranged from <3% at site SM2 up to a maximum coverage of ~40% at site SM1 (Table 1). Mussels were also present in the intertidal at densities of at least 20% at all 4 sites (IM1–4), with maximum coverage in the intertidal recorded at site IM4 (25.29 ± 5.07%). The mean density (±SE) of *Asterias rubens* throughout the study period ranged from a complete absence at all but one intertidal site (IM2), to a maximum of 40,586 ± 5,648 starfish·ha^{-1} at subtidal site SM1. Starfish were most abundant at the subtidal sites with mussel cultivation activity (SM1–3) and were generally absent in the intertidal areas regardless of whether mussels were present. Starfish were also present at all 3 subtidal sites without mussel cultivation activity (SNM1–3) but at lower densities ranging from 4,550 ± 3,080 starfish·ha^{-1} (SNM1) to 9,980 ± 3,868 starfish·ha^{-1} (SNM2).

The relationship between mussel density (% coverage) and starfish abundance (ha^{-1}) at the subtidal sites with mussel cultivation (SM1–3) are plotted separately in Figure 2 to investigate the effect of different mussel densities on the abundance and distribution of starfish. Mussels were generally more abundant at sites SM1 and SM3 and followed a seasonal pattern of increasing density between April and July in 2006 and 2007. This general pattern of increasing numbers in spring/summer was mirrored 2–3 mo later (September to December) each year by an increase in the abundance of starfish. Mussel and starfish densities then declined over the next 6–7 mo between September and March, reaching minimum abundance between March/April and May respectively (SM1: see Fig. 2). However this seasonal pattern was less clear at site SM2 where mussels and starfish were less abundant, although small peaks in mussel density during the summer months were again mirrored by increases in starfish abundance in 2006 and 2007.

From the number of starfish caught by 15 mussel fishery dredges (catch-per-unit effort: $n = 15$) and the numbers of days spent fishing (5 days week^{-1} for 7 mo) during the period September 2007 to April 2008, a reduction in starfish numbers attributable to fishing mortality was estimated and compared with the decline in numbers observed on the mussel lays (Fig. 3). Starfish abundance over a 7-mo period reduced from $\sim 1.7 \times 10^6$ individuals to 1.0×10^3 individuals. During the same period the mussel company removed $\sim 1.7 \times 10^6$ starfish resulting in the almost complete removal of starfish from the subtidal mussel bed.

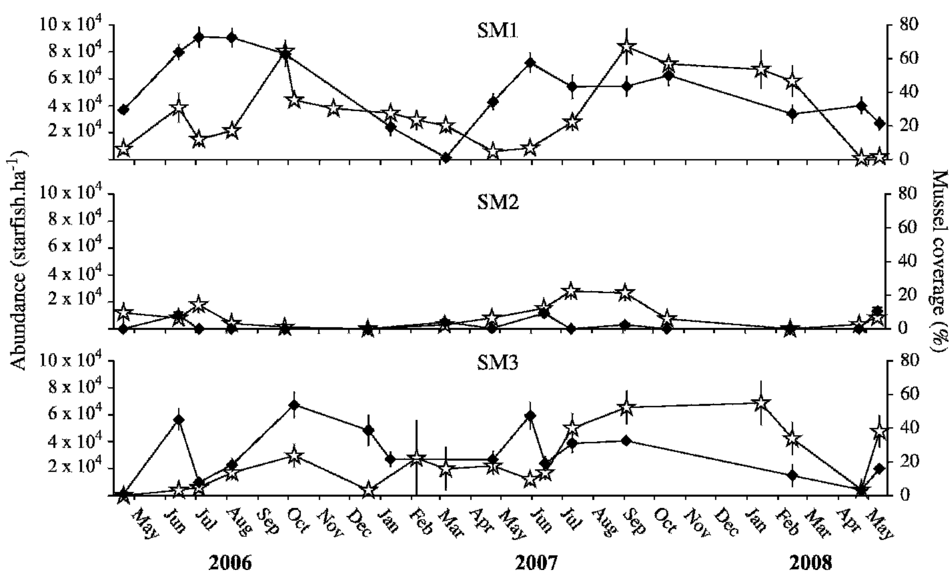

Figure 2. The relationship between starfish, *Asterias rubens* abundance (mean ± SE: open symbols) and % mussel, *Mytilus edulis* coverage (closed symbols) at three subtidal sites (SM1–3) in the Menai Strait between April 2006 and May 2008.

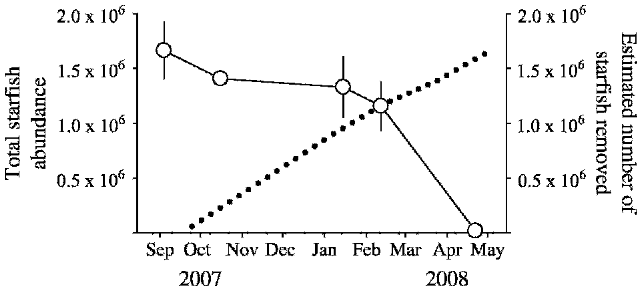

Figure 3. Changes in the number of starfish, *Asterias rubens*, present on the subtidal mussel lays (open symbols) and the estimated number of starfish removed by the activities of the mussel fishery (dots) during the mussel harvesting period between September 2007 and April 2008.

Estimates of the mean (±SE) monthly starfish abundance at three subtidal sites without mussel cultivation (SNM1–3) and three sites with mussel cultivation (SM1–3) were averaged to investigate patterns in starfish distribution in two distinct areas; "site a" (without mussel cultivation activity) and "site b" (with mussel cultivation activity) (Fig. 4). Brief peaks in starfish abundance at "site a," mirrored by increasing seawater temperature, between April and August in 2006, 2007 and 2008 were immediately followed by peaks in abundance at "site b" coinciding with the rapid decline in starfish numbers at "site a." These apparent patterns in starfish abundance at both the subtidal sites with (SM1–3), and without (SNM1–3) mussel cultivation between July and September 2006 and between June and September 2007 are viewed in greater detail in Figure 5. Starfish were more abundant between July and August at sites SNM1–3 (a-c: see Fig. 5), disappearing completely from September onwards and becoming more abundant at sites SM1–3 (d to f: see Fig. 5), particularly at site SM1. This pattern of movement suggests a possible migration during late summer (September onwards) from areas without mussels to lays with mussels (see Fig. 5). The majority of starfish found at sites SM1–3 in September 2006 were <25 mm diameter (Fig. 6), probably because of the recruitment of juveniles into the population. Although all the starfish collected between ~July and August from both groups of sites (SM1–3 and SNM1–3) were <125 mm in diameter, the majority was <50 mm. Few of the starfish were <20 mm in diameter prior to their annual disappearance in September from SNM1–3. Some of these starfish may have migrated into the lays with mussels (i.e., SM1 to SM3) as our distributions perhaps show (Fig. 5). However, a large number of the starfish appearing in area SM1 during September were small individuals (between 5–20 mm in diameter) (Fig. 6), perhaps suggesting that a proportion of immigration into the area was from other subtidal regions.

While we have observed autumnal starfish migration into areas of the Menai Strait transplanted with mussels (SM1–3), it is unclear why starfish are present in numbers at times of the year in deeper water (sites SNM1–3: "site a") where food sources such as mussels are absent. Starfish reproductive condition increased between February and March in 2007 concomitant with increasing starfish abundance at "site a" (SNM1–3 grouped) with no mussel cultivation activity (Fig. 7). Shortly after starfish abundance peaked in June (>15,000 starfish ha^{-1}) reproductive condition fell to zero the next month mirrored by a gradual reduction in starfish abundance until September. This pattern was repeated in 2008 with peaks in reproductive condition and abundance occurring slightly earlier in the year (April/May). Concomitant with the peaks in reproductive condition, starfish were less dispersed at "site a" (SNM1–3) with high coefficients of variation between April and June 2007 and in April 2008 (Fig. 8). Taken together these data suggest that the starfish became more aggregated at times when they were highly abundant and in peak reproductive state.

DISCUSSION

Commercial activities in the Menai Strait mussel fishery result in the relaying of mussel stock (~30–40 mm) annually from April onwards throughout the summer onto subtidal mussel beds (SM1–3). The majority of harvestable mussels are then removed 6–12 mo later, between September and March. Mussels are present for most of the year on these subtidal mussel beds (SM1–3), although between March and April they are at low densities after harvesting and before the new smaller stock are laid on the beds. Although mussels were present during the six-month period preceding the September harvest, starfish numbers remained at relatively low levels on the mussel beds (SM1–3) until a large influx of starfish occurred at the beginning of the commercial harvest in September. Starfish have well developed chemoreceptive and rheotactic capabilities (Sloan 1980) and it is likely that they were attracted by odors emanating from mussels damaged by the mussel dredges. Drolet & Himmelman (2004) observed that *Asterias vulgaris* (Verrill) would orient up-stream in the presence of water currents and prey odors in a flume system to locate their distant prey. *Asterias rubens* shows positive rheotaxis moving upstream in the presence of water currents to locate its prey (Castilla & Crisp

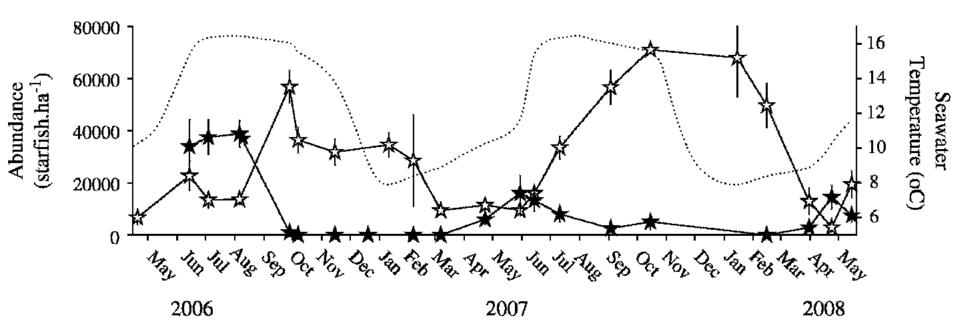

Figure 4. Mean (±SE) seasonal abundance of *Asterias rubens* (starfish ha^{-1}) at 'site a' (SNM1–3: closed stars) and 'site b' (SM1–3: open stars), and seawater temperature (dotted line) in the Menai Strait from April 20, 2006 to May 15, 2008.

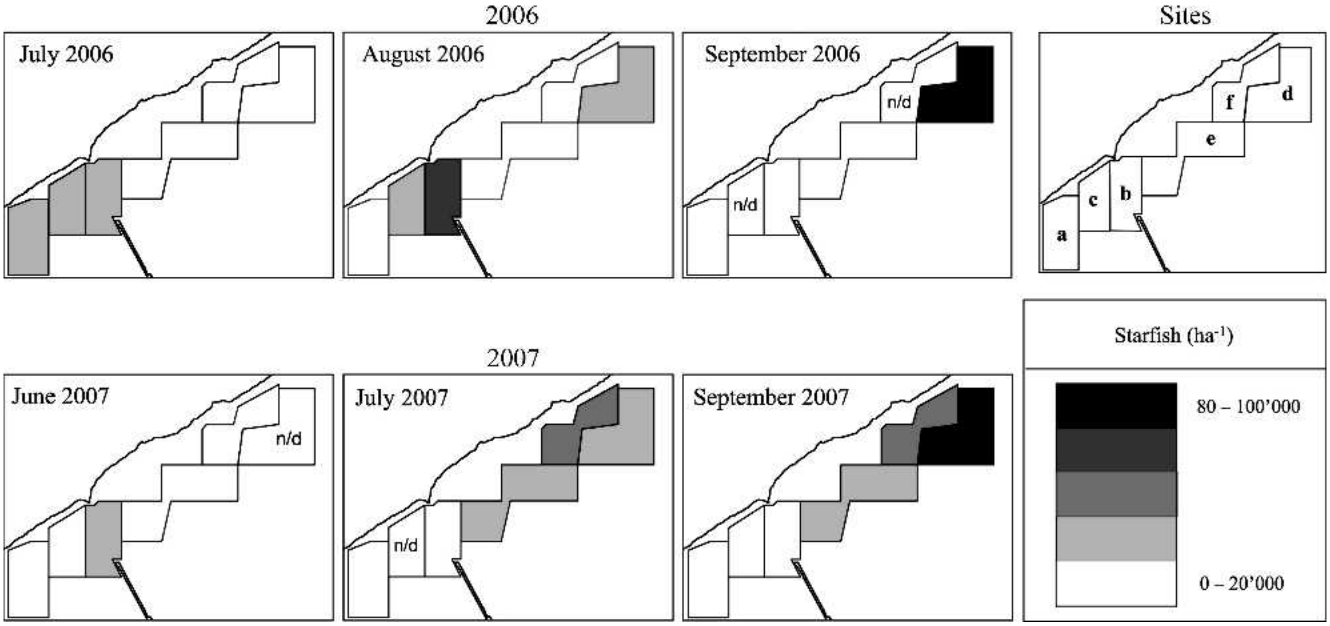

Figure 5. Spatial distribution of *Asterias rubens* (starfish ha^{-1}) during June to September 2006 and 2007 in subtidal areas without mussel cultivation (SNM1: a, SNM2: b, SNM3: c, see "site" box) and with mussel cultivation (SM1: d, SM2: e, SM3: f) in the Menai Strait. n/d denotes no data collected.

1973) and uses tidal currents to detect and move towards mussel populations (Dare 1982). Starfish in the Menai Strait are likely to be responding to odors carried along by tidal currents and to travel up-stream towards the damaged mussels on the subtidal bed (SM1–3). Size frequency distributions of *A. rubens* during this period also suggested the appearance of juvenile recruits migrating onto the subtidal mussel beds. Juvenile recruitment was observed only once during the two-year study, which agrees

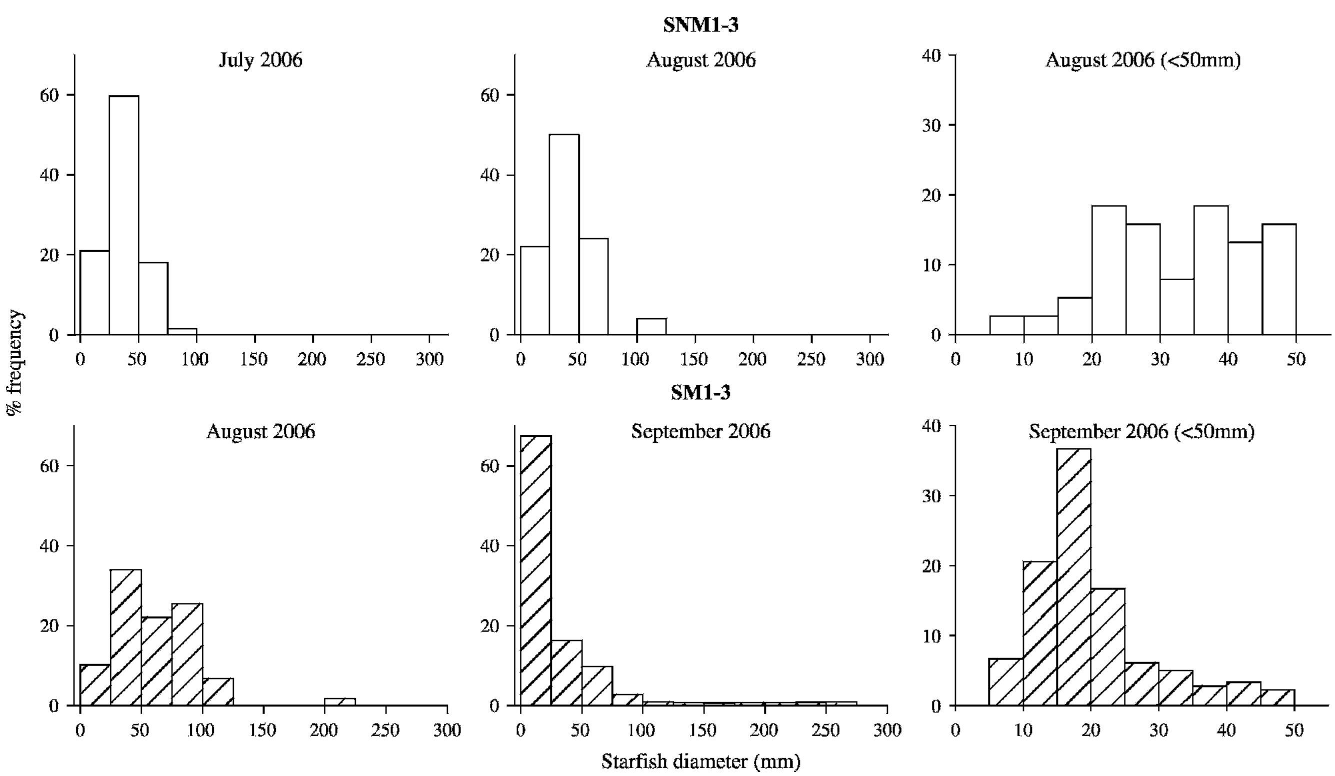

Figure 6. Length frequency distributions of *Asterias rubens* sampled in subtidal areas without mussel cultivation (SNM1–3: open bars) and subtidal areas with mussel cultivation (SM1–3: hatched bars) between July & September 2006.

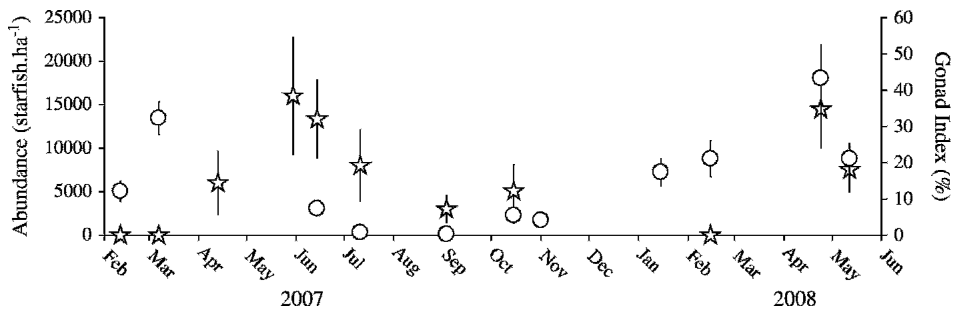

Figure 7. Comparison of the seasonal variation in the mean (± SE) abundance of starfish *Asterias rubens* (starfish·ha^{-1}: stars) and the annual mean (± SE) gonad somatic index (%: circles) collected from the subtidal sites without mussel cultivation ('site a': SNM1–3 grouped) in the Menai Strait between February 2007 and May 2008.

with a number of previous studies that have reported unpredictable and rare recruitment in starfish species (e.g., Ebert 1983). Dare (1982), for example, noted that recently settled *Asterias rubens* were rarely observed amongst mussels in the Morecambe Bay, United Kingdom mussel fishery and recruitment of juvenile, 4 mo postspawning *Astropecten irregularis* (Pennant), in Red Wharf Bay, United Kingdom was also minimal, with sightings in only 1 of a 3-y study (Freeman et al. 2001). In our study the majority of the starfish were located on the subtidal mussel bed in the southeastern half of mussel lay 3 (SM3) and the adjoining subtidal section of mussel lay 2 (SM1) in response to the transplantation of the highest densities of mussels and trawling activity during the winter.

The gradual reduction in mussel density on the subtidal beds (SM1–3) over the winter period is a direct result of commercial harvesting operations and an indirect result of predation by starfish and crabs. Starfish numbers declined simultaneously as they were collected as by-catch during the mussel harvest resulting in the almost complete removal of starfish from the subtidal mussel beds (SM1–3). These starfish are removed from the fishery along with the mussels and either transported overseas with the harvested mussels or disposed of in the high intertidal where they are consumed by birds or desiccate during low tides. The threat of desiccation in intertidal areas may also explain the lack of starfish reported in the intertidal throughout the study period.

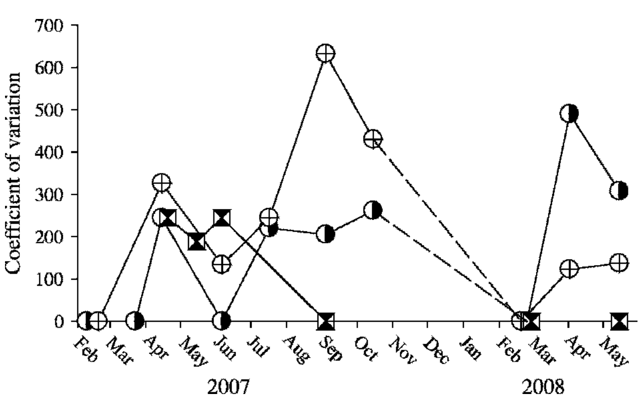

Figure 8. Seasonal variation (February 2007 to May 2008) in the indices of dispersion (coefficient of variation) of *Asterias rubens* at "site a" without cultivation (SNM1: semifilled right, SNM2: cross-hair, SNM3: square/hour-glass filled) in the Menai Strait between February 2007 and May 2008. Dashed sections of lines indicate where no data were collected.

Prior to starfish migrating onto the subtidal mussel beds in September, they were highly abundant for short periods of time between April and September in the deeper water of "Bangor pool" (sites SNM1–3), where mussels were absent. Our observations suggest that fecund individuals migrate into this area in response to an urge to aggregate and spawn in the spring (April to May) when seawater temperatures are increasing. Increasing seawater temperature has been shown to be important in controlling spawning in asteroids (Hancock 1958, Loosanoff 1964, Hamel & Mercier 1995). The burrowing starfish, *Astropecten irregularis*, for example, spawns in early summer (May to June) in Red Wharf Bay, Anglesey, United Kingdom after a rise in seawater temperature (Freeman et al. 2001). The close proximity of spawning starfish in aggregations ensures high gamete concentrations and consequently a higher chance of successful fertilization (Scheibling 1980, Levitan et al. 1992, Freeman et al. 2001). *Leptasterias polaris* (Muller and Troschel), exhibit complex aggregative interactions for up to 8 wk prior to spawning (Hamel & Mercier 1995) and seasonal variations in the dispersion of *Oreaster reticulatus* (Linnaeus) have been associated with the annual reproductive cycle (Scheibling 1980), a behavior that is mirrored in other echinoid species (Buchanan 1966). The deeper water in the "pool" may also provide a more stable physiological environment (Ellis & Rogers 2000), because seawater temperatures are lower and salinity fluctuations smaller than in the shallow waters around subtidal mussel beds (SM1–3). Availability of food is also known to affect the reproductive potential of starfish (Galtsoff & Loosanoff 1939, Pearse 1965), therefore the presence of an abundant food source of mussels in the autumn and winter (September to March) on subtidal beds (SM1–3) would allow the starfish to accumulate energy reserves for later gonad development.

It is likely that *A. rubens* are migrating away from the subtidal mussel bed towards the end of the harvest (March/April) because of the lack of food. The decline in the abundance of the starfish *Leptasterias polaris* and *A. vulgaris* after the disappearance of a subtidal mussel bed, led Gaymer et al. (2001) to speculate that the low abundance of mussel prey may have induced the starfish to migrate to other areas. Starfish in the Menai Strait may be reacting in the same way to the presence and then absence of mussels, a hypothesis supported by reports of starfish migrating long distances in search of prey (e.g.; Sloan 1980, Sloan & Aldridge 1981, Dare 1982, Menge 1982, McClintock & Lawrence 1985). *Asterias rubens* was believed to migrate in response to changes in the abundance and distribution of the slipper limpet *Crepidula* *fornicata* (Linnaeus) associated with oysters in Essex, United Kingdom. The starfish moved offshore after the removal of large numbers of oysters and its preferred prey, *C. fornicata* (Hancock 1958).

In the interim periods between spawning (spring/summer) and feeding bouts during the winter, starfish were occasionally found in area, SM2, between the subtidal mussel beds (SM1 and 3) and the deeper subtidal areas (SNM1–3: ''Bangor Pool'') where they were most probably in transit between the two areas. An understanding of the movements of *A. rubens* in response to feeding and reproduction around the commercial mussel beds in the Menai Strait will allow, together, with data on foraging behavior, an assessment of the loss of mussels to starfish predation on these commercial mussel beds.

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