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Investigation into the decline of the Horse Mussel (*Modiolus modiolus*) reef in the Pen Llŷn a'r Sarnau Special Area of Conservation

Report no: 974

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Crynodeb gweithredol

Mae rhaglen Rhwydweithiau Natur, a ariennir gan Lywodraeth Cymru, yn ceisio mynd i'r afael â'r argyfwng natur drwy wella bioamrywiaeth a chydnerthedd mewn safleoedd gwarchodedig. O fewn Ardal Cadwraeth Arbennig (ACA) Pen Llŷn a'r Sarnau (PLAS), mae monitro hirdymor wedi datgelu dirywiad sylweddol mewn riffau cregyn dilyw (*Modiolus modiolus*), cynefinoedd sy'n cynnal gwerth bioamrywiaeth uchel. Mae'r riffau hyn wedi'u rhestru o dan Reoliadau Cadwraeth Cynefinoedd a Rhywogaethau 2017, adran 7 o Ddeddf yr Amgylchedd (Cymru) 2016, ac OSPAR. Er gwaethaf yr amddiffyniadau hyn, mae monitro ers 2004 wedi dangos dirywiad parhaus, gan ysgogi'r ymchwiliad hwn i ddeall yr achosion a llywio rheolaeth yn y dyfodol.

Cynhaliwyd yr ymchwiliad mewn dau gam. Yn gyntaf, adolygwyd data monitro presennol ac ategwyd ef ag arolygon newydd i ddarparu asesiad cyfredol o gyflwr y riff. Roedd monitro hanesyddol yn cynnwys arolygon gan ddefnyddio gwaith sganio sonar o'r ochr, seinydd atsain aml-belydr (multibeam echosounder neu MBES), ac arolygon cwadrat yn seiliedig ar blymio mewn dau safle monitro parhaol.. Ychwanegodd gwaith diweddar arolwg cwymp fideo a lusgir (drop-down video neu DDV) ar draws y riffau yn 2022–2023; arolwg seinydd atsain aml-belydr cynhwysfawr yn 2024 gan gynnwys cymharu bathymetreg â setiau data cynharach (2005, 2015) i fesur newidiadau yng nghwmpas a morffoleg y riff; a samplu maint y riff yn ôl ei amlder yn 2023. Cadarnhaodd dadansoddiad ostyngiad sylweddol yng nghwmpas y riff (tua 61% ers 2005), gyda darnio a cholli cymhlethdod strwythurol. Datgelodd dadansoddiad maint yn ôl amlder boblogaeth sy'n heneiddio a ddominyddir gan dair carfan gref (1988, 1998, 2003) a recriwtio cyfyngedig ers hynny, er gwaethaf tystiolaeth o gytrefu sil diweddar.

Roedd yr ail gam yn cynnwys asesiad pwysau strwythuredig i nodi'r ffactorau sy'n achosi'r dirywiad, gan ddechrau gydag asesiad sensitifrwydd yn seiliedig ar dystiolaeth forol a'i fireinio ar gyfer amodau penodol i'r safle drwy adolygu llenyddiaeth, gan sgorio yn erbyn pum maen prawf, ac wedi'i adolygu gydag arbenigwyr mewnol. Nodwyd wyth pwysau, wedi'u grwpio yn gategorïau hanesyddol, parhaus, ac sy'n dod i'r amlwg.

Mae'n debyg bod dirywiad riff Ardal Cadwraeth Arbennig Pen Llŷn a'r Sarnau yn ganlyniad i bwysau rhyngweithiol lluosog sydd wedi bod yn drech na ei drothwy gwydnwch. Yn hanesyddol, roedd offer pysgota symudol yn achosi difrod ffisegol a darnio. Fodd bynnag, mae newid hinsawdd yn bwysau cynyddol arwyddocaol, gyda thymheredd y môr yn debygol o effeithio ar wasgariad larfa, llwyddiant anheddu, a goroesiad oedolion, tra'n gwanhau strwythur y riff. Mae methiannau recriwtio a welwyd mewn rhanbarthau eraill, fel Öresund, Sweden, a newid troffig a ddogfennwyd yng Ngogledd yr Iwerydd, yn atgyfnerthu rôl newid hinsawdd fel ysgogydd hollbwysig. Gall pwysau ysglyfaethu hefyd fod yn dwysáu, yn gysylltiedig â newidiadau ar lefel ecosystemau fel cynnydd mewn niferoedd crancod heglog a newidiadau yn nynameg y we fwyd. Gall effeithiau cyfunol cynhesu, aflonyddwch ffisegol (o offer pysgota sefydlog), ac ysglyfaethu atal adferiad a chyflymu dirywiad. Mae bygythiadau sy'n dod i'r amlwg fel clefydau a rhywogaethau goresgynnol yn parhau i fod yn bryder.

Bydd cyflawni statws cadwraeth ffafriol ar gyfer riff Ardal Cadwraeth Arbennig Pen Llŷn a'r Sarnau yn heriol o dan yr amodau presennol a'r rhai a ragwelir. Mae modelu rhagfynegol yn awgrymu y gallai'r safle ddod yn anaddas ar gyfer *M. modiolus* o dan senarios hinsawdd yn y dyfodol, gan wneud adfer y rhywogaeth hon o bosibl yn anymarferol yn yr hirdymor. Gallai strategaethau amgen, sy'n blaenoriaethu gwydnwch a swyddogaeth ecolegol, helpu i gynnal bioamrywiaeth a chynhyrchiant. Er nad oedd y dystiolaeth sydd ar gael yn nodi pwysau anthropogenig lleol fel pysgota ag offer sefydlog fel achos sylweddol o ddirywiad, bydd rheoli a lleihau'r pwysau hyn lle bo modd yn helpu i gynnal rhywfaint o wydnwch i wrthsefyll newid hinsawdd. Mae monitro parhaus yn hanfodol, gan gynnwys cofnodi tymheredd, arolygon recriwtio, ac asesiadau rheolaidd o faint a strwythur y riff. Bydd mynd i'r afael â bylchau gwybodaeth allweddol, megis effeithiau offer pysgota sefydlog, straen tymheredd, cysylltedd cynrhonaidd, risg clefydau, a rhywogaethau goresgynnol, yn hanfodol ar gyfer rheolaeth wybodus a gwydnwch hirdymor. Mae'r dirywiad hwn yn tynnu sylw at effaith newid hinsawdd ar yr amgylchedd morol ac yn atgyfnerthu'r angen i weithredu polisi newid hinsawdd ehangach i leihau'r risg o effeithiau tebyg ar gynefinoedd eraill.

Executive summary

The Nature Networks (NN) programme, funded by Welsh Government, seeks to address the nature emergency by improving biodiversity and resilience in protected sites. Within the Pen Llŷn a'r Sarnau (PLAS) Special Area of Conservation (SAC), long-term monitoring has revealed a significant decline in Horse Mussel (*Modiolus modiolus*) reefs, habitats that support high biodiversity. These reefs are listed under the Conservation of Habitats and Species Regulations 2017, Section 7 of the Environment (Wales) Act 2016, and OSPAR. Despite these protections, monitoring since 2004 has shown ongoing deterioration, prompting this investigation to understand the causes and inform future management.

The investigation was carried out in two stages. First, existing monitoring data were reviewed and supplemented with new surveys to provide an up-to-date assessment of reef condition. Historical monitoring included side-scan sonar, multibeam echosounder (MBES), and dive-based quadrat surveys at two permanent monitoring sites. Recent work added a towed drop-down video (DDV) survey across the reefs in 2022–2023; a comprehensive MBES survey in 2024 including comparing bathymetry with earlier datasets (2005, 2015) to quantify changes in reef extent and morphology; and size-frequency sampling in 2023. Analysis confirmed a significant reduction in reef extent (approximately 61% since 2005), with fragmentation and loss of structural complexity. Size-frequency analysis revealed an aging population dominated by three strong cohorts (1988, 1998, 2003) and limited recruitment since, despite evidence of recent spat settlement.

The second stage consisted of a structured pressures assessment to identify drivers of the decline, starting with Marine Evidence based Sensitivity Assessment (MarESA) and refined for site-specific conditions through literature review, scoring against five criteria,

and reviewed with internal experts. Eight pressures were identified, grouped into historic, ongoing, and emerging categories.

The decline of the PLAS SAC reef is likely the result of multiple interacting pressures that have exceeded its resilience threshold. Historically, mobile fishing gear caused physical damage and fragmentation. However, climate change is an increasingly significant pressure, with rising sea temperatures likely to affect larval dispersal, settlement success, and adult survival, while weakening reef structure. Recruitment failures observed in other regions, such as Öresund, Sweden, and documented trophic shifts in the North Atlantic, reinforce the role of climate change as a critical driver. Predation pressure may also be intensifying, linked to ecosystem-level changes such as increased spider crab abundance and shifts in food web dynamics. Combined effects of warming, physical disturbance (from static fishing gears), and predation may inhibit recovery and accelerate decline. Emerging threats such as disease and invasive species remain a concern.

Achieving favourable conservation status for the PLAS SAC reef will be challenging under current and projected conditions. Predictive modelling suggests the site may become unsuitable for *M. modiolus* under future climate scenarios, making restoration of this species potentially unfeasible in the long term. Alternative strategies, that prioritise resilience and ecological function, could help maintain biodiversity and productivity. While available evidence did not identify local anthropogenic pressures such as static gear fishing as a significant cause of decline, managing and reducing these pressures where possible will help in maintaining a degree of resilience to climate change. Continued monitoring is critical, including temperature logging, recruitment surveys, and regular assessments of reef extent and structure. Addressing key knowledge gaps, such as the impacts of static fishing gear, temperature stress, larval connectivity, disease risk, and invasive species, will be vital for informed management and long-term resilience. This decline highlights the impact of climate change on the marine environment and reinforces the need for wider climate change policy implementation to reduce the risk of similar impacts on other habitats.

General introduction

Nature Networks (NN) is a programme funded by Welsh Government aimed at addressing the nature emergency in Wales through increasing biodiversity, improving the condition of protected sites and enhancing the resilience and connectivity of our habitats and species. Within our Marine Protected Areas (MPAs), long-term monitoring has shown that some important habitats and species are in decline.

As part of the NN programme, the “Investigations into the decline of benthic habitats and species” project seeks to identify the drivers of these declines, with the goal of supporting the recovery of these vulnerable habitats and species. This report investigates the decline of the Horse Mussel (*Modiolus modiolus*) reefs, off the north coast of the Llŷn peninsula in the Pen Llŷn a’r Sarnau (PLAS) Special Area of Conservation (SAC).

M. modiolus are important due to their ability to form biogenic reefs that support high biodiversity and provide productive habitats for ecologically and commercially valuable species. As a result, *M. modiolus* reefs are recognized as conservation priorities and are protected under multiple national and international frameworks. They are listed under Section 7 of the Environment (Wales) Act 2016, as an Annex 1 habitat under the Conservation of Habitats and Species Regulations 2017, and listed as a threatened and declining habitat under OSPAR (Oslo-Paris Convention). These reefs have declined across their range due to environmental and human pressures, exacerbated by the species’ sensitivity and slow recovery (Rees 2009).. Monitoring at the PLAS SAC began in 2004 and has shown ongoing deterioration in reef extent and health. This report, based on both historical data and new data collected for the project, aims to assess recent changes, identify potential drivers of decline, and inform future conservation and management efforts.

Background to Horse mussels (*Modiolus modiolus*)

M. modiolus are an arctic-boreal species of bivalve ranging from Scandinavia and Iceland in the north to the Bay of Biscay in the south (Figure 1). They can occur as isolated individuals, small clumps, or form biogenic reefs or beds. This reef formation however is limited in distribution, with the southernmost reefs thought to occur in the Irish Sea to the North of the Llŷn peninsula in Wales. One reef is within the PLAS SAC and an additional reef is found off Porthdinllaen to the northeast of the SAC boundary (Figure 2).

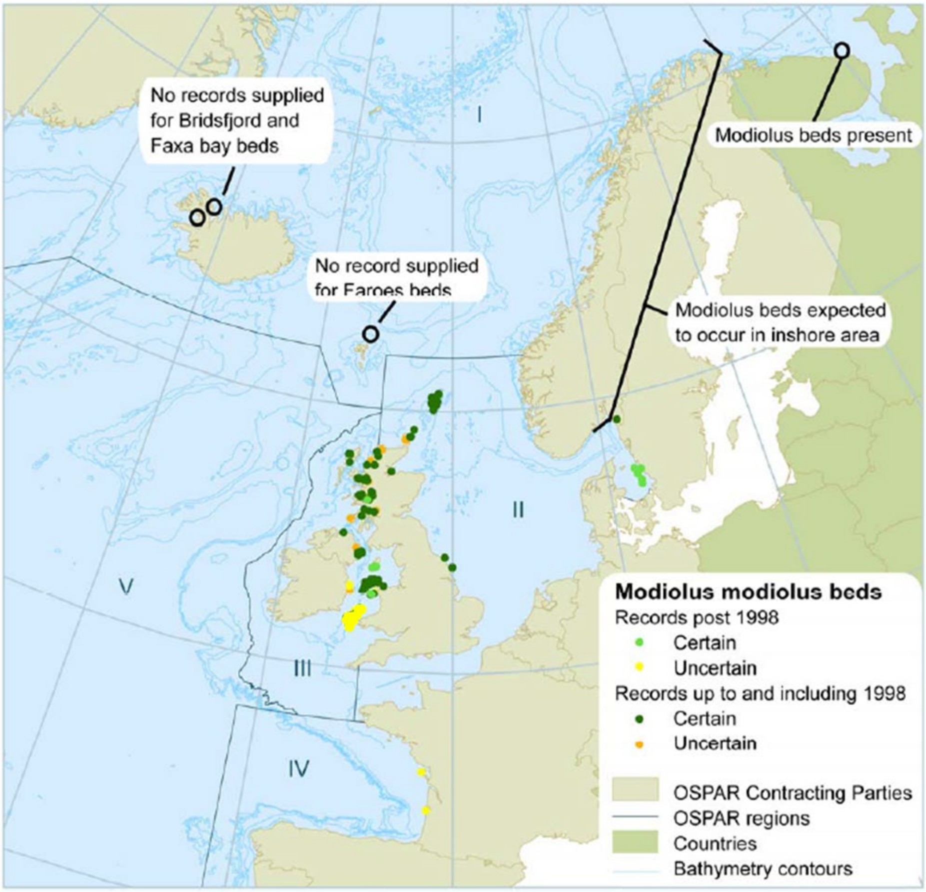


Figure 1. Distribution of *Modiolus modiolus* reefs in the OSPAR area. Note: the uncertain records from the southern Irish Sea were juvenile *M. modiolus* and not reef (adapted from Rees 2009).

M. modiolus can be found on a variety of substrates, ranging from soft sediment (e.g. Strangford Lough, Northern Ireland) to coarse ground and hard substrata (e.g. North of the Llŷn Peninsula, Wales). Occurrence may be epifaunal, though partial burial within the substrate is more commonly observed. They are found in diverse tidal conditions, from open coast tide-swept areas to sheltered sea lochs (e.g. Loch Creran, Scotland) (Mair et al. 2000; Rees 2009). Where biogenic reefs exist, they provide habitat for a wide range of flora and fauna and are recognized as biodiversity hotspots (Fariñas-Franco et al. 2023). There is strong evidence that *M. modiolus* reefs act as critical habitat for fishery species, supporting high abundances of commercially important shellfish such as *Aequipecten opercularis* (queen scallop), *Buccinum undatum* (common whelk) and *Maja brachydactyla* (spider crab), and functioning as key feeding and nursery areas (Kent et al. 2017).

The growth of *M. modiolus* is rapid over the first 4 to 6 years, a period when predation pressure is high. Once reaching an adult shell length of around 40 mm, they become less vulnerable to predation. At this stage, growth slows significantly, as energy is allocated to reproduction (Seed and Brown 1978; Anwar et al. 1990). *M. modiolus* are a long-lived species (living over 50 years), with slow adult growth rates which are influenced by geographic location and environmental factors. They can take between 4-6 years to reach 35 - 40 mm and around 20 years to reach 70mm (Seed and Brown 1978; Anwar et al. 1990).

M. modiolus reach sexual maturity between 3-6 years becoming either male or female (occasional hermaphroditism does occur). They are broadcast spawners with a planktonic dispersal phase. The timing and frequency of spawning is poorly understood and varies across reefs (i.e. may be defined spawning period or constant/repeat release throughout the year (Brown, 1984). The pelagic larval duration (PLD) is approximately 35 days after which settlement can occur though larvae may remain in the water column for up to 5 months (Farinas-Franco and Roberts, 2023). The specific cues for settlement are not known but they require suitable substrates and several studies have suggested the presence of dense adult aggregations is important (Fariñas-Franco et al. 2023). As well as providing settlement substrates they provide refuge from predation within the clumps and byssal thread matrix. Successful recruitment to the adult population depends on successful settlement and survival during the early stages. Recruitment is highly variable across years, with gaps of approximately 5 to 10 years and an often bimodal size distribution (Mair et al. 2000).

The connectivity and dispersal patterns of *M. modiolus* populations in the Irish Sea and Scotland have been studied using larval dispersal simulations and genetic analysis (Gormley et al. 2015a; Mackenzie 2017; Mackenzie et al. 2022). Results of these studies suggest that *M. modiolus* populations are largely interconnected, with larvae able to travel between 150 km (Gormley et al. 2015a) to 500 km (Mackenzie et al. 2022). Historic declines in *M. modiolus* reefs in the Irish Sea and North Sea, attributed to physical impacts from mobile fishing gear, may have reduced larval abundance and connectivity between reefs (Service and Magorrian 1997; Callaway et al. 2007; Fariñas-Franco and Roberts 2018). Despite some variation in connectivity, it has been recommended to manage populations as inter-dependent stepping-stones across the Irish Sea (Gormley et al. 2015).

Due to their high sensitivity to physical disturbance, *M. modiolus* reefs are under threat and/or in decline in all regions where they occur which is linked to their life history traits including long lifespan and sporadic recruitment. A clear decrease in this habitat in UK waters was observed from the 1950s to the 1990s, largely attributed to historic impacts from mobile fishing gear (Rees 2009).

Pen Llŷn A’r Sarnau Special Area of Conservation *M. modiolus* reef

The *M. modiolus* reef within the PLAS SAC is situated in the south of Caernarfon Bay, an inlet of the Irish Sea between Anglesey and the Llŷn Peninsula (Figure 2). The reef is formed of densely packed *M. modiolus* amongst dead shells, creating an extensive reef area (~4 km^2) located about 4 km offshore. Estimated to be at least 150 years old, the reef is primarily composed of long-lived individuals, some over 50 years in age. The *M.*

modiolus reef forms bioherms or undulating waves on the seabed, at depths of ~20 - 40 m with live *M. modiolus* on the crests and empty shell in the troughs. Reef deposits reach a thickness of 1 m on top of the underlying lag gravels (Lindenbaum et al. 2008) .

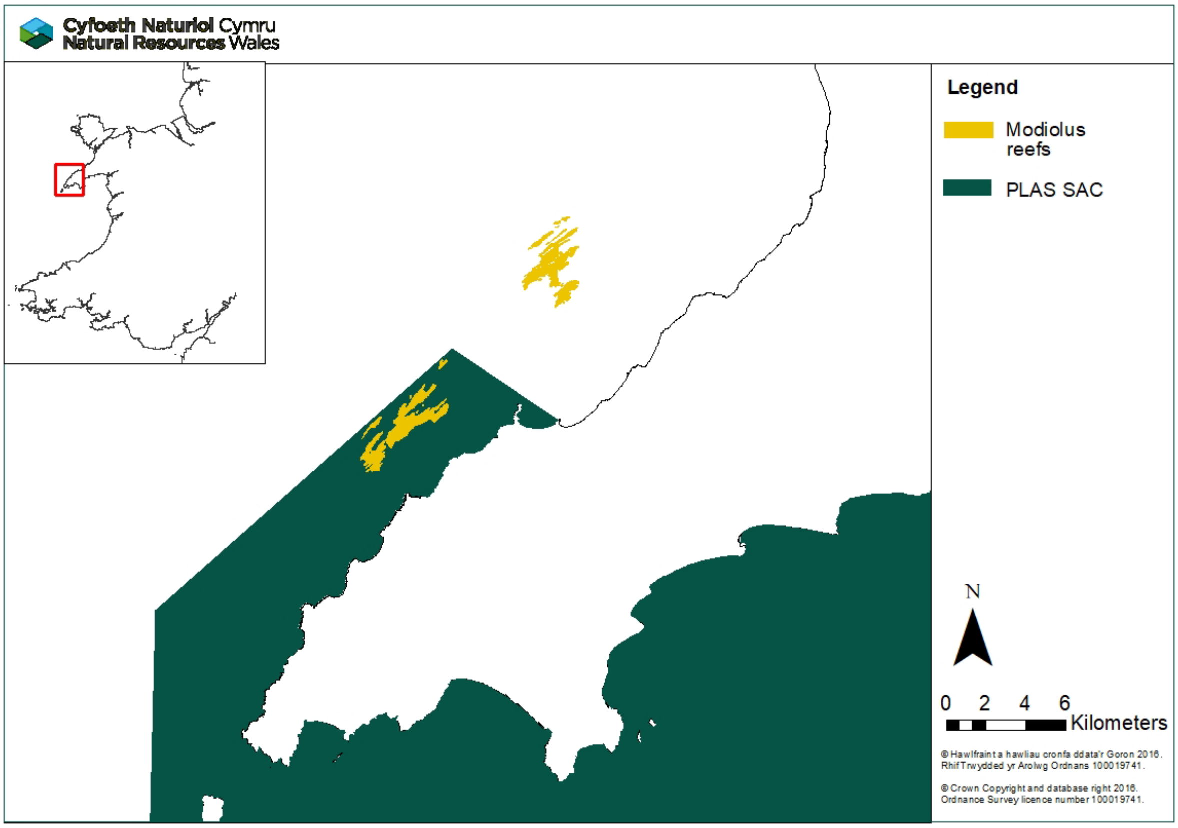


Figure 2: *Modiolus modiolus* reefs off the north coast of the Llŷn Peninsula, inside and outside the Pen Llŷn a’r Sarnau Special Area of Conservation boundaries.

Figure 3: Example of healthy *Modiolus modiolus* reef within the Pen Llŷn a'r Sarnau Special Area of Conservation with typical epifaunal community dominated by *Alcyonium digitatum* (Deadman's Fingers) and *Ophiothrix fragilis* (Common brittle star).

The reef within the SAC was first mapped between 1994 and 1999, leading to its designation in 2004 as an Annex I reef feature of the PLAS SAC under the EU Habitats Directive (92/43/EEC). As a biogenic reef, it qualifies due to its ecological importance, structural complexity, and role in supporting high biodiversity. As an important component of the Annex I reef feature it is regularly monitored and managed to ensure it is in favourable condition as per the conservation objectives.

The reef has been protected from mobile fishing gear since 1998 due to its high sensitivity to physical damage. Historically the reef was protected under Byelaw 21 of the former North Western and North Wales Sea Fisheries Committee (NWNWSFC), under the Sea Fisheries Regulation Act 1966. The Marine and Coastal Access Act 2009 repealed the 1966 Act and dissolved the NWNWSFC in 2010, transferring inshore fisheries management to the Welsh Government. Byelaw 21 was later revoked and replaced by Article 4 of The Sea Fish (Specified Sea Areas) (Prohibition of Fishing Method) (Wales) Order 2012, which also extended protection to a second *M. modiolus* reef that was discovered north of Porthdinllaen, outside the SAC boundary (Figure 2) (Welsh Government 2012). Additionally, the Scallop Fishing (Wales) (No.2) Order 2010 restricts scallop dredging within PLAS SAC, including the *M. modiolus* reefs (Welsh Government 2010).

The *M. modiolus* habitat found in these two areas is classified as *Modiolus modiolus* beds with hydroids and red seaweeds on tide-swept circalittoral substrata (SS.SBR.SMus.ModT) (JNCC 2022). *Ophiothrix fragilis, Alcyonium digitatum, Asterias rubens* and *Buccinum undatum* are some species commonly associated with this biotope.

Objectives of this investigation

The objectives of this report are to bring together historical and newly collected data to:

- Evaluate recent changes in the extent and condition of the PLAS SAC *M. modiolus* reef, describing its current state and ongoing decline.
- Identify and assess potential pressures contributing to reef degradation at this site.
- Score and rank these pressures based on their relative risk to reef resilience.
- Inform future conservation and management strategies to support *M. modiolus* habitat protection and ecological function.

The following sections address these objectives.

Monitoring and current status

The condition of the *M. modiolus* reefs has been monitored since 2004 when the PLAS SAC was designated and monitoring began. Monitoring focuses on assessing the reef extent, reef integrity and reef dynamics (Table 1). Regular side-scan sonar surveys have been conducted to monitor changes in the extent of the reef, with additional multibeam echosounder (MBES) surveys completed to determine changes in topography (See Appendix A). Two “permanent” dive monitoring sites (Site 1 & Site 2) were established (Figure 5), each consisting of 15 fixed quadrat locations. Within each quadrat, cell-frequency counts of live and dead mussels are recorded in-situ and a video record taken (Figure 4). In addition, a large, weighted pyramid structure was sunk at site 1 as a site marker and temperature loggers and spat settlement pads were deployed.

Table 1: Monitoring methods employed by Countryside Council for Wales (CCW), now succeeded by Natural Resources Wales (NRW) to assess the status and condition of the PLAS SAC *M. modiolus* reef

Attribute	Indicator	Technique	Survey years
Reef extent	Large-scale changes in the structure and area of the reef	Side-scan sonar and multibeam echosounder surveys	1998, 1999, 2005, 2006, 2008, 2009, 2011, 2012, 2014, 2015, 2022
Reef integrity	General reef health	Quadrat sampling by divers to assess live:dead ratio of mussels and reef-associated fauna	2004, 2005, 2007-2009, 2011- 2014
Reef dynamics	Recruitment and age structure. Indicator of current/recent influences on reef. Early warning of potential problems	Spat/larval settlement pads Targeted sampling to monitor age and size frequency distribution	2004-2008 1994, 1999, 2009, 2023

Figure 4: Divers monitoring reef condition and recording in-situ live cell counts of *Modiolus modiolus* at the Pen Llŷn a'r Sarnau Special Area of Conservation reef (Natural Resources Wales dive monitoring images 2011)

Reef integrity/condition

Dive surveys

Since monitoring began, a decline in the condition of the *M. modiolus* reef was observed at the two dive monitoring sites (Figure 5) within the SAC. Routine quadrat surveys showed a reduction in the density of live *M. modiolus* at both Site 1 and Site 2 (Figure 6, Figure 7).

This decline was greatest at Site 1 (where there was more regular data), though a decline also occurred at Site 2. Average cell frequency counts at Site 1 dropped from 19 to 10 between 2004 and 2005 and then down to 5 in 2007. In addition, the strong wave form associated with these sites flattened out, with no waves apparent. After 2011 dive surveys to conduct cell counts (at the monitoring sites) were stopped since there were few live *M. modiolus* reported inside the quadrats.

Additional monitoring sites were selected using multibeam and side-scan survey data to identify areas with extensive *M. modiolus* bedforms, as these were expected to be areas with live *M. modiolus* and healthy reef. At each site quadrats were placed only on reef crests, where live *M. modiolus* are located, to ensure comparability with the monitoring sites. A random stratified approach was used for quadrat placement. Although data from sites visited in 2009 exist, they were excluded because in-situ counts were not conducted. Subsequent analysis relied on stitched quadrat images, which are not directly comparable to the monitoring datasets. However, data collected at four additional sites visited in 2010 (Site 4 and 5) and 2011 (Modiolus X and Y) recorded live *M. modiolus* densities (average cell frequency counts) which were similar to those seen at the start of monitoring at Sites 1 and 2 (between 15 – 20) (Figure 6). This suggests the decline observed at the core monitoring sites was not occurring uniformly across the reef. Despite this, the lack of recovery at Sites 1 and 2, combined with historical anthropogenic impacts, and the reduction in extent, led to the reef being assessed as “unfavourable” in both the 2018 and 2025 SAC condition assessments (Jackson-Bué et al. 2025). This prompted the need for the current investigation to determine the extent and potential causes of the observed decline

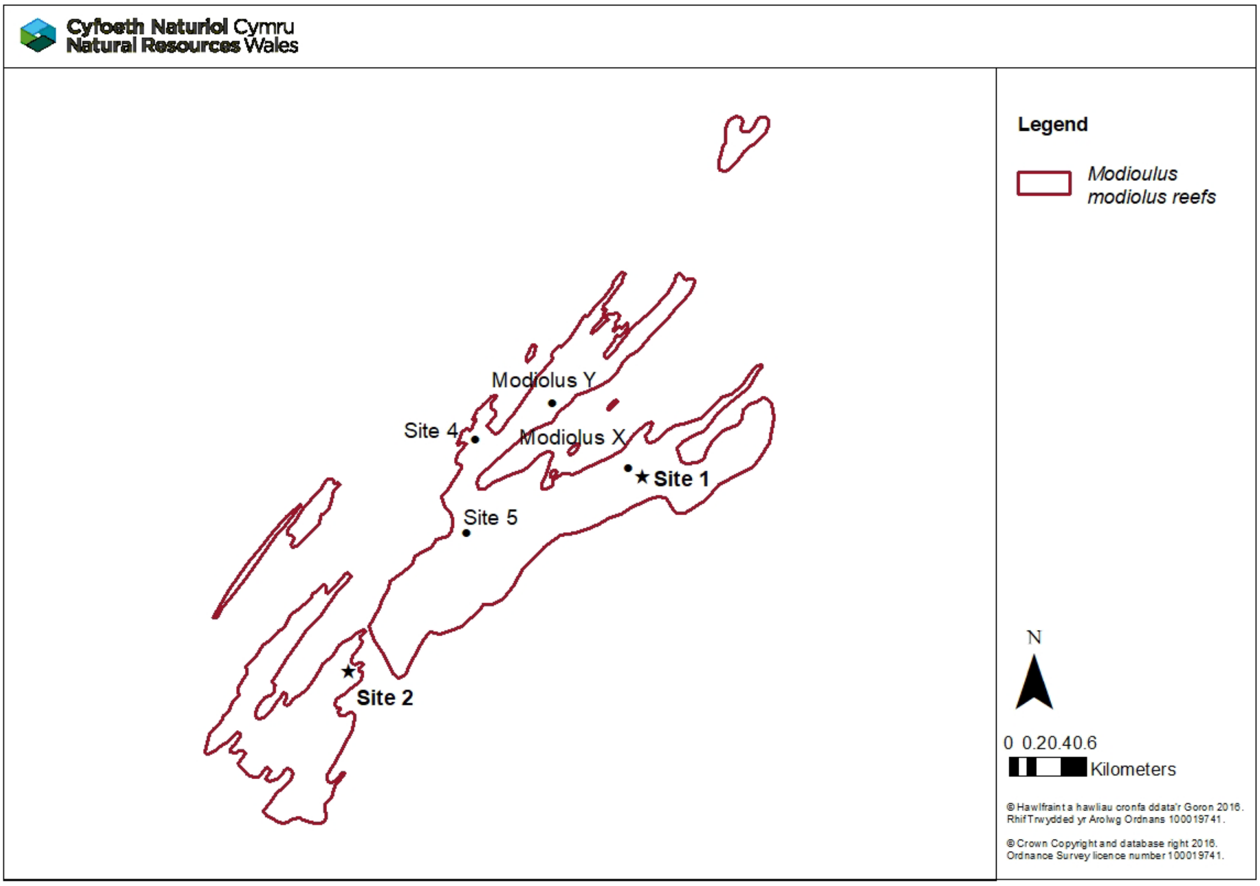


Figure 5: Quadrat sampling locations across the Pen Llŷn a'r Sarnau Special Area of Conservation *Modiolus modiolus* reef, showing the permanent monitoring Sites 1 and 2 (black stars) and additional sites (black circles) visited in 2010 (Site 4 and 5) and 2011 (Modiolus X and Y).

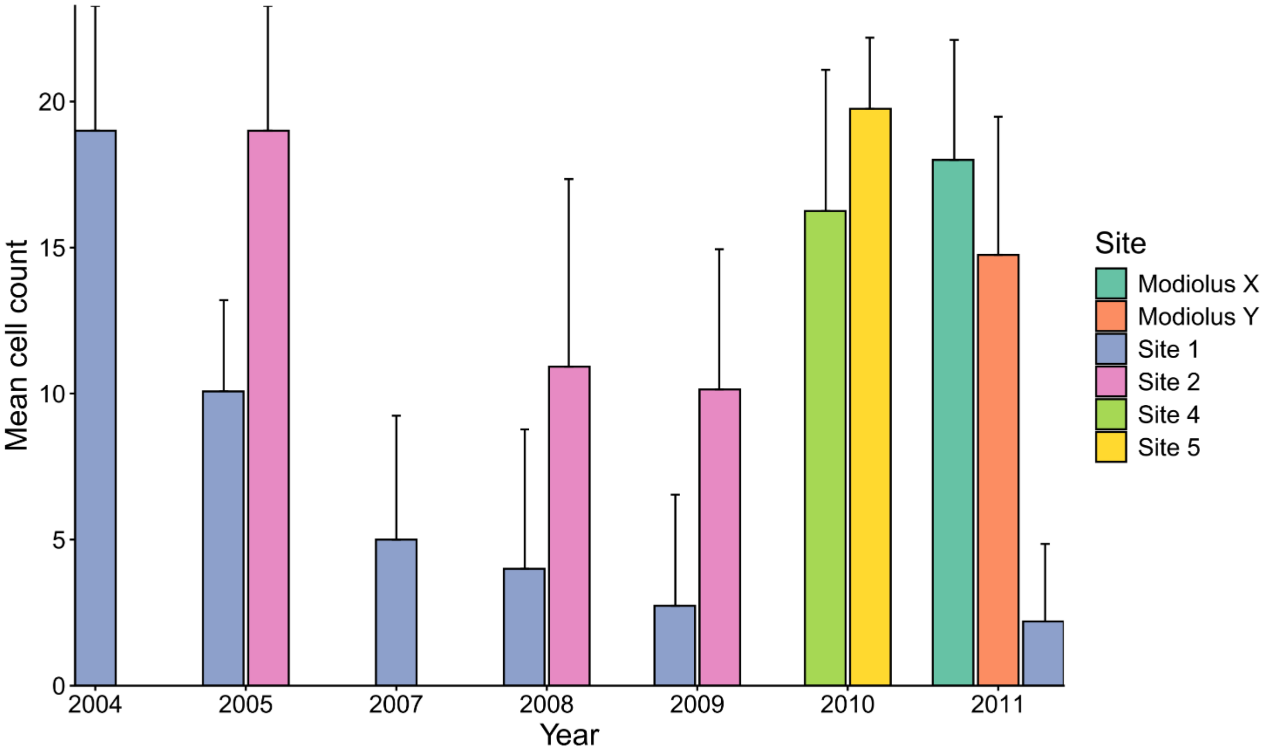


Figure 6: Mean cell counts (± standard deviation) of live *Modiolus modiolus* in the Pen Llŷn a'r Sarnau Special Area of Conservation, recorded at monitoring Sites 1 and 2 between 2004 and 2011, and at additional Sites 4 and 5 (2010) and Modiolus X and Y (2011). Note that no data were collected in 2006 so it is omitted from the time series.

Figure 7: Stitched quadrat images showing the same quadrat recorded in 2004, 2007 and 2011 at monitoring Site 1, illustrating the decline in *Modiolus modiolus* and its associated epifauna. In 2004 there is a clear presence of white *Alcyonium digitatum* which has been shown to indicate live *M. modiolus*, whereas by 2007 and 2011 the images show mostly dead shells, with few or no live *M. modiolus* remaining.

Towed drop down video (DDV) survey

In 2022 NRW conducted a towed DDV survey across the known extent of the *M. modiolus* reef (34/50 stations were successfully surveyed across the reef) to trial its use as a future monitoring method. Analysis of images from the survey recorded abundance of live and dead *M. modiolus*, as well as other attributes such as key associated epifauna (e.g. *A. digitatum*). Bangor University also conducted a DDV survey in 2023 as part of a Fisher Industry Science Partnership (FISP) funded study looking at the impacts of whelk potting on the reef (Clarke et al. 2025, unpublished).This survey visited the remaining areas not completed during the NRW survey. *M. modiolus* densities across the reef were calculated from live/dead counts recorded from still images from the DDV (Figure 8). As expected, results from the image analysis showed higher species abundances and higher species richness where there were higher *M. modiolus* densities, in agreement with previous studies (Rees et al. 2008; Sanderson et al. 2008; Fariñas-Franco et al. 2023).

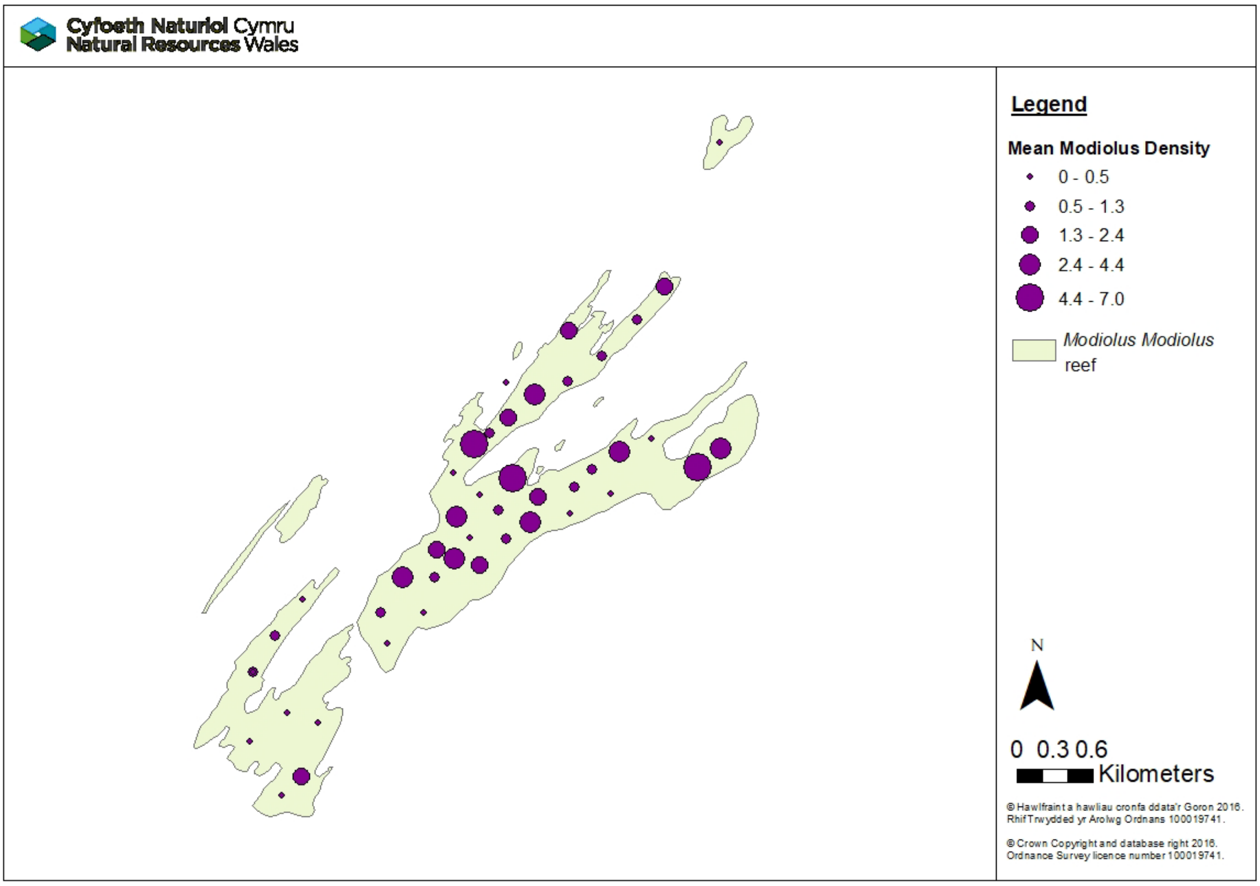


Figure 8: Mean *Modiolus modiolus* densities (purple circles) estimated from towed drop-down video (DDV) images recorded across the Pen Llŷn a’r Sarnau Special Area of Conservation in 2022 and 2023 by Natural Resources Wales and Bangor University (Clarke et al. 2025, unpublished).

Reef extent

Side-scan sonar surveys

Side-scan sonar surveys of the reef have been undertaken in multiple years (Table 1), however, not all surveys provided sufficient spatial coverage or data quality to derive comparable estimates of reef extent. Early side-scan surveys from the late 1990s are therefore excluded due to incomplete coverage and interpretative uncertainty, and quantitative side-scan extent estimates are presented from 2005 onwards. These indicate an approximately 62% reduction in reef extent, from 3.88 km² in 2005 to 1.47 km² in 2022, alongside a visible reduction in reef definition and structure. Although quantitative extent estimates are only presented from 2005 onwards, interpretations of earlier side-scan data suggest the reef was more extensive in the late 1990s than in the mid-2000s, with evidence of increased fragmentation and a less cohesive, more irregular reef structure between 1999 and 2006, indicating the decline began prior to 2005

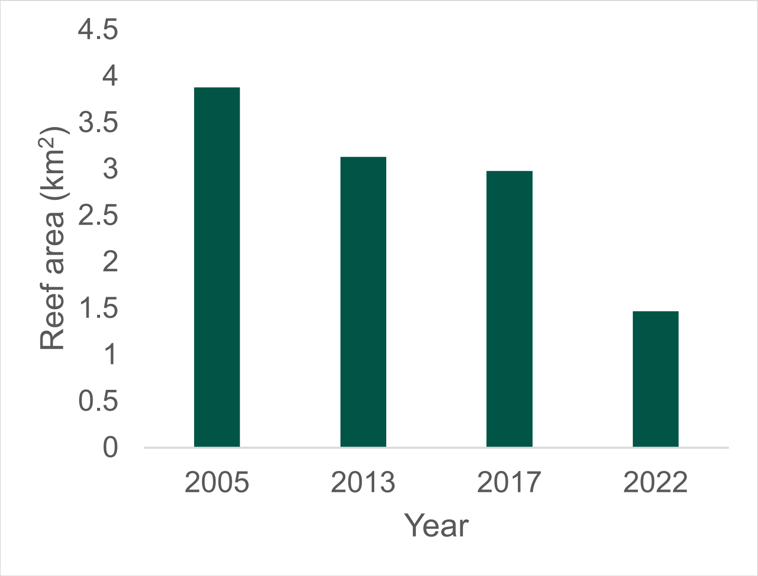


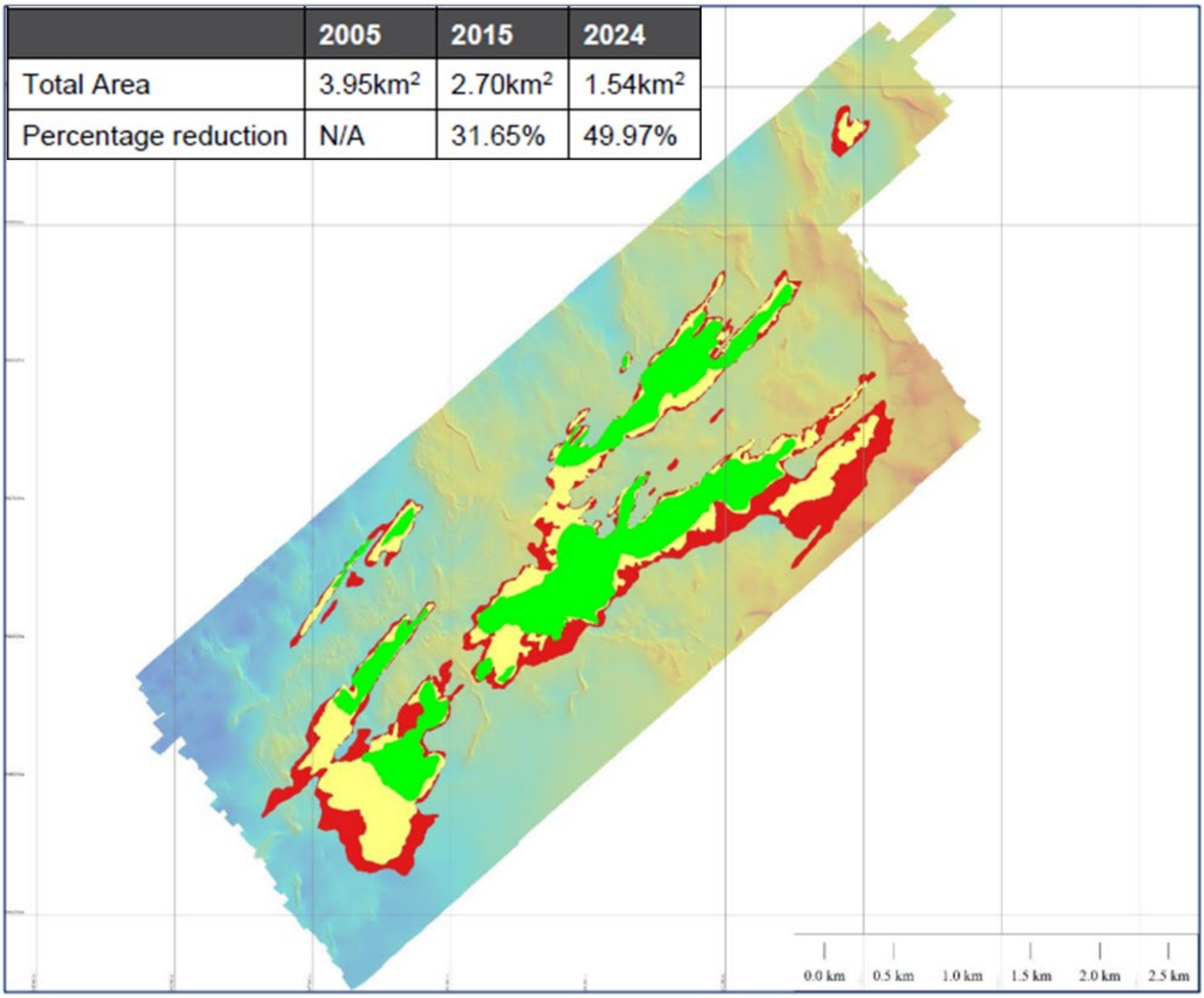
Figure 9: Change in *Modiolus modiolus* reef area (km^2) in the Pen Llŷn A’r Sarnau Special Area of Conservation determined by sidescan sonar from 2005 to 2022 (taken from Jackson-Bué et al. 2025)

Multibeam Echosounder surveys (MBES)

Figure 10: Survey pole and T-Bar in deployed position on Pedryn during multibeam echosounder survey of the Pen Llŷn A'r Sarnau Special Area of Conservation *Modiolus modiolus* reef and the additional reef area north of Porthdinllaen, in 2024.

As part of this NN investigation, an MBES survey was conducted across both of the *M. modiolus* reef areas (inside the SAC and outside) during settled weather in June 2024 (Wilcock, 2024). The survey was carried out through a contract with Binnies UK Ltd and subcontractor Hydrofix Ltd, using NRW's survey vessel Pedryn, and Hydrofix and NRW staff (Figure 10). A time series analysis was conducted to identify bathymetric changes between the 2024 survey data and earlier datasets from 2005 and 2015. This confirmed the side-scan results, showing a clear decline in reef extent since 2005, with the 2024 data revealing that previously continuous beds have fragmented into smaller, isolated patches (Figure 11). The reef has declined by approximately 60.76% in extent between 2005 and 2024, based on the three available datasets. While this equates to an average loss of around 0.13 km² per year, the limited dataset does not support assumptions of a consistent or linear rate of decline.

When viewed as a percentage of total area, the rate of decline was greater between 2015–2024 (49.97%) than between 2005–2015 (31.65%). Initial losses occurred around the bed perimeter (2005–2015) but have since progressed toward the centre (2015–2024). In addition to reduced extent, comparisons of bed elevation across years show a loss of internal structure, with general flattening of the bed (Figure 12). As the bioherms erode, surrounding troughs appear to be infilling with shell material from the bioherms, further altering the reef's morphology.



	2005	2015	2024
Total Area	3.95km²	2.70km²	1.54km²
Percentage reduction	N/A	31.65%	49.97%

Figure 11: Pen Llŷn A'r Sarnau Special Area of Conservation *Modiolus modiolus* reef extents determined using multibeam echosounder survey data, showing the reducing reef extent from 2005 (red) to 2015 (yellow) to 2024 (green). The inset table shows the measured area and percentage reduction between the years (taken from Wilcock, J. 2024).

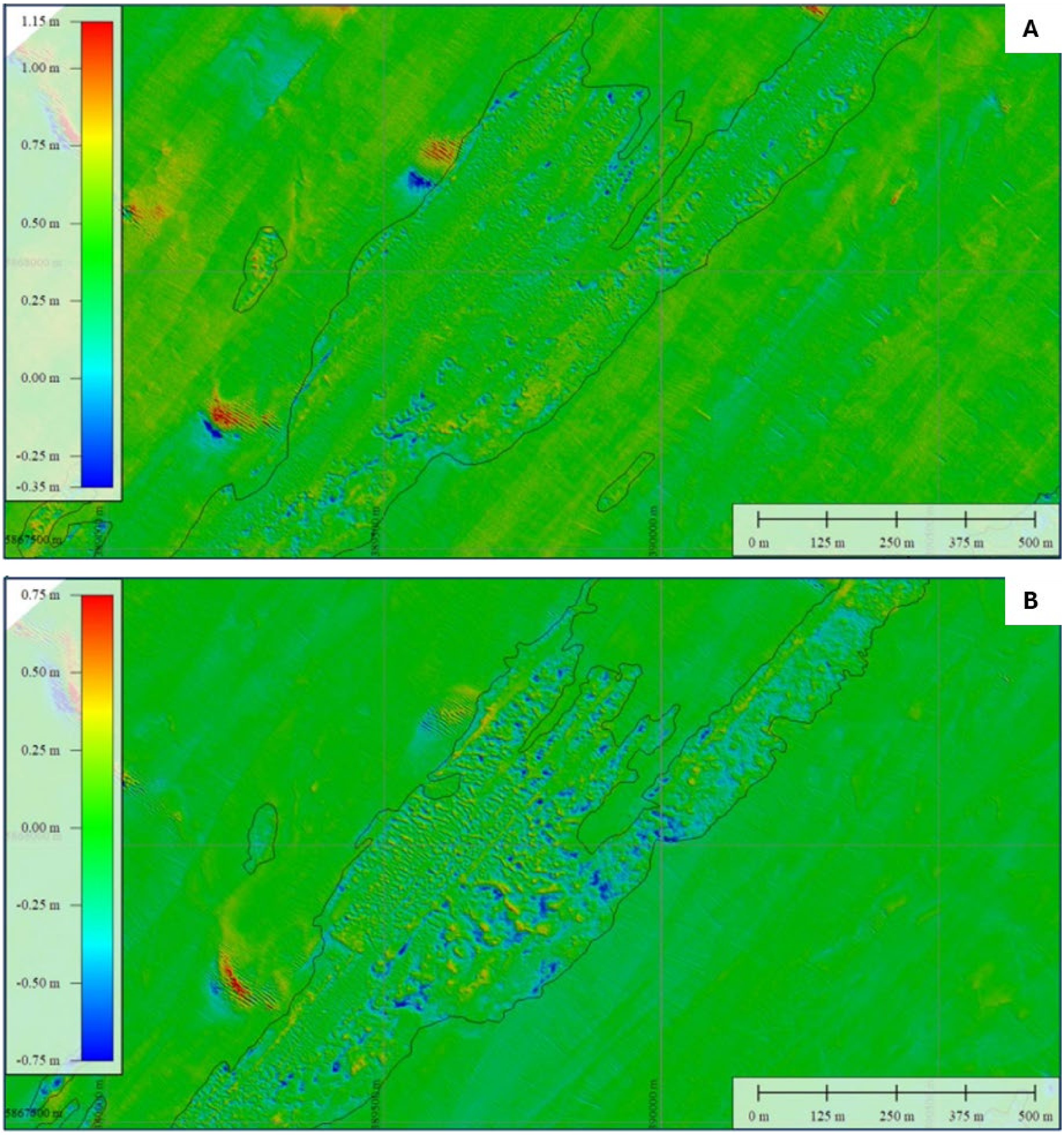


Figure 12: Change in *Modiolus modiolus* bed extent from 2005 – 2024 using grid detail: A) difference grid detail from 2005 to 2015. B) difference grid detail from 2015 to 2024. Blue shades denote decreases in bed level over time, red shades denote increase. Reef bed extents are shown by the black lines. Note that due to the average 0.4 m difference between the two surfaces, the colour scale has been skewed accordingly so green represents no change (taken from NRW Evidence Report No. 851, Wilcock, J. 2024).

Reef dynamics

Recruitment

The extent and density of *M. modiolus* reef can be used to assess condition, but to understand current and future influences on the reef, measures of population dynamics such as size-frequency distributions were used. Spat collectors were deployed at the reef from 2004 to 2008. The resulting data was limited due to methodological inconsistencies. Additionally, targeted sampling to monitor the age and size frequency distribution of the population was also carried out in 1999 and 2009. In 2023 samples were collected again by divers from an area of high-density reef in the centre of the bed (Figure 13), identified in the DDV survey. In total, five 0.25 m^2 quadrats were cleared of *M. modiolus* and the size frequency distribution was compared to the previous sampling events (Figure 13). Quadrats were cleared using a trowel and all *M. modiolus* were placed in a heavy duty plastic bag, keeping the clumps intact where possible. These were then carefully broken down in the lab over a 1 mm sieve to retain spat contained within the clumps and the byssus. All *M. modiolus* were measured to obtain the size frequency of the sample.

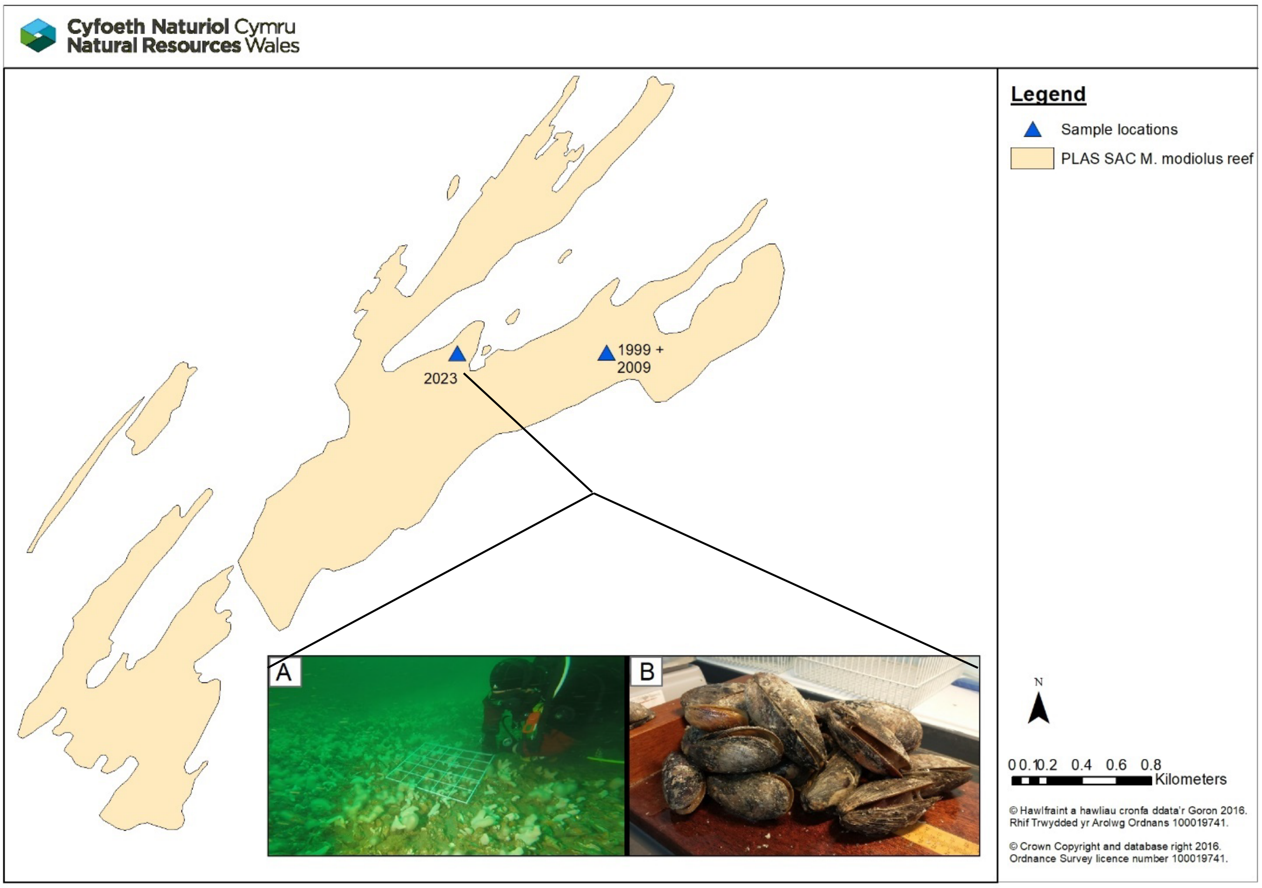


Figure 13: The location of *Modiolus modiolus* samples taken from the Pen Llŷn A’r Sarnau Special Area of Conservation reef in 1999, 2009 and 2023 for size structure analysis.

Images: A) Diver marking out an area of the *M. modiolus* reef for filming and taking a cleared quadrat for population sampling. B) samples of *M. modiolus* from the reef collected in 2023 in the laboratory for analysis

A total of 220 spat (<12 mm) were found in the samples, indicating spawning and settlement is occurring at the reef (Figure 14). However, when the size frequency data for juvenile and adult size classes were compared to the 1999 and 2009 data it was observed that there were low numbers of *M. modiolus* under 70 mm compared to previous years. The relative frequency of larger individuals was also greater, indicating a potentially aging population.

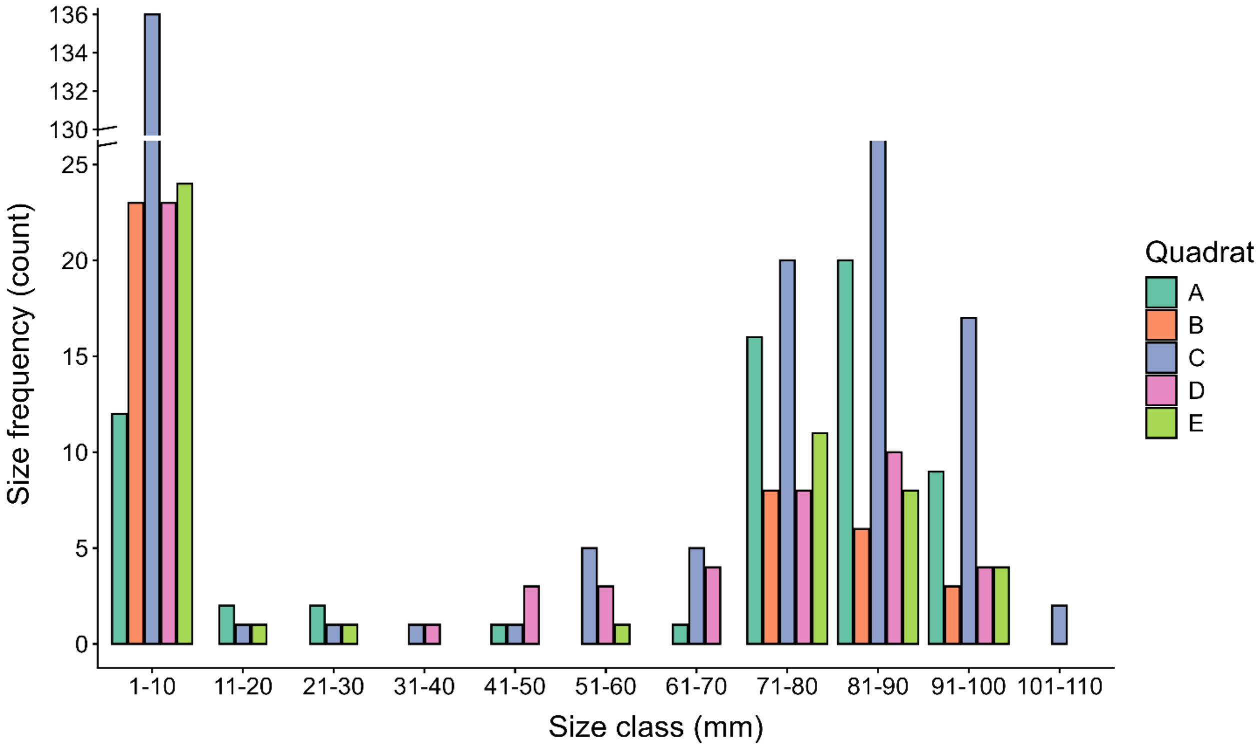


Figure 14: Size frequency histogram of *Modiolus modiolus* sampled at the Pen Llŷn A'r Sarnau Special Area of Conservation reef in 2023, showing the size structure found in each of the 5 quadrats (A-E) taken from a central region of the reef. Quadrat C had the highest frequencies; this was the densest area sampled and showed the highest number of spat.

Using data on the age of individuals at a given length determined for the population by Brash et al. (2018), the age and settlement years were calculated for each dataset. This enabled cohorts to be tracked through time and identified years of good settlement, that lead to recruitment to the adult population (

Figure 15). Looking at the 1999 samples, successful settlement in 1988 created a strong cohort (seen as the ~52 mm peak in the frequency distribution) that could be tracked forward becoming the bulk of the adult population sampled in 2009 (the 72-76 mm peak in the 2009 data). In the 2023 samples, this cohort have become the oldest individuals (the 96 mm peak in the 2023 data series). Another strong settlement year occurred 10 years later in 1998 (seen as the ~52 mm peak in the 2009 data series) creating another strong cohort that could be tracked forward becoming the bulk of the adult population sampled in 2023 (the ~84 mm peak). A further successful recruitment occurred in 2003 (seen as the ~76 mm peak in the 2023 data series).

As observed at other *M. modiolus* reefs, successful recruitment is sporadic, occurring approximately every 2 to 10 years (Brash et al. 2018). The current population within the PLAS SAC is shaped by three strong cohorts from 1988, 1999, and 2003. Since then, there has been low recruitment success as seen by the low frequency of under 70 mm *M. modiolus* in the 2023 samples when compared to the 1999 and 2009 data. The size structure data indicates a potentially aging population.

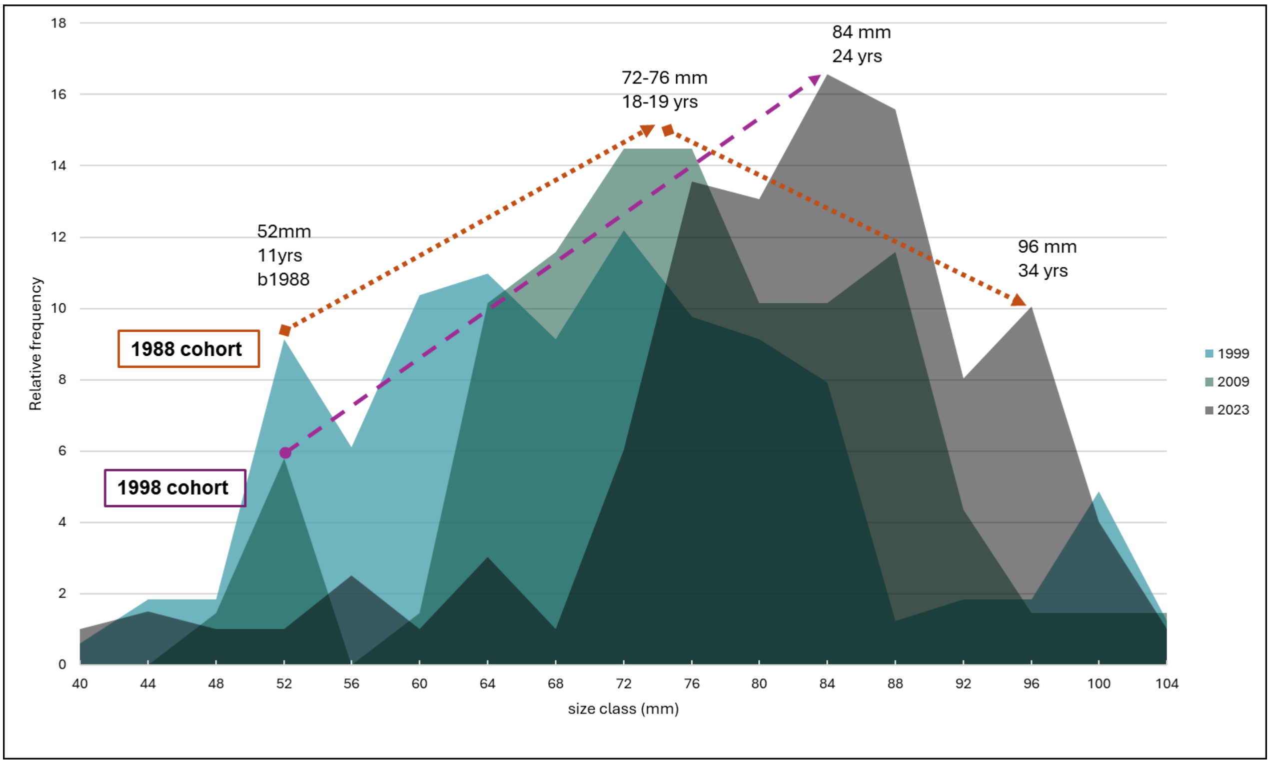


Figure 15: Relative size frequency of *Modiolus modiolus* sampled at the Pen Llŷn A'r Sarnau Special Area of Conservation reef in 1999 (light blue), 2009 (teal) and 2023 (grey). Age-at-length data from Brash et al.(2018) were used to track cohorts through time. Successful settlement in 1988 led to a strong cohort (orange dotted line) appearing as a peak of ~52 mm mussels in the 1999 samples, ~72-76 mm mussels in the 2009 samples

and ~96 mm in the 2023 samples. Similarly successful settlement in 1998 led to a strong cohort (purple dashed line) appearing as a peak of ~52 mm mussels in the 2009 samples, and ~84 mm in the 2023 samples.

Taken together the findings of spat in the 2023 samples, but low recruitment success (low numbers of juveniles found), indicate several possibilities. There could have been a recent (within the last year) settlement event that may become a strong cohort that will recruit to the adult population in the future. Alternatively, this abundance of spat settlement may not be adequate to provide a strong cohort or may have occurred only in this area of the reef. There is a great deal of small-scale variation in spat numbers within *M. modiolus* reefs in general (B. Sanderson pers. comm). Additionally, there may be other pressures preventing successful recruitment to the adult stock, such as predation or climate.

Connectivity

For effective management of the *M. modiolus* reef and analysing factors affecting recruitment, it is important to have an understanding of their connection with other populations. The connectivity of the PLAS SAC reef to other Irish Sea populations was studied by Gormley et al. (2015a), including a population in the north of the Isle of Man (Point of Ayre (POA)) and two Northern Ireland populations (Strangford Lough and Ards Peninsula) (Figure 16). Larval dispersal was investigated using a biophysical model and the connectivity determined using genetic analysis. Overall, the genetic results suggested an inter-connected Irish Sea metapopulation, with stronger connectivity between the two sites in Northern Ireland and between the PLAS SAC reef and the POA. However, the available data do not yet allow us to identify source or sink populations within this network The larval dispersal modelling showed potential for connectivity of up to 150km, though there were some discrepancies with the genetic analysis. For example, the genetic connectivity found between the PLAS SAC reef and the POA populations was not identified from the larval modelling, where the PLAS SAC reef did not connect directly to any other site. However, there are known *M. modiolus* populations off the south of the Isle of Man (Little Ness) and an area off west Anglesey that were not included in this study. These (and other unknown areas) could contribute to the connectivity by acting as stepping stone populations, providing intermediate habitats that facilitate larval movement between reefs. Additionally, the hydrodynamic conditions used in the modelling were based on data from one year and dispersal patterns are likely to vary significantly from year to year.

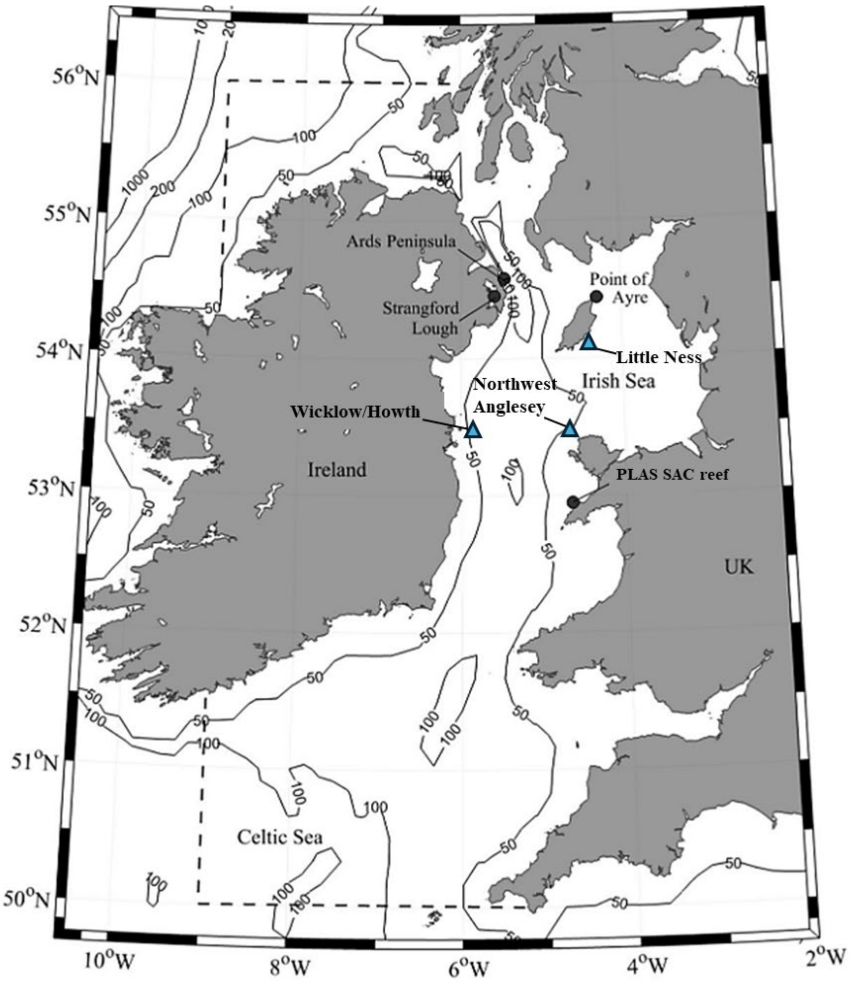


Figure 16: A bathymetric map of the Irish Sea, showing the four sample sites (black circles) used to investigate the connectivity of *Modiolus modiolus* in Gormley et al. 2015. Also shown are known potential stepping stone populations (blue triangles). Wicklow/Howth and Little Ness are included in a new round of genetic analyses currently being undertaken.

In general, simulated larvae moved southward, away from the PLAS reef, over the 30 day pelagic larval duration (PLD), travelling around the head of the Llŷn Peninsula into the northern part of Cardigan Bay (Gormley et al. 2015a). However, a portion of larvae each month also travelled north towards western Anglesey, particularly in April and May when residual currents were weaker. Summer releases, especially in June and August, were the most "energetic," meaning they travelled further, followed by spring releases in April and May.

Further work is needed to improve our understanding of the connectivity of the PLAS SAC *M. modiolus* reef, particularly in light of the ongoing observed decline. To address this, a new round of genetic analyses is currently being undertaken through a collaboration between NRW, Atlantic Technological University (ATU) and Heriot-Watt University. This study will include both the original sampling sites and additional locations such as Little

Ness (south of the Isle of Man) and an Irish population off the coast of Wicklow (see Figure 16). Importantly, the analyses will use improved genetic markers to determine the direction of gene flow and investigate source and sink populations. This information is important for informing potential restoration work and for effective management of MPAs. The results will be available in 2026.

Pressure assessment methodology

Initially, potential pressures were identified using the Marine Evidence based Sensitivity Assessment (MarESA) carried out for the *M. modiolus* biotope classified for the PLAS SAC reef *(Modiolus modiolus* beds with hydroids and red seaweeds on tide-swept circalittoral substrata, SS.SBR.SMus.ModT) (Tillin, H.M and Tyler-Walters, H. 2015). Since the MarESA assessments are generic and not site-specific, this list of pressures was reviewed to identify pressures relevant to the area of concern, in this case the PLAS SAC north of the Llŷn Peninsula, and pressures that were not relevant to the investigation were removed from the list. A spreadsheet of these pressures was generated and an extensive literature review was then conducted building on the MarESA evidence base, covering both the sensitivity of the species and the history of the pressure in the area. The impact of the identified pressures was scored (Table 2) and ranked to assess the relative risk of pressures to reef resilience (Table 13:). Impact scoring was based on five criteria: timing, intensity, frequency, spatial scale, and species sensitivity, each evaluated on a four-point scale (Table 2). These scores were then multiplied to generate and overall risk score. A confidence rating (low, medium, high) was also assigned to reflect the strength and availability of supporting evidence. These assessments, including the evidence base and pressure evaluations, were presented during an internal workshop, where both the pressure scores and confidence ratings were reviewed by a panel of experts, including site officers, benthic specialists, and water quality specialists.

Table 2: Pressure impact scoring definitions

Impact score criteria	Definition
Timing	Likelihood of a pressure occurring during the observed decline period (2004-2023) **1** = Only outside the decline period **2** = Mostly outside the decline period (including continuous pressures that occurred before and after the decline period as well as throughout) **3** = Mostly within the decline period (including pressures present before and/or after for a limited time duration) **4** = Only within the decline period

Impact score criteria	**Definition**
Intensity	The relative magnitude of the pressure. **1** = Very low intensity **2** = Low intensity **3** = High intensity **4** = Very high intensity
Frequency	How often the pressure occurs **1** = One-off or short-term event **2** = Frequent for a short duration, or infrequent over a longer period **3** = Frequent (may be intermittent but ongoing) **4** = Continuous
Spatial scale	Proportion of the feature affected by the pressure **1** = <10% of the feature **2** = >10% – <50% of the feature **3** = >50% – 80% of the feature **4** = >80% – 100% of the feature
Sensitivity of species	The likelihood of change when a pressure is applied to a feature. This reflects the feature's ability to tolerate or resist change, and its capacity to recover from impact: **1** = Not sensitive **2** = Low sensitivity **3** = Medium sensitivity **4** = High sensitivity
Risk	Timing x Intensity x Frequency x Spatial scale x Sensitivity of species

Ocean warming

Definition of pressure: The long-term increase in the average temperature or the world’s oceans caused by the retention of thermal energy due to the buildup of ‘greenhouse’ gases, such as CO_2 and CH_4.

Sensitivity of species

The sensitivity assessment (MarESA, Marlin.ac.uk) classified *M. modiolus* resistance to increase in sea temperature as a result of global warming as *"none to low"* with resilience rated *as "very low" and* overall sensitivity as "high" (Tillin, H.M and Tyler-Walters, H. 2015). This evaluation was based on three scenarios. The first “middle emission scenario” where there is a 3°C rise in sea surface temperature (SST) and near bottom temperature (NBT) (coastal to the shelf). The second “high emission scenario” where there is a 4°C rise in SST and NBT. The third “extreme emission scenario” where there is 5°C rise in SST and NBT (coastal to the shelf).

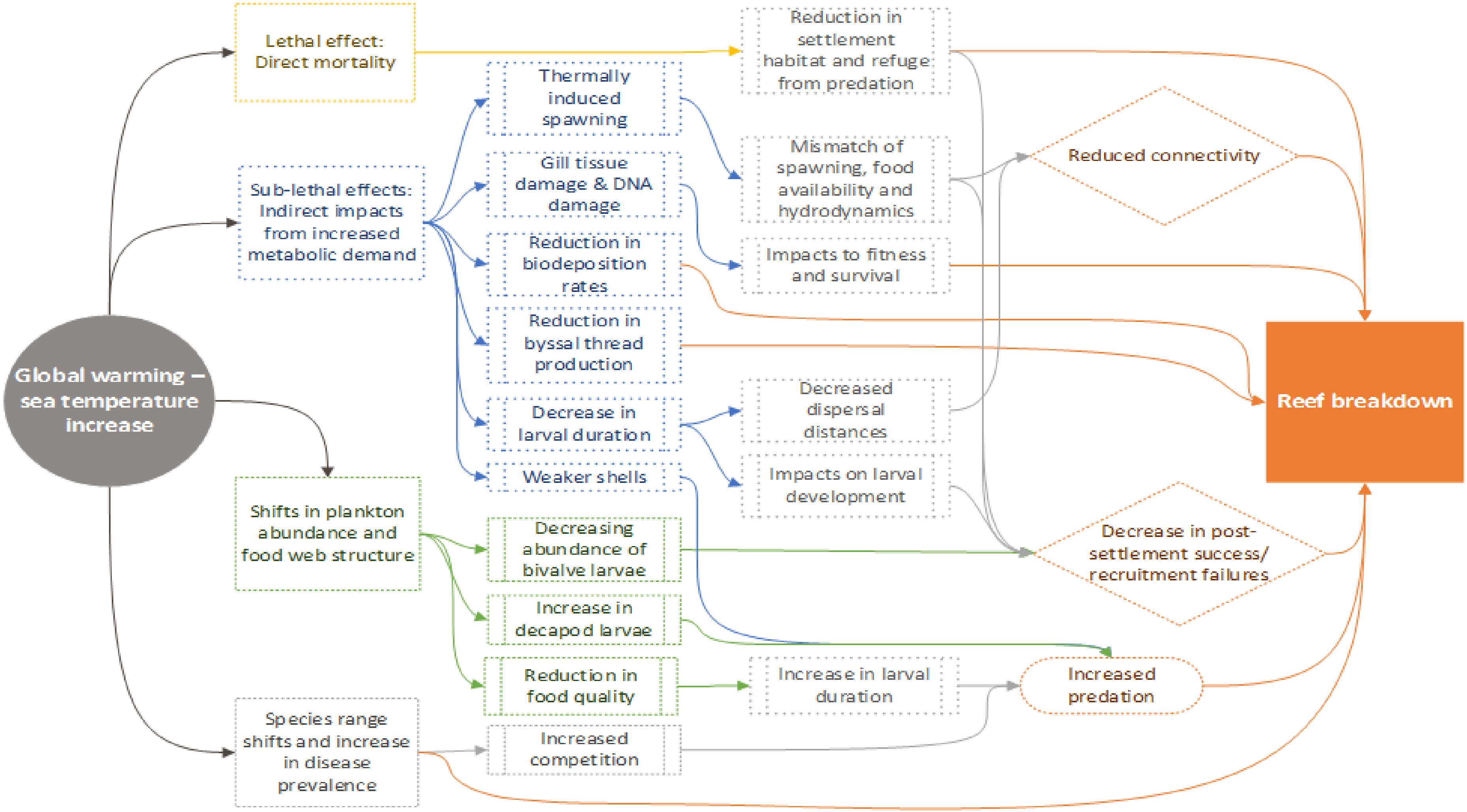


Figure 17: Flow chart illustrating the impacts of ocean warming on *Modiolus modiolus* reefs and the potential pathways through which warming may contribute to weakening or breakdown of reef structure (from left to right)

Loss of habitat

M. modiolus can be found from the Barents Sea in the north to the Bay of Biscay in the south, though their biogenic reef formation is limited to the centre of their range where average sea bed temperatures range from 5-17°C (Mackenzie 2017). Temperature is thought to define these distributional limits with the northern limit determined by a 7-10°C temperature threshold needed to initiate spawning (Brown 1984). At the south of *M. modiolus* distribution where temperatures are warmer, spawning is therefore possible most of the year with evidence of different spawning strategies across their geographical range corresponding to temperature (Brown 1984; Jasim and Brand 1989). The southern limit of reef formation is thought to be determined by an upper temperature threshold where high temperatures increase mortality and reduce growth (Read and Cumming 1967). Although individual *M. modiolus* are found in warmer waters, with records intertidally (Davenport and Kjøsvik 1982), they are predominantly a subtidal species (typically down to 70m) with higher numbers found in water that rarely rises above 15°C (Rees 2009). As a subtidal species they are buffered from the short-term temperature changes experienced by intertidal species, but as a result are less well adapted to fluctuations in temperature. In addition, as a sedentary species they cannot move to avoid unsuitable conditions and as ectotherms they are more sensitive to climate change since their body temperature is strongly controlled by that of the surrounding water. Therefore, they are expected to be highly sensitive to thermal stress (described below). A study modelling *M. modiolus* ecological niche and bioclimatic envelope in UK waters predicted a northward retreat of suitable habitat as sea temperatures rise, with complete loss of “most suitable” (areas with highest probability of *M. modiolus* occurrence) habitat in all regions studied by 2080 (Gormley et al. 2013). The model also predicted the loss of 100% of “most suitable” habitat within Welsh MPA region by 2030.

Lethal and sub-lethal effects

There is limited direct evidence on the thermal sensitivities of *M. modiolus* and available studies have primarily focused on the adult stage (Read and Cumming 1967; Kent 2015; Mackenzie 2017; Lesser and Kruse 2004). These studies have shown lethal effects (Read and Cumming 1967; Mackenzie 2017) and sub-lethal effects (Lesser and Kruse 2004; Kent 2015). Sub-lethal effects included DNA damage to haemolymph and gill cells, reduction in byssal thread production (Figure 18) and bio-deposition rate, and thermally induced spawning. Direct mortality (lethal effect) was observed at water temperatures between 23-28°C, though sub-lethal effects were observed from approximately 16°C. In particular, byssus thread production declines as temperatures exceed 13°C which is likely to reduce attachment strength between individual mussels and to the underlying substrate, thereby weakening reef cohesion and increasing susceptibility to physical disturbance. Although there are limited studies on *M. modiolus,* these findings are in line with those from other bivalve species (Clements et al. 2018; Mackenzie et al. 2014).

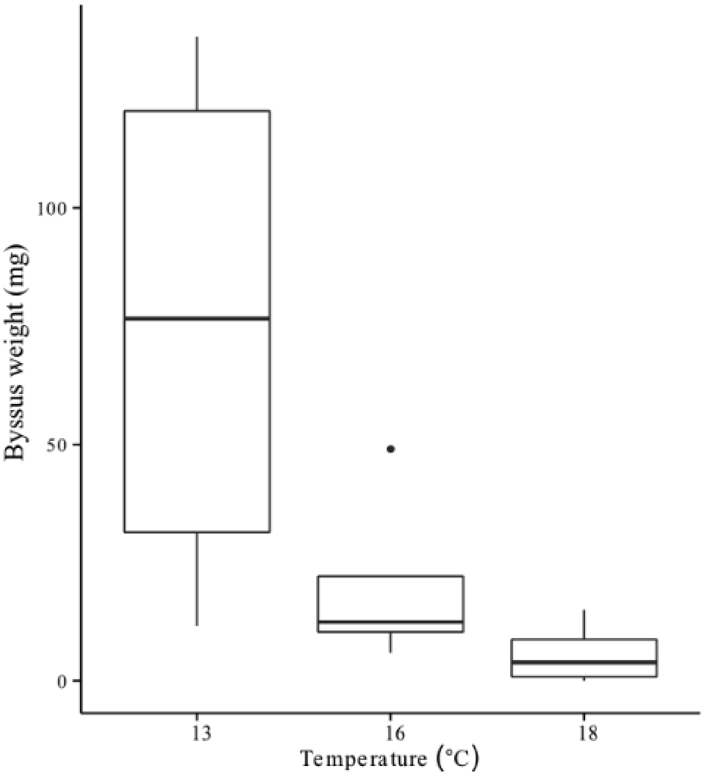


Figure 18: *Modiolus modiolus* byssus thread production after seven days at three temperatures with 1 month acclimation. Samples reflect the weight of byssus thread for each experimental tank (n=4) and show a significant effect of temperature on byssus production overall (ANOVA; F =5.82, p=0.024) (taken from Kent 2015).

The effects of temperature across life-stages are essential to consider, though complex. There are no studies on the impacts of temperature on *M. modiolus* larvae, though studies of impacts on other marine species have shown for example, increased mortality of larvae, latent effects of temperature on post settlement survival (Bayne 1965; Laurel et al. 2008; Rayssac et al. 2010; Enricuso et al. 2019) and impacts on larval dispersal (O’Connor et al. 2007). Increasing sea temperatures have been shown to accelerate larval development in marine species, reducing time in the plankton and therefore dispersal distances, having impacts on connectivity (O’Connor et al. 2007; Lett et al. 2010). These findings are based on broad multispecies analyses, including 72 species across six phyla from polar, temperate, and tropical regions including temperate molluscs, indicating that the general temperature–development trends are consistent across similar cold- and temperate-water species (O’Connor et al. 2007).

Food availability and larval development

Metabolisms accelerate with temperature, increasing the demand for food. As temperatures increase, if food is limiting then there will be physiological trade-offs and it is thought this may determine the southern extent of populations (Peck et al. 2002; Fitzgerald-Dehoog et al. 2012; Thomas and Bacher 2018). In the NE Atlantic, warming seas have led to major declines in plankton, with a ~50% decrease in copepod abundance over the past 60 years (1960-2019). This shift to a “microbial food web” is dominated by *Synechococcus spp* (a picophytoplankton), which is considered a poor-quality food source due to its small size and lack of essential fatty acids (Schmidt et al. 2020; Holland et al. 2023). Therefore, as sea temperatures increase not only is there a potential mismatch between spawning and food availability but there may also be a reduction in the quality and quantity of available food. This can slow larval development (Kheder et al. 2010), increasing the time larvae spend in the water column, making them more vulnerable to predation and reducing recruitment (Kirby et al. 2008; Talmage and Gobler 2011).

Reef breakdown

The temperature-related impacts described above make *M. modiolus* reefs highly vulnerable to ocean warming. Direct mortality, coupled with sub-lethal effects such as reduced byssal thread production, may destabilise reefs, leading to less dense and weaker aggregations, loss of settlement habitat, and reduced refuge from predators. Temperature-driven shifts in plankton communities further affect larval development, settlement success, connectivity, and predation pressure. Together, these processes could drive progressive reef breakdown and loss of the biodiversity supported by this biogenic reef habitat (Figure 17).

Evidence of global warming at the PLAS reef

The PLAS SAC *M. modiolus* reef can be traced as far back as 1846, based on dredging records and Admiralty Chart surveys (Forbes, 1850, in Lindenbaum et al. 2008). However, it was not formally identified and mapped by scientists until the 1960s. Since that time, the local temperature regime has undergone a significant shift with a period of lasting high sea temperatures in UK shelf waters beginning during the mid - 1990s (Figure 19) (Hughes et al. 2017; Cornes et al. 2025).

Regional temperature records from the Irish Sea reflect this long-term pattern of warming. Since 2000, SSTs have remained consistently above the 1991-2020 average, with particularly high values recorded in 2022 and 2023 (

Figure 20) (Cornes et al. 2025). The reef occurs in relatively shallow, tidally energetic coastal waters that are expected to be vertically well mixed, with little to no seasonal stratification. As a result, SBTs are likely to be equal or very close to SSTs (Sharples et al. 2020; Cornes et al. 2025). Using SST data therefore provides a reliable indicator of temperature conditions and trends at the reef. Irish Sea records show a strong upward trend between 1985 and 2024, averaging an increase of around 0.8°C per decade. This suggests that average annual SSTs at the reef are now at least 2°C warmer than in the mid-1980s, with most of this warming occurring since the 1990s. Model simulations indicate that sea surface temperatures will continue to rise throughout the 21st century, with average annual SSTs projected to increase by a further 3.11°C by 2100.

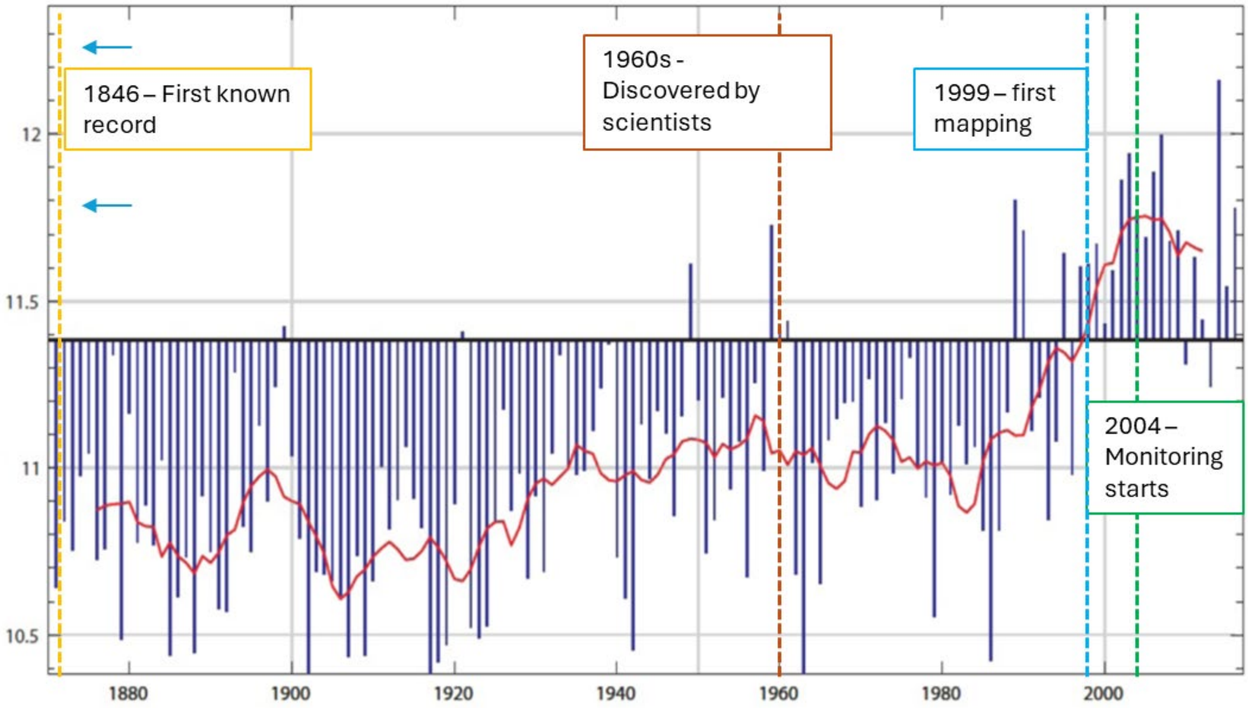


Figure 19: Time series average sea surface temperature (SST) (in degrees Celsius) in UK shelf waters for the period 1870 to 2016. The blue bars show the annual values relative to the 1981-2010 average and the smoothed red line shows the 10-year running average. Data are from the HadiSST1.1 data set (adapted from Hughes et al. 2017).

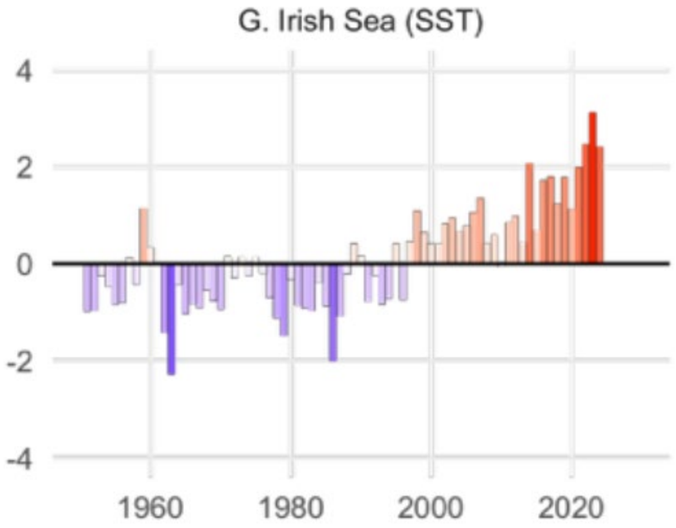


Figure 20: Normalised sea temperature anomalies (1950 to 2017) relative to the reference period of 1991-2020, from the Charting Progress Irish Sea series, combining the Port Erin, Isle of Man series until 2011, the Western Irish Sea Data Buoy series (53.78° N; 5.63° W) Jan 2012 – Oct 2013 and modelled values thereafter (taken from Cornes et al. 2025).

Dive monitoring at the PLAS *M. modiolus* reef began in 2004, after this warming period had begun. Temperature loggers deployed at the reef between 2003-2008 and 2012-2021, as well as at other sites within the SAC, show fluctuations in annually averaged sea temperatures, with no clear trend (Figure 21). Some loggers indicated an increase in the number of days with higher temperatures, and some showed no clear pattern (Hatton-Ellis, et al. 2025). This mixed picture is likely due to the relatively short observational window and the naturally high variability of shallow coastal waters. Additionally, this is consistent with UK-wide observations of a temporary slowdown in warming between 2003 and 2013, following a decade of rapid warming before 2006 (Hughes et al. 2017).

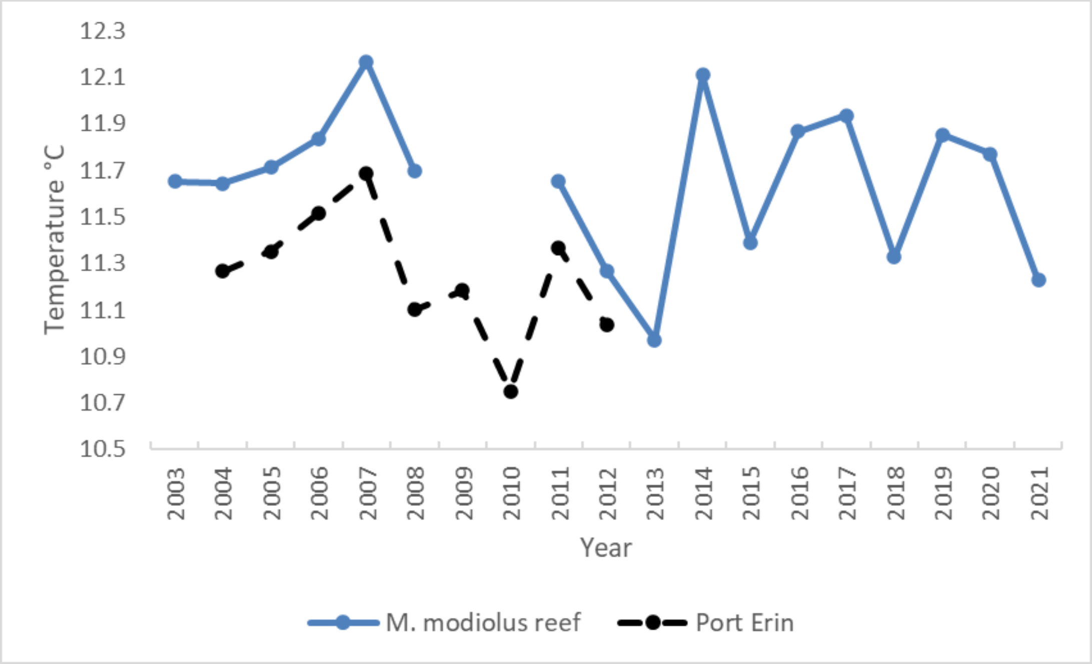


Figure 21: Average annual seawater temperature (°C) recorded by temperature loggers deployed on the *Modiolus modiolus* reef within the Pen Llŷn a'r Sarnau Special Area of Conservation between 2003–2008 and 2012–2021 (blue line). The black dashed line shows the corresponding long-term annual mean sea surface temperature (SST) from the Port Erin monitoring station for comparison (Cefas 2026).

The monthly average sea temperatures recorded from loggers at the Pen Llŷn a'r Sarnau Special Area of Conservation *Modiolus modiolus* reef ranged from approximately 8 to 16°C (± 0.7°C) (between 2003 and 2021), with peak temperatures of 16.7°C logged in 2021 and a diver-recorded 17°C in 2023, a year characterised by record-breaking global and regional sea surface temperatures (SSTs) (Copernicus 2024) (Figure 22). The range in minimum and maximum temperatures recorded each month is greatest during the summer and autumn highlighting strong interannual variability. Although the logger dataset does not show a trend in average annual temperatures, comparison with the long-term Port Erin SST record provides important context. The Port Erin dataset is used in Figure 21 (one of the UK's longest coastal monitoring records), supplemented by buoy data and modelled values (Cornes et al. 2025). When the two datasets are compared over their overlapping period (2003–2012), the reef loggers and Port Erin series show similar annual patterns, although when compared seasonally reef temperatures are generally 0.5 – 1 °C warmer from late spring to autumn, resulting in a higher annual average. This likely reflects localised conditions at the reef, such as shallow depth and site-specific mixing processes, which can produce slightly elevated near-bed temperatures relative to wider regional measurements.

Despite this difference in temperature, the similar annual variability indicates that the Port Erin record is a suitable proxy for looking at longer-term trends. The Port Erin dataset extends back to the early twentieth century, and can therefore be used to reflect the thermal conditions historically experienced at the reef. Comparison of early-century Port Erin temperatures with those recorded during the logger period indicate an approximately 1.5 °C rise in average annual temperature, supporting the conclusion that long-term Irish Sea warming is also likely to be influencing conditions at the PLAS *M. modiolus* reef (Figure 21).

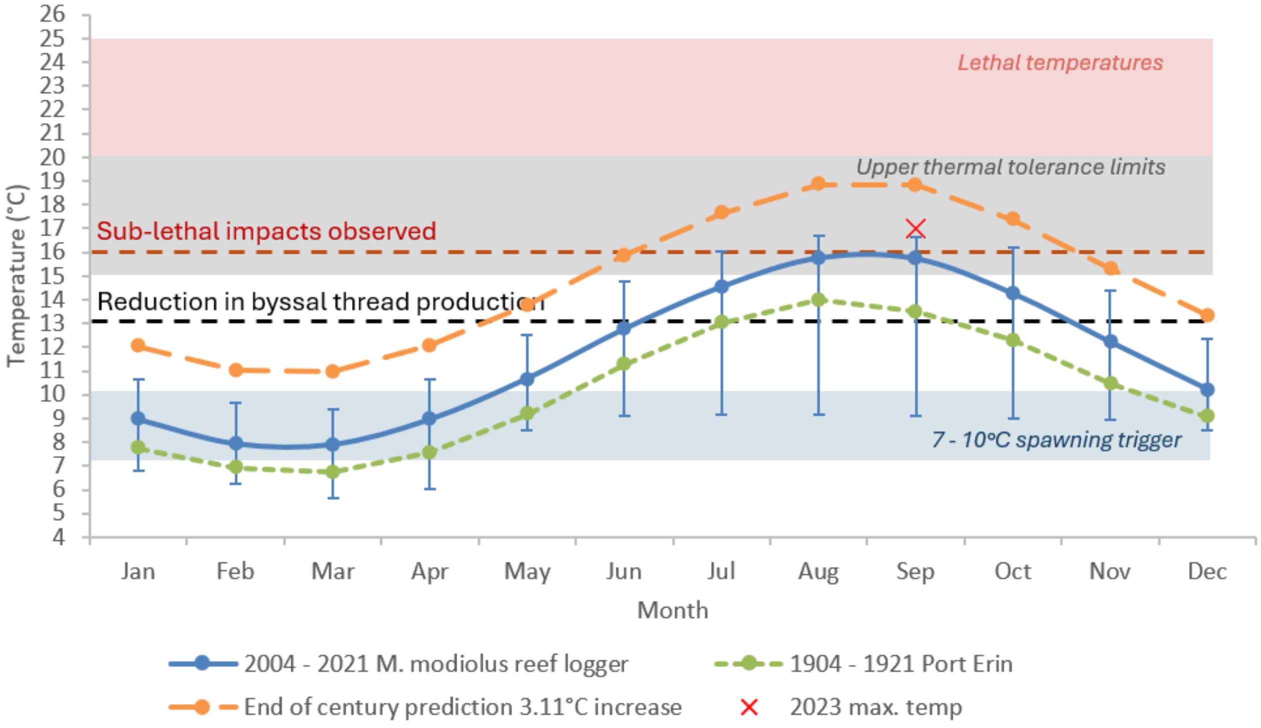


Figure 22: Monthly mean seawater temperature (°C) at the Pen Llŷn a'r Sarnau Special Area of Conservation *Modiolus modiolus* reef calculated from logger data collected between 2004 and 2021 (blue line), with error bars showing monthly minimum and maximum temperatures. Projected future temperatures under a +3.11 °C warming scenario are shown by the orange dashed line, and early-20th-century Port Erin temperatures (1904–1921) by the green dashed line. Shaded bands and dashed lines indicate key biological thresholds for *M. modiolus*, including spawning temperatures (7–10 °C), reduced byssal thread production (>13 °C), onset of wider sub-lethal impacts (~16 °C), upper thermal tolerance (15–20 °C), and lethal temperatures (>20 °C).

The North Llŷn *M. modiolus* reefs (PLAS SAC and area north of Porthdinllaen) are predicted to be under threat from increases in sea temperature due to their location at the southern edge of the known range of reef formation (Hiscock et al. 2004; Gormley et al. 2015a; Brash et al. 2018). They already experience temperatures within the upper thermal limits suggested for this species (i.e. 15-20°C), with the warmest temperatures recorded a the reef reaching ~ 17°C in late summer (e.g. 2021 and 2023). Although these values remain below lethal thresholds (23–28 °C), they fall within the range where sub-lethal impacts have been observed in studies, including reduced byssal thread production, impaired feeding, cellular damage and thermally induced spawning (~13–16 °C) (Lesser and Kruse 2004; Kent 2015; Mackenzie 2017). These effects weaken reef structure and represent the most ecologically significant mechanism through which warming within the Irish Sea may influence reef condition. Temperature also regulates reproduction, with *M. modiolus* requiring a narrow 7–10 °C window to initiate spawning, meaning that warmer winters and springs may restrict or shorten opportunities for successful recruitment. The reefs also experience the greatest variation in temperature when compared to more northern populations (Mackenzie 2017). Under lab conditions when compared to other populations, *M. modiolus* from the PLAS SAC showed the strongest negative response to warming, i.e. high post experimental mortality and induced spawning (Mackenzie 2017) . Modelled future projections also predict the potential loss of 100% of “most suitable” habitat in Wales by 2030 (Gormley et al. 2013). While a projected end-century increase of ~ 3.11 °C would keep average late-summer temperatures just below lethal thresholds (≈19–20 °C), these values are firmly within those associated with sub-lethal effects and are likely to furher compromise reef integrity, reproduction, and long-term resilience. This indicates that the key risk is not temperature-driven mortality but cumulative sub-lethal stress, particularly declining byssal thread production, which begins above ~13 °C.

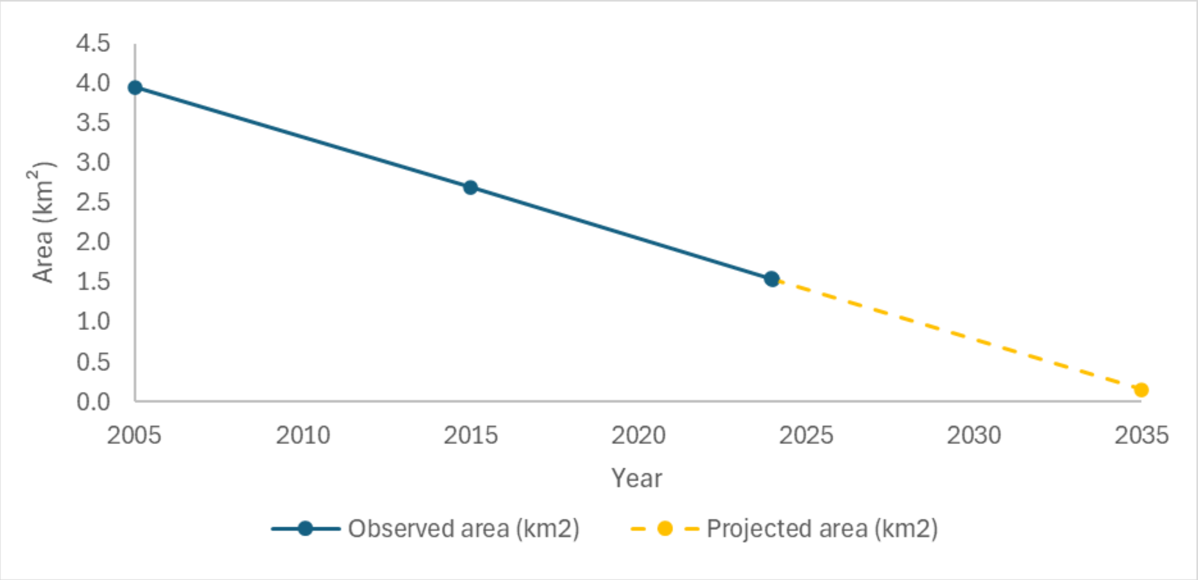


Figure 23: Decline in *Modiolus modiolus* reef extent (km^2) recorded at the Pen Llŷn a’r Sarnau Special Area of Conservation based on multibeam survey data. The blue solid line

shows observed mapped area from multibeam surveys, while the dashed yellow line shows projected future loss assuming continuation of the long-term observed rate of decline.

Observed reef structural and ecological changes are consistent with signs of progressive physical deterioration. Extent data derived from multibeam surveys indicate an approximately 60% reduction in reef area since 2005 and a general flattening of the reef, with losses initially occurring around the reef edges. This pattern is illustrated in Figure 23, which shows both the observed decline and the projected trajectory if the long-term observed rate of loss continues. This weakening at the edges may lead to winnowing and erosion, reducing reef density. Lower-density assemblages are likely to provide poorer settlement habitat, reduce protection from predators and contribute to poor recruitment, consistent with limited evidence indicating an ageing population and poor recruitment in the last two decades. Although these changes likely arise from multiple interacting pressures, including historic fishing impacts and limited recovery capacity, they are consistent with the kinds of cumulative sub-lethal thermal stresses described above, particularly weakened byssal thread production and disruption of the narrow 7–10 °C spawning window, which could destabilise reef structure, reduce recruitment and amplify the effects of other pressures.

Overall, while sea temperatures at the reef have not increased during 2003–2023, the reef has been exposed to a warmer Irish Sea climate established prior to the monitoring period, and repeated warm summers now regularly expose it to sub-lethal stress that interacts with historic fishing impacts and low recovery capacity, making warming a likely contributing pressure rather than the sole cause of decline.

Pressure assessment scores

The sensitivities and evidence described above were used to assess the impact of ocean warming on the PLAS SAC *M. modiolus* reef (Table 3). A timing score of 2 was assigned because the increase in sea temperature is an ongoing pressure that occurred throughout the time period but mostly outside (a continuous pressure that occurred before and after the decline period as well as throughout). Intensity was assigned 2 reflecting the low intensity changes over the 2003 – 2023 assessment window, though it should be noted this is part of a long-term and significant warming trajectory (1.5 - 2 °C since early 1900s). Frequency was assigned 4 as this was a permanent (continuous) change and spatial scales was scored 4 since it would have affected the whole site. A high sensitivity score (4) was given to reflect the high vulnerability to global warming. The confidence was medium for this assessment due to the good but limited supporting literature and data.

Table 3: Assessment for **ocean warming** pressure. Scores range from 1 (low) to 4 (high). Timing = the likelihood that the pressure occurred during the decline period (2004 – 2023); intensity = the relative magnitude of the pressure; frequency = how often the pressure occurs; spatial scale = the proportion of the feature affected by the pressure; sensitivity = a

feature’s susceptibility to change and ability to recover under pressure. For detailed definitions, see Table 2.

Timing	Intensity	Frequency	Spatial scale	Sensitivity	Risk	Confidence
2	2	4	4	4	256	Medium

Penetration and/or disturbance of the substrate below the surface of the seabed, including abrasion

Definition of pressure: Damage to sub-surface seabed

Sensitivity of species

The sensitivity assessment (MarESA, Marlin.ac.uk) classified *M. modiolus* resistance to penetration and/or disturbance of the substrate below the surface of the seabed, including abrasion as "low" with resilience rated as "low" and overall sensitivity as "high" (Tillin, H.M and Tyler-Walters, H. 2015) .

As *M. modiolus* are a sedentary infaunal or semi-infaunal benthic species, they are vulnerable to activities that impact the seabed. They have been found to decline in areas subject to bottom-towed fishing gear (Service and Magorrian 1997; Callaway et al. 2007; Rees 2009; Strong et al. 2016). The penetration of the fishing gear on the seabed removes erect epifauna growing on the *M. modiolus* (e.g. *A. digitatum*) decreasing diversity as well as breaking up and removing the bivalves, leading to a general flattening of the reef structure (Holt et al. 1998; Strain et al. 2012; Cook et al. 2013). Studies also indicate an increased risk of predation, as trawling attracts higher numbers of scavenging fish and shellfish that feed opportunistically on damaged *M. modiolus* and other shellfish, with fragmentation of mussel clumps increasing exposure and making individual mussels more accessible to predators (Veale et al. 2000; Kenchington et al. 2007).

Due to their slow growth, long lifespan and sporadic recruitment, they have been recorded as having very slow (12-20 years) to no recovery (Wiborg 1946; Mazik et al. 2015; Strong et al. 2016). For example, an increase in extensive bottom fishing (otter trawls and scallop dredge gear) between 1970s and 1990s in Strangford Lough resulted in the loss of over 40% of the *M. modiolus* reef (Roberts et al. 2011). Despite a ban on bottom towed gear in this area in 2003, there has been no evidence of recovery with continued declines in some areas of the Lough (Fariñas-Franco et al. 2018b). In light of this evidence, OSPAR recommended strengthening the protection of this habitat including introducing legislation to protect *M. modiolus* (Rees 2009). Subsequently, the UK and Sweden implemented fisheries measures that ban bottom-towed gear where they occur within a designated conservation site.

Evidence of penetration and/or disturbance of the substrate below the surface of the seabed, including abrasion at the PLAS SAC reef

Both North Llŷn *M. modiolus* reefs have been closed to bottom-towed fishing gear since 1998 and are currently protected under The Sea Fish (Specified Sea Areas) (Prohibition of Fishing Method) (Wales) Order 2012 with a buffer zone to mitigate secondary impacts, caused by sedimentation from nearby fishing activity. Despite this protection, a vessel was observed scallop dredging during the winter of 2011 and 2012 within the PLAS SAC reef area, in the summer of 2012 dredge marks were found in the same location by side-scan data (Cook et al. 2013) (Figure 24).

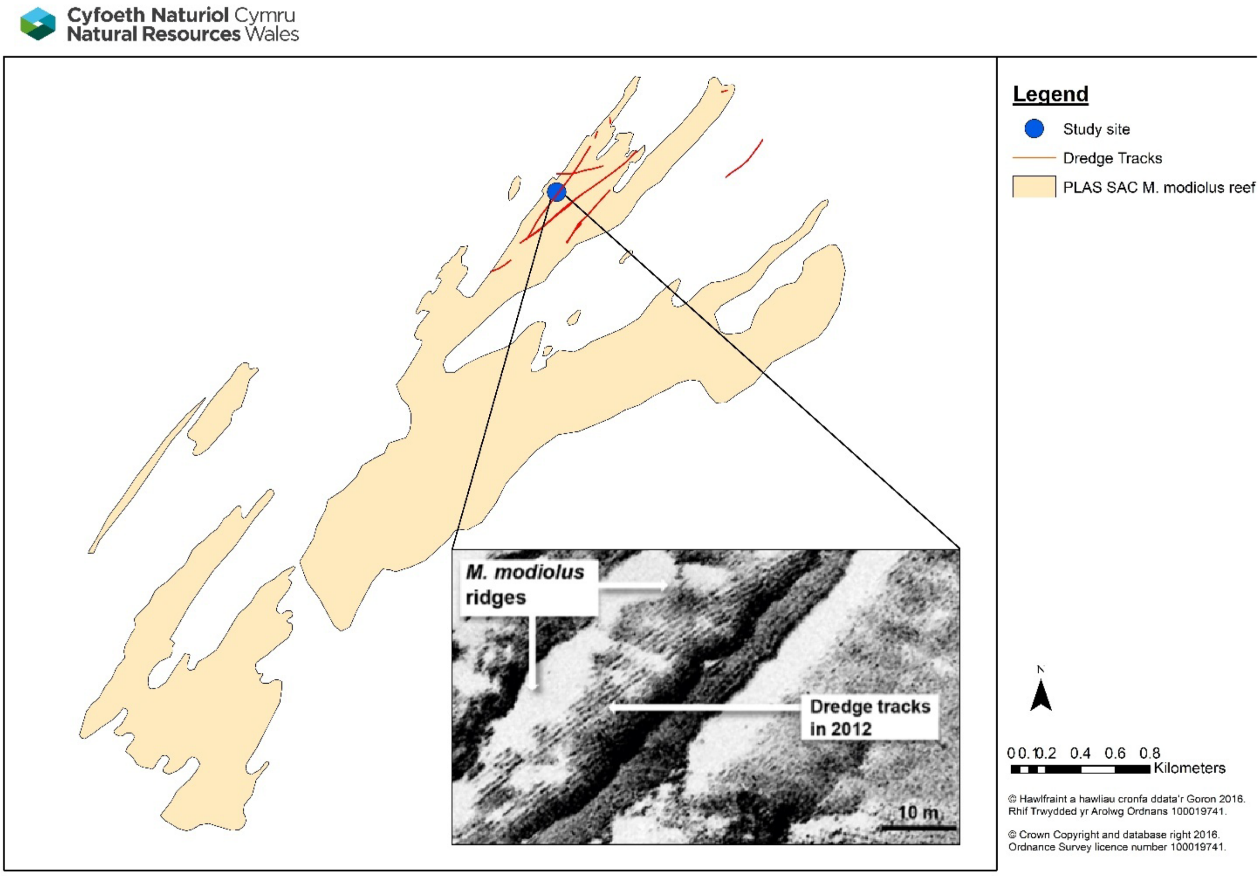


Figure 24: Location of scallop dredge marks at the Pen Llŷn a'r Sarnau Special Area of Conservation *Modiolus modiolus* reef identified from side scan sonar images from 2012 (orange lines). The side-scan image shows marks from scallop dredges across the surface of the *M. modiolus* ridges (taken from Cook et al. 2013).

A targeted assessment was conducted in July 2012 to evaluate the physical impact of the scallop dredge on the reef. Quadrats (0.25 × 0.25 m) were randomly placed in areas with conspicuous dredge marks and in adjacent undisturbed control sites. High-resolution video imagery was used to document and analyse the benthic fauna. Although reductions in *M. modiolus* abundance were not statistically significant, clump structures in impacted areas were visibly flattened. However, significant declines in epifaunal abundance and diversity were recorded, providing evidence of physical disturbance to the associated communities (Figure 25). These findings are consistent with previous studies demonstrating the vulnerability of *M. modiolus* reefs to bottom-towed fishing gear and the limited recovery potential of such habitats (Cook et al. 2013; Strong et al. 2016; Sameoto et al. 2021). The scallop dredge tracks were still visible on sidescan imagery in 2014, three years later, showing the persistent effect of this physical impact on the reef.

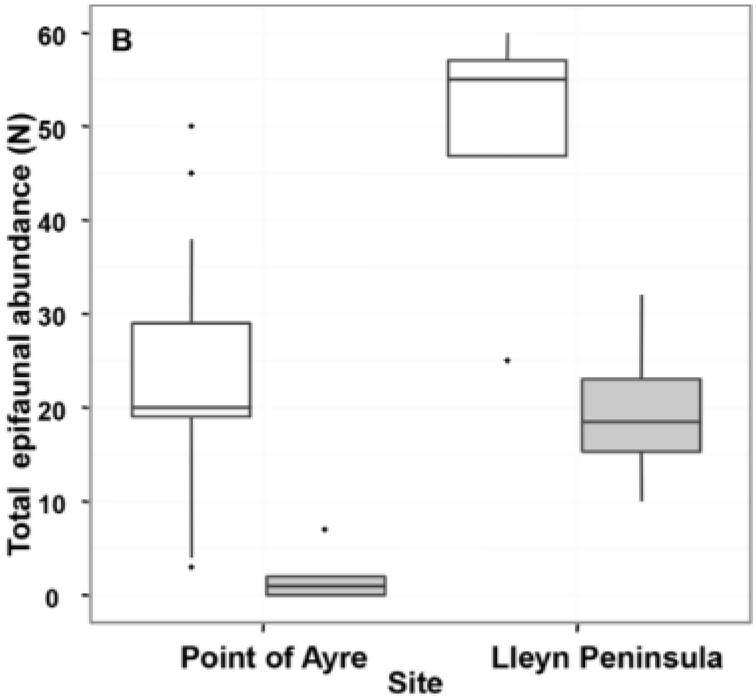


Figure 25: Significant reductions in epifauna following bottom-towed fishing gear recorded on impacted (grey) and unimpacted (white) *Modiolus modiolus* reefs at the Point of Ayre in the Isle of Man and the Pen Llŷn a'r Sarnau Special Area of Conservation reef north of the Llŷn Peninsula (taken from Cook et al. 2013).

In addition, vessel monitoring system (VMS) data from scallop fishing vessels between 2012 and 2022 indicate that occasional scallop fishing activity may have occurred within the SAC at discrete locations on the reef (Figure 26). However, these data should be interpreted cautiously, as VMS points classified as 1 – 4 knots represent presumed rather than confirmed fishing activity, and may also reflect non-fishing vessel movements. Additionally, some vessels also engage in potting, which may lead to misclassification of fishing activity type. The 0.01° grid resolution used can place activity inside the closed area even when vessels were operating outside it. Data from side-scan surveys taken after 2014 have not yet been analysed to confirm whether these apparent incursions resulted in detectable seabed impact. The VMS data indicates higher levels of “presumed fishing” across the additional reef area outside the SAC, to the north of Porthdinllaen. Side-scan data analysed up to 2010 also shows high occurrence of scallop dredge scars across the this reef area, before it was closed to bottom towed gear. Given the high sensitivity of *M. modiolus* reefs to physical damage and the slow to negligible recovery observed at other impacted sites, it is possible that any continued activity in the area may have contributed to the reef’s limited recovery . Furthermore, historical fishing impacts prior to the closure to mobile gear may also have played a role in the degradation of reef structure and associated biodiversity (Fariñas-Franco et al. 2018b). However, there is some uncertainty in the interpretation of VMS data, as pings do not always indicate active fishing.

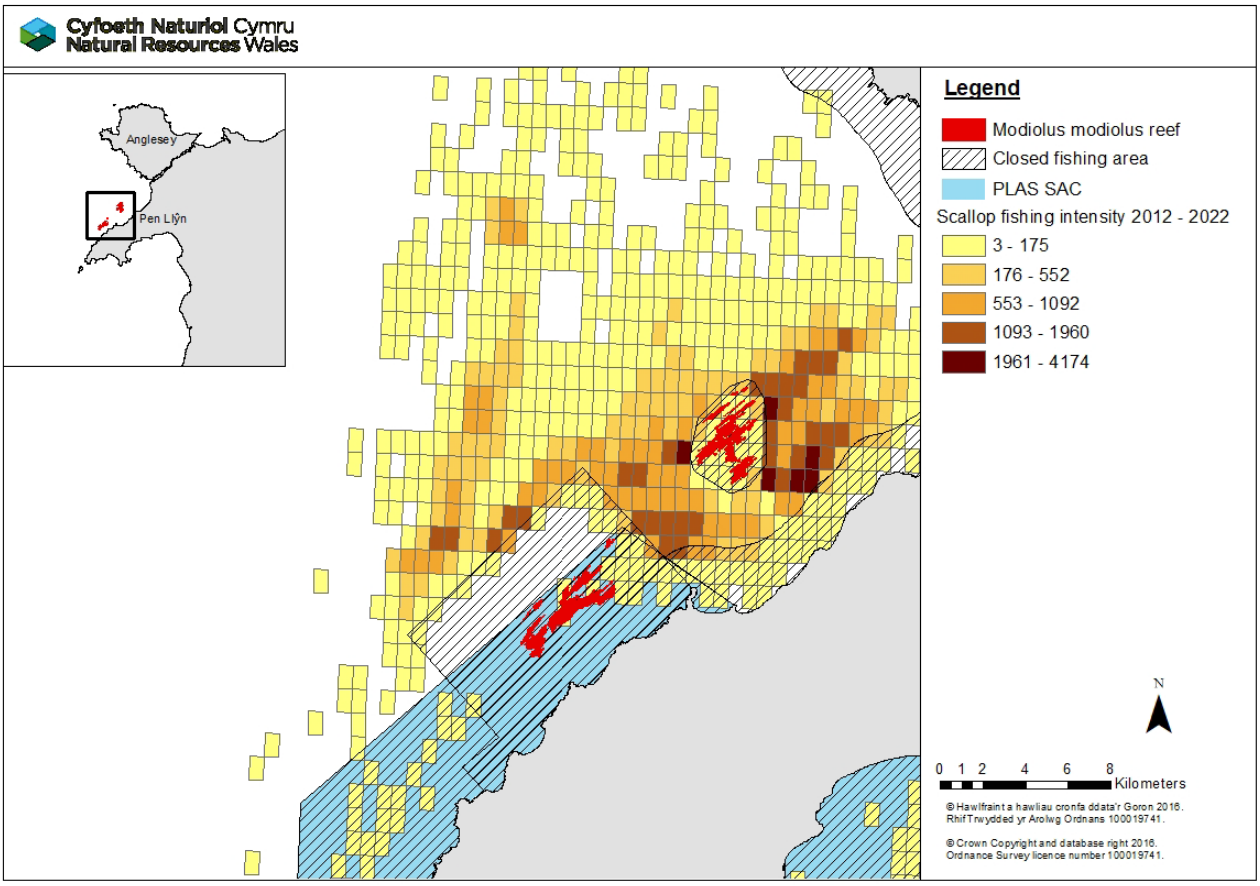


Figure 26: Scallop fishing vessel activity around the Pen Llŷn a’r Sarnau Special Area of Conservation *Modiolus modiolus* reef, over the 2012 to 2022 scallop fishing seasons, derived from Welsh Government Vessel Monitoring Systems (VMS) data. The VMS records vessel location, speed, and heading at each “ping.” Following Welsh Government filtering, pings were classified as presumed fishing when vessels were travelling between 1 and 4 knots and were more than 1 km from ports. Filtered pings were aggregated to 0.01° grid cells, and the “intensity” shown represents the number pings per grid cell, a proxy for relative vessel activity, rather than a direct measure of effort (e.g. hours fished or area swept). To protect fisher anonymity, no data are shown for grid cells containing pings from fewer than three vessels. These data should be interpreted cautiously, as VMS points

classified as 1–4 knots represent presumed rather than confirmed fishing activity, and may also reflect non-fishing vessel movements.

Physical impacts from historic fishing activities have been attributed to the widespread decline of *M. modiolus* reefs (Service and Magorrian 1997; Callaway et al. 2007; Fariñas-Franco and Roberts 2018) and it is possible that this has contributed to the decline observed at the PLAS SAC reef, through slow to no recovery from direct impacts. Historic towed-gear activity prior to the 1998 prohibition may have destabilised the reef structure, potentially initiating longer-term fragmentation that continues to influence its condition today. Many areas of the UK's coastal seas, including the Irish Sea, have experienced sustained fishing pressure over time (Witt and Godley 2007; Stelzenmüller et al. 2008). It is therefore likely other *M. modiolus* reefs have been lost or impacted. This may have secondary effects such as reduced connectivity and larval recruitment. These factors may be contributing to the breakdown and recruitment failures observed at the PLAS SAC reef.

Pressure assessment scores

The sensitivities and evidence described above were used to assess the impact of penetration and/or disturbance of the substrate below the surface of the seabed, including abrasion on the PLAS SAC *M. modiolus* reef (Table 4). A timing score of 3 was assigned because although this pressure mostly occurred before the time period there is high likelihood of the impact of past activity (past mobile fishing gear impacts) continuing during the decline period. Intensity was assigned a score of 4 reflecting the magnitude of impact from mobile fishing gear. Frequency was assigned a score of 2 to reflect the pressure was infrequent over a longer period but did occur within the period of decline, and spatial scales was scored 2 since available evidence suggests it would likely have affected part of the site. A high sensitivity score (4) was given to reflect the high vulnerability to sub-surface penetration and/or disturbance. The confidence was high for this assessment due to the availability of supporting literature and data.

Table 4: Assessment for **penetration and/or disturbance of the substrate below the surface of the seabed**, including abrasion. Scores range from 1 (low) to 4 (high). Timing = the likelihood that the pressure occurred during the decline period (2004 – 2023); intensity = the relative magnitude of the pressure; frequency = how often the pressure occurs; spatial scale = the proportion of the feature affected by the pressure; sensitivity = a feature's susceptibility to change and ability to recover under pressure. For detailed definitions, see Table 2.

Timing	Intensity	Frequency	Spatial scale	Sensitivity	Risk	Confidence
3	4	2	2	4	192	High

Abrasion/disturbance of the substrate on the surface of the seabed

Definition of pressure: Damage to seabed surface features (species and habitats)

Sensitivity of species

The sensitivity assessment (MarESA, Marlin.ac.uk) classified *M. modiolus* resistance to an abrasion or disturbance to the surface of the substratum or seabed as ″ low" with resilience rated as "low" and overall sensitivity as "high" (Tillin, H.M and Tyler-Walters, H. 2015) .

M. modiolus are highly sensitive to physical abrasion and disturbance. Key anthropogenic activities that cause abrasion/disturbance to the surface of the seabed include anchoring, infrastructure (e.g. cable laying) and fishing. Of the three activities, fishing can have the most widespread impact on *M. modiolus* reefs and can be split into static gears (e.g. pots and nets) and mobile fishing gears (e.g. bottom-towed gear). There is one known study on the effects of static fishing gears on *M. modiolus* reefs (Clarke et al. 2025, unpublished). Direct physical effects associated with pot fishing (crushing, scouring, abrasion) may occur during repeated deployment and hauling (Rees et al. 2021). *M. modiolus* reefs are known to be highly sensitive to abrasion caused by mobile gear (as discussed under “Penetration and/or disturbance of the substrate below the surface of the seabed, including abrasion”) with mobile fishing gear shown to remove erect epifauna, decrease diversity and break up and remove *M. modiolus*, leading to a general flattening of the reef structure (Holt et al. 1998; Strain et al. 2012; Cook et al. 2013) with slow or no recovery (Dinesen and Morton 2014).

Most studies on fishing impacts on benthic habitats have focussed on mobile gears with few investigating the effects of static gears. Static gears have generally been assumed to have low or no impact on benthic habitats and species (Fennell et al. 2021). A series of long-term (>4 year) studies in the Lyme Bay MPA concluded that potting was more damaging than previously thought with negative effects on the benthos, and significantly typical long-lived and slow growing species, such as reef builders (Gall et al. 2020; Rees et al. 2021). These studies identified a threshold for fishing effort and recommended that managers reconsider the conservation goals of partially protected MPAs. They suggested applying this approach to determine fishing intensity thresholds to help achieve well-managed MPAs that benefit both fisheries and conservation. In contrast, other short (2 month) and long (4 years) term studies found no impact from commercial crustacean potting on benthic assemblages (Eno 2001; Coleman et al. 2013; Stephenson et al. 2017), though none of these studies have looked at impacts to biogenic reefs.

Evidence of abrasion/disturbance of the substrate on the surface of the seabed at the PLAS SAC reef

Both North Llŷn *M. modiolus* reefs (PLAS SAC & area north of Porthdinllaen) are closed to mobile fishing gear but there are no restrictions on amounts of static gear that can be fished (Figure 27). The effects of mobile gear are discussed further under the section on “Penetration and/or disturbance of the substrate below the surface of the seabed”. The use of static fishing gear is the main anthropogenic activity that occurs at the reef that could cause abrasion or disturbance to the surface of the seabed. The use of penetrating anchors with whelk pots is prohibited across the reef, however, whelk pots, connecting lines and weights used as anchors may cause abrasion and disturbance to the surface of the seabed (Welsh Government 2024). Parlour pots targeting crab and lobster and static nets are also fished across the reef, with the pots, lines connecting pots, footropes of nets and anchors potentially causing abrasion and disturbance to the surface of the seabed.

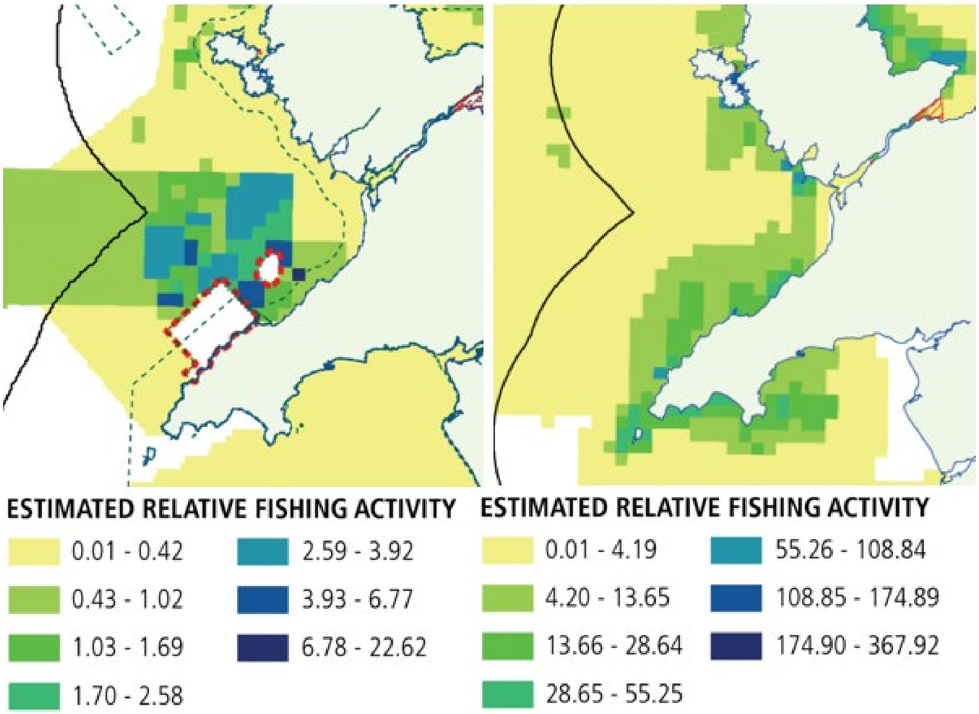


Figure 27: Fishing activity around the Pen Llyn a’r Sarnau area: Left - mobile gear activity (e.g. beam, dredge, otter trawl). Right - Static gear activity (e.g. rod and line, longline, pots, gill nets). Red dashed line indicates the boundaries of the area closed to mobile fishing gear (covering *Modiolus modiolus bed* areas) as part of the Scallop Fishing (Wales) (No.2) Order 2010 and The Sea Fish (Specified Sea Areas) (Prohibition of Fishing Method) (Wales) Order 2012. **Source: Welsh National Marine Plan (Welsh Government, 2019).**
** Note: This map is indicative and for illustrative purposes only. Fishing activity data originate from multiple sources with differing coverage, methods, and resolution, and therefore carry inherent limitations. More detailed or updated datasets may be available via the Welsh Government Marine & Fisheries Division or the Marine Planning Portal.*

Whelk fishing in the UK has expanded significantly since the late 1990s, driven by rising demand from the Korean market (Figure 28). It is one of the most valuable shellfish sectors in Wales, with landings in the Irish Sea increasing by 227% between 2011 and 2016 (Emmerson et al. 2018). After this 10-year high, however, landings declined and vessel numbers fell in 2018 and 2019. This reduction could be due to a combination of factors, including an increase in the minimum landing size for whelk, adverse weather conditions, or declining prices (Welsh Government 2020). While overall effort has generally increased in response to rising market value, it is also important to note that some local fisheries, such as those around the Llŷn Peninsula, operate with a small, stable inshore fleet whose activity is constrained by vessel size, landing logistics and the need to alternate effort across multiple target species.

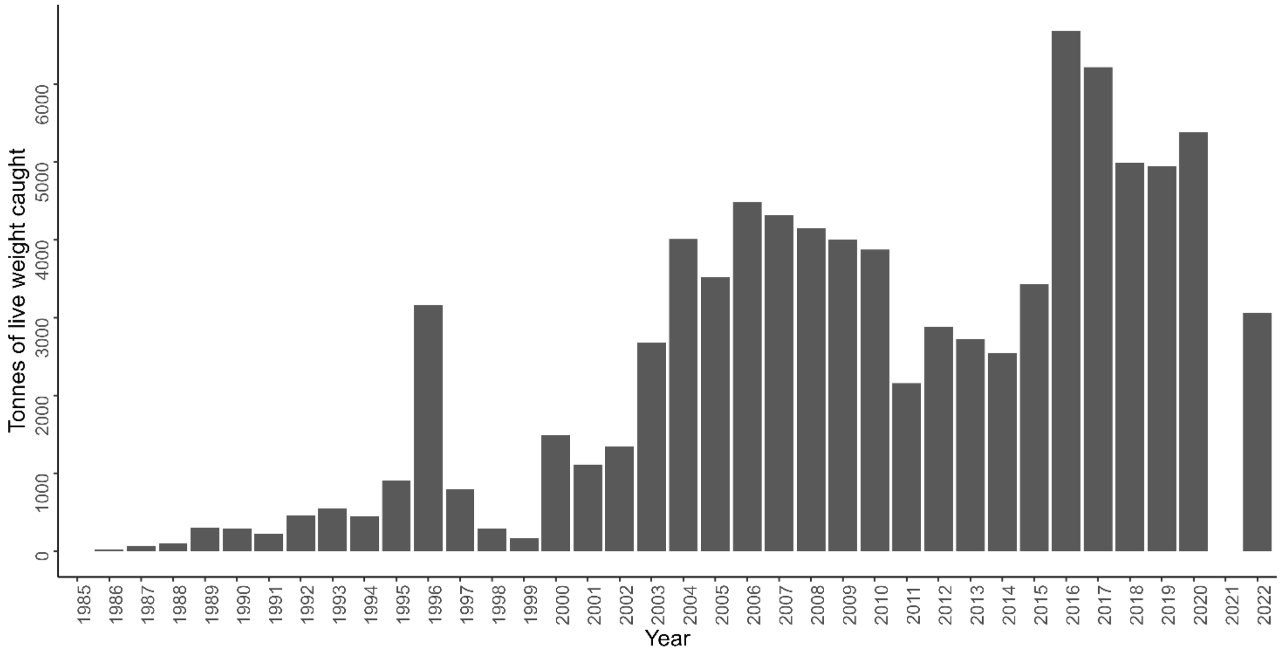


Figure 28: Whelk (*Buccinum undatum*) landings data sourced from International Council for the Exploration of the Sea (ICES) from 1985 - 2022 in the Irish Sea. Landings data are derived from combined reports from England, Wales, Northern Ireland and Scotland (ICES 2025).

While a recent study on the impacts of whelk potting on the *M. Modiolus* reef is available there is limited information on location and intensity of potting for crab and lobster and netting activities on the reef.

The local whelk fishery (approximately 5 under 10 m vessels) regularly targets whelk on the *M. modiolus* reefs, with typically 200 to 300 pots set per vessel each year. Less effort has been recorded on the reef since 2024. A recent study by Clarke et al. 2025 (unpublished) estimated the distribution of whelk potting across the reef between 2017 to 2023 using onboard vessel plotter data from the local fishing fleet, showing the highest fishing effort occurred in the areas of reef with greatest *M. modiolus* density (Figure 29). Previous research also found significantly higher catches of whelk on the reef compared to off-reef habitats (Kent et al. 2016). When compared with the current reef extent mapped using multibeam data (Figure 11), fishing activity appears to coincide with the remaining reef areas.. Although there is no spatial effort data available before 2017, fishers report their distribution of effort has remained broadly consistent for around 30 years (Clarke et al. 2025, unpublished).

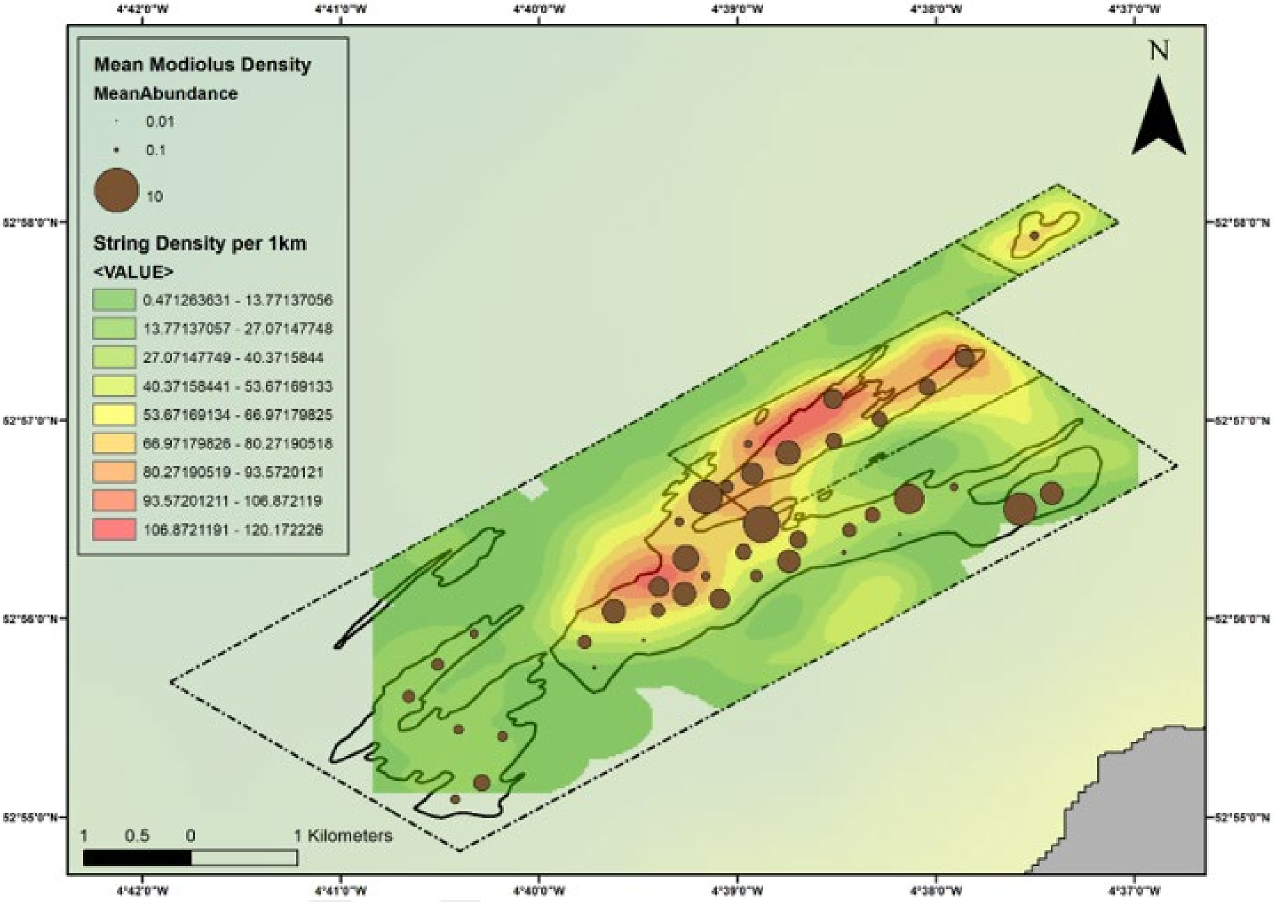


Figure 29: Mean *Modiolus modiolus* densities across the Pen Llŷn a'r Sarnau Special Area of Conservation reef estimated from images across each camera station across 2022 and 2023 surveys in relation to whelk potting effort (string density per 1 km^2) across the reef (between 2017 – 2023). The solid black polygon indicates the reef extent derived from Natural Resources Wales sidescan data (Clarke et al. 2025, unpublished).

Clarke et al. 2025 (unpublished) investigated whelk pot movement and potential impacts on the PLAS SAC reef using accelerometers and acoustic telemetry to quantify pot movement. Pot movements were greatest during prevailing northerly winds. Rees et al. (2021) hypothesised that damage to slow-growing, reef building taxa was due to repeated hauling, deployment and movement of the gear whilst on the seabed due to tidal movements and weather. Clarke et al 2025 (unpublished) confirms pot movement increased related to environmental conditions, however, movements during pot hauling and redeployment were not quantified. Kent (2015) observed strings of pots being dragged for approximately 10 minutes in this area and whelk fishing activities near Ireland have been reported to directly impact *M. modiolus*, with individuals occasionally retrieved in whelk pots (J. Farinas-Franco Pers.comm, 2024). Diver observations within the SAC have also recorded lost or displaced whelk gear on the reef, with ground ropes observed to cut through and abrade the biogenic structure (C. Lindenbaum Pers. comm, 2024).

Clarke et al 2025 (unpublished) calculated the area of seabed impacted by an individual pot in any 24-hr fishing period to be 6.98 m^2 (Figure 29). The experimental pot string was deployed in the latter third of the season (September – November), a period characterised by prolonged periods of adverse weather which may have resulted in an upward bias in the swept-area estimates. Since pots are unlikely to be set on the same area of reef on each deployment, cumulative impacts are challenging to quantify. As the 6.98 m^2 estimate reflects the movement of a single pot, the total area of seabed interacted with during fishing operations would be greater when considering that each of the local vessels routinely fishes several hundred pots on a bi-weekly basis throughout the season, although the behaviour of a full string of pots will differ from that of an individual experimental pot.

To investigate the potential impact of whelk pots on the reef, Clarke et al 2025 (unpublished) conducted a 24-hr experimental pot deployment monitored before and after by divers. Although this detected no significant impact on reef community or structure, there were local depletions of *A. digitatum* (dead man's fingers), *Paguroidea* (hermit crabs) and *Galatheiodea* (squat lobsters), potentially due to mobile species leaving the disturbed area, with damage to *A. digitatum* from abrasion caused by pot movement. Since the deployment was limited in scope (short-term and only possible during neap tides and calm weather), it did not examine impacts associated with repeat hauling and deployment under a range of weather conditions.

The significant decline in reef extent and condition observed during SAC monitoring between 2004 – 2023 overlaps with a period of sustained whelk potting activity in the area, which has been ongoing since the early 1990s (Kent et al. 2016) and forms part of a wider increase in whelk landings across the Irish Sea (ICES 2025). Cumulative stressors, including climate change, may further increase vulnerability as warming seas can weaken shell integrity and reef cohesion, potentially making *M. modiolus* more susceptible to physical disturbance from fishing gear. Conversely, whelks are known predators of *M. modiolus*, and the fishery may be reducing natural predation pressure. These interactions highlight the complexity of ecological pressures acting on the reef and the need for long-term, species-specific research to fully understand the combined effects.

Pressure assessment scores

The sensitivities and evidence described above were used to assess the impact of abrasion/disturbance of the substrate on the surface of the seabed on the PLAS SAC *M. modiolus* reef (Table 5). This assessment relates specifically to whelk potting activity and does not include other seabed-contacting activities (e.g. crustacean potting or static nets), which may exert different levels or types of abrasion pressure.

A timing score of 3 was assigned because the potential increase in this pressure due to whelk potting activity occurred mostly within the time period of the decline. Intensity was assigned 2 reflecting that the pressure from whelk fishing in this area will have been fairly low and stable compared to the all Wales landings data). Frequency was assigned 3 to reflect this was a frequent (may be intermittent but ongoing) pressure and spatial scales was scored 2 since available evidence suggests it would likely have affected part of the site. A high sensitivity score (4) was given to reflect the high vulnerability to surface abrasion/disturbance. The confidence was medium for this assessment due to the lack of available crustacean potting data.

Table 5: Assessment for **abrasion/disturbance of the substrate on the surface of the seabed**. Scores range from 1 (low) to 4 (high). Timing = the likelihood that the pressure occurred during the decline period (2004 – 2023); intensity = the relative magnitude of the pressure; frequency = how often the pressure occurs; spatial scale = the proportion of the feature affected by the pressure; sensitivity = a feature's susceptibility to change and ability to recover under pressure. For detailed definitions, see Table 2.

Timing	Intensity	Frequency	Spatial scale	Sensitivity	Risk	Confidence
3	2	3	2	4	144	Medium

Predation

Definition of pressure: Damage and mortality resulting from the direct feeding of one organism (the predator) on another (the prey).

Sensitivity of species

This pressure was not listed as part of the MarESA sensitivity assessment. It has been included in this investigation due to its potential impact on *M. modiolus* populations.

M. modiolus undergoes rapid growth in the first 4-6 years, reaching an adult size (~35-40 mm), which makes them less vulnerable to predation (Seed and Brown 1978). However, juvenile mussels experience high predation pressure, often resulting in a bimodal population structure with many recently settled individuals and adults, but few or no individuals in between (Bertness and Grosholz 1985). Various predators, including *B. undatum* (common whelk), *Maja brachydactyla* (spider crab), *Pagurus bernhardus* (hermit crab), *Liocarcinus depurator* (harbour crab), *Necora puber* (velvet swimming crab), starfish such as *Asterias rubens* (common starfish), and *Homarus* species (lobster), target juvenile *M. modiolus*. Adult mussels are typically safe from *B. undatum*, which preys on weak or dead individuals (Nielsen 1974). Fish such as cod, plaice, and flounder also consume damaged *M. modiolus* after trawling (Kenchington et al. 2007).

Climate driven increases in sea temperature, have altered plankton dynamics, with a marked decline in copepod abundance and a shift in meroplankton composition in the NE Atlantic in the last 60 years (Schmidt et al. 2020; Holland et al. 2023). While echinoderm, decapod, and cirripede larvae have increased, bivalve larvae have declined. This trend suggests that rising temperatures are increasing the reproductive output of predators like decapods and echinoderms, likely increasing predation pressure on bivalves across all life stages (Kirby et al. 2007, 2008).

Evidence of predation at the PLAS SAC reef

Data collected in June 2023 from the PLAS SAC *M. modiolus* reef indicate limited recruitment over the past two decades and an aging population, although spat were recorded during this sampling. Since regular spat sampling has not been carried out across the reef, there is limited evidence on whether spat settlement is spatially or temporally limited. The presence of spat but lack of recruitment to the adult stock suggests settlement numbers may be too low. This could be due to factors such as low reproductive output, reduced connectivity or high larval mortality. Alternatively there could have been an increase in predation on the recently settled juveniles, increasing post-settlement mortality. The breakdown of the reef could be exacerbating predation pressure by reducing refuge availability. Additionally it is important to consider whether there have been increases in predator species.

M. modiolus reefs are biodiversity hotspots with significantly higher abundances of *B. undatum* and *M. brachydactyla* compared to off-reef habitats (Kent et al. 2016). It may be less likely that *B. undatum* numbers have increased due to the active whelk fishery, although baited pots may attract more predators to the reef. There is no available evidence on this. Anecdotal evidence suggests a large increase in the abundance of *M. brachydactyla* around Llŷn Peninsula in the last 20-30 years driven by climate change (Pantin et al. 2015; *Pers comm*). Mytilids have been found in the stomachs of *M. brachydactyla* and they have been observed eating previously opened *M. edulis*. Their diet is influenced by prey availability, consuming more algae in shallow waters and bivalves, crustaceans, polychaetes, sponges and echinoderms in deeper water (Bernárdez et al. 2000). Reports from Normandy and Brittany indicate that high numbers of *M. brachydactyla* are depleting *M. edulis* stocks impacting the fishery suggesting high numbers off the Llŷn could impact the reef. Conversely, *M. brachydactyla* are used as bait in whelk pots so it is possible numbers are regulated by this activity (Kent et al. 2016). However, there is no available data to quantify these impacts.

It is also possible that historic declines of other species such as *Squalus acanthias* (spurdog), a key predator of pelagic fish but also crustaceans during the 1960-1980s, may have had indirect impacts on reef ecology. For example, a reduction in spurdog would likely have released predation pressure on crustaceans, potentially allowing their populations to increase and indirectly intensifying predation on *Modiolus* juveniles. Such trophic cascades remain poorly understood but could be an important factor influencing recruitment failure.

Pressure assessment scores

The sensitivities and evidence described above were used to assess the impact of predation on the PLAS SAC *M. modiolus* reef (Table 6). A timing score of 2 was assigned because this is an ongoing pressure with no strong evidence of an increase in this pressure during the time period. Intensity was assigned 2 reflecting the presumed low intensity impact of predation. Frequency was assigned 3 to reflect the ongoing pressure and spatial scales was scored 4 since available evidence suggests it would likely have affected the whole site. A medium sensitivity score (3) was given to reflect the moderate vulnerability to predation. The confidence was low for this assessment due to the limited availability of supporting literature and data.

Table 6: Assessment for **predation**. Scores range from 1 (low) to 4 (high). Timing = the likelihood that the pressure occurred during the decline period (2004 – 2023); intensity = the relative magnitude of the pressure; frequency = how often the pressure occurs; spatial scale = the proportion of the feature affected by the pressure; sensitivity = a feature’s susceptibility to change and ability to recover under pressure. For detailed definitions, see Table 2.

Timing	Intensity	Frequency	Spatial scale	Sensitivity	Risk	Confidence
2	2	3	4	3	144	Low

Ocean acidification

Definition of pressure: The process by which increased atmospheric CO_2 is absorbed by seawater, leading to a reduction in pH, changes in carbonate chemistry, and potential harm to marine organisms, particularly calcifiers.

Sensitivity of species

The sensitivity assessment (MarESA, Marlin.ac.uk) classified *M. modiolus* resistance to ocean acidification as "no-evidence" with resilience rated as "no-evidence" and overall sensitivity as "no-evidence" (MarLin).

Ocean acidification has caused an approximately 30% drop in pH from around 8.2 to 8.1 since pre-industrial times. However, there is limited evidence of ocean acidification impacting marine organisms or processes around the UK and north-east Atlantic. There are few long-term high-quality observational time series of both chemical and biological data to identify biological changes (Findlay et al. 2022). It is also thought that current levels of acidification may not cause direct observable changes. In general it is thought that bivalves such as *M. modiolus* are at increased risk as they are calcifying organisms. Early-life stages (larvae and embryos) are potentially the most susceptible to reduced pH levels and aragonite saturation state (a measure of how favourable seawater conditions are for forming calcium carbonate shells). Studies have observed impacts such as a reduction in fertilization success, hatching rate, growth, metamorphosis and survival at near-future acidification (Tan and Zheng 2020; Leung et al. 2022). Evidence suggests juvenile and adult bivalves are more tolerant, though reduction in growth, feeding and shell strength have also been observed (Leung et al. 2022). As a long-lived species, *M. modiolus* are likely at higher risk than shorter lived bivalves due to their low adaptive capacity. There is only one direct study on the physiological impacts of ocean acidification on *M. modiolus* (Lopes 2012). After 40 days at current and future Intergovernmental Panel on Climate Change (IPCC) predicted pH levels, there were no observed differences in respiration rates and somatic growth. The individuals used in this study were collected from the PLAS SAC reef. However this study was limited in scope and duration. For example, it did not investigate other impacts such as shell strength or reproductive trade-offs, and could not capture longer-term impacts due to running little more than 1 month.

Evidence of ocean acidification at the PLAS SAC reef

There is a lack of multi-decadal chemical and biological time-series measurements in the UK to link observable changes in biology to ocean acidification (Findlay et al. 2022). The earliest data in the time-series from the Stonehaven (northeast Scotland) and Western Channel Observatory (L4 and E1) (southwest England) recording stations starts in 2008, after monitoring began and the decline in *M. modiolus* was first recorded at the PLAS SAC reef (Figure 30). There is no available direct evidence on the impact of ocean acidification at the PLAS SAC reef. Studies suggest that near future conditions could result in reef breakdown through reduction in byssus strength (Zhao et al. 2017), failures in settlement and recruitment (Tan & Zheng 2020, Leung et al. 2022) and vulnerability of adults as a result of weaker shells (Fitzer et al. 2015).

There has only been one direct study into the effect of pH on *M. modiolus* from the PLAS SAC reef. No impact was observed on adult *M. modiolus* though it was a limited and short-term study, and other life stages were not included.

Ocean acidification is one of a suite of pressures driving potential change at the *M. modiolus* reef, but there are not enough data or evidence to attribute this to the current observed decline. This is likely a future risk especially to early-life stages.

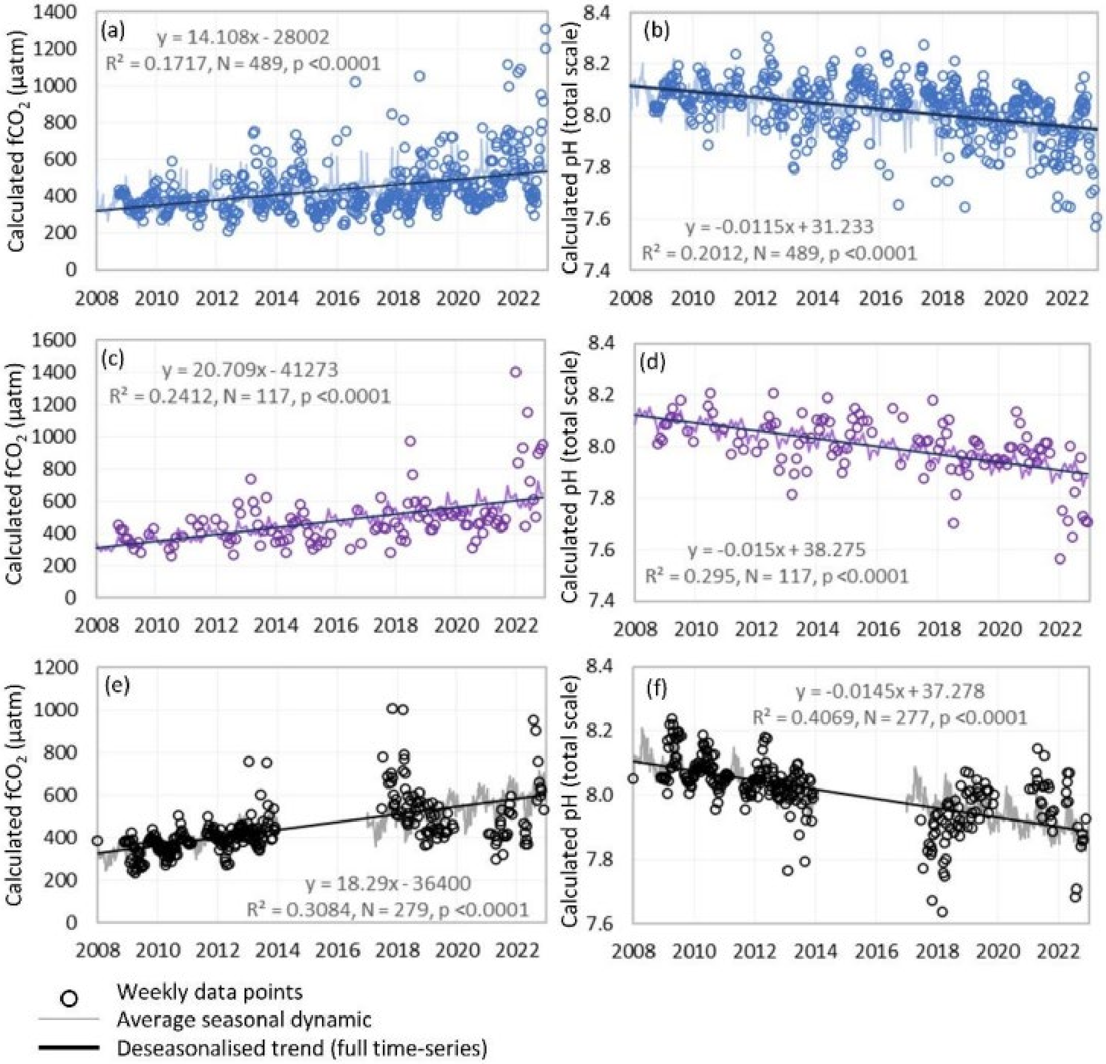


Figure 30: Time–series data (open circles) for Western Channel Observatory (WCO) L4 (a and b), E1 (c and d) and Stonehaven (e and f) showing surface water fCO2 (a, c and e) and pH (b, d and f). Both values are calculated from measured dissolved inorganic carbon and total alkalinity. Average seasonal trends are shown by the thin coloured lines (blue, purple, grey); and the average trends for each full time–series are shown by the lines of best fit (thick black lines). Note the y-axis scales differ between subplots. (Taken from Findlay et al. 2025)

Pressure assessment scores

The sensitivities and evidence described above were used to assess the impact of ocean acidification on the PLAS SAC *M. modiolus* reef (Table 7). A timing score of 2 was assigned because this pressure would likely occur mostly outside the time period. Intensity was assigned 1 reflecting the current very low intensity impact of ocean acidification. Frequency was assigned 3 to reflect the ongoing pressure and spatial scale was scored 4 since it would affect the whole site. A low sensitivity score (2) was given to reflect the low vulnerability to ocean acidification. The confidence was medium for this assessment due to the limited availability of supporting literature and data.

Table 7: Assessment for **ocean acidification**. Scores range from 1 (low) to 4 (high). Timing = the likelihood that the pressure occurred during the decline period (2004 – 2023); intensity = the relative magnitude of the pressure; frequency = how often the pressure occurs; spatial scale = the proportion of the feature affected by the pressure; sensitivity = a feature's susceptibility to change and ability to recover under pressure. For detailed definitions, see Table 2.

Timing	Intensity	Frequency	Spatial scale	Sensitivity	Risk	Confidence
2	1	3	4	2	48	Medium

Introduction of parasites/microbial pathogens

Definition of pressure: The introduction of relevant microbial pathogens or metazoan disease vectors to an area where they are currently not present (e.g. *Martelia refringens* and Bonamia, Avian influenza virus, viral Haemorrhagic Septicaemia virus)

Sensitivity of species

The sensitivity assessment (MarESA, Marlin.ac.uk) classified *M. modiolus* resistance to introduction of parasites/microbial pathogens as "no-evidence" with resilience rated as "no-evidence" and overall sensitivity as "no-evidence" (Tillin, H.M and Tyler-Walters, H. 2015).

Evidence on pathogens and parasites that affect *M. modiolus* is limited. The most commonly observed parasites are pea crabs (*Pinnotheres sp.*) which are well-known for their parasitic relationship with bivalves. These have been recorded in *M. modiolus* with a 2 - 47% infestation level (Brown and Seed 1977; Becker and Türkay 2017). Studies on the impacts of pea crabs on their host are limited with some evidence that host growth is reduced. For example, New Zealand green-lipped mussels infected with pea crabs were 30% smaller in total weight (Trottier et al. 2012) and *M. edulis* growth was reduced after long-term infestation(Bierbaum and Ferson 1986). There are no studies on the impacts to *M. modiolus*. Additionally, the boring sponge, *Cliona intestinalis*, has been described as infesting ageing populations of *M. modiolus,* resulting in damage to around 20% of individuals (Comely 1978). The sponge weakens shells increasing vulnerability to physical impacts.

As filter feeders, bivalves may accumulate high number of potential viral, bacterial and protozoan pathogens that have been attributed to major mortalities. For example the oyster herpes virus has been attributed to the mass mortality of oysters around the world and the protozoan pathogen *Marteilia refringens* has been identified as causing mass mortalities in *Ostrea edulis* and *Mytilus edulis* in Europe (Zannella et al. 2017; Kerr et al. 2018; Charles et al. 2020). There is sparse evidence available for *M. modiolus* with one unpublished study reporting infections with *Marteilia refringens* or other *Marteilia* sp. though no indication of its pathogenicity (Bower et al. 1994). *Modiolus barbatus* was found to contain three pathogenic species (*Gymnophallus* sp., *Nematopsis* sp. and a haplosporidian), although their pathological risk was assessed to be very low (Mladineo 2008).

The most significant impacts observed for *M. modiolus* come from pathogenic algae. A bloom of the dinoflagellate *Gonyaulax tamarensis,* a paralytic shellfish poisoning (PSP) toxin, was identified as being highly toxic to *M. modiolus* (Shumway 1990) and the parasitic microalgae *Coccomyxa sp.* has been linked to a reduction in their reproductive output (Vaschenko et al. 2013).

Evidence of parasites/microbial pathogens at the PLAS SAC reef

In 2023, *M. modiolus* samples were collected from the reef to assess its health. During dissections, a very high *Pinnotheres sp.* infestation rate was noted with 80% of mussels over 25 mm containing 1 or 2 individuals (Figure 31). There are no previous records for comparison from the PLAS SAC reef with the only other data available for the Irish Sea from 50 years earlier. This study found much lower (ca 2%) infestation (Brown and Seed 1977). There are no studies on the impacts of this association on *M. modiolus,* though as mentioned above, work on other bivalves suggests they could limit growth. However, these observations were noted for shorter lived species, so perhaps not applicable to the long-lived *M. modiolus*. In addition, while limited growth alone is unlikely to have caused the observed decline, infestation may weaken mussels, making them more vulnerable to other pressures such as predation. Alternatively, ageing or physiologically stressed mussels maybe be more susceptible to hosting *Pinnotheres spp.,* so their presence may serve as a potential indicator of host condition. Further research is needed to understand this relationship and possible impacts of *Pinnotheres sp.* infestation on *M. modiolus*.

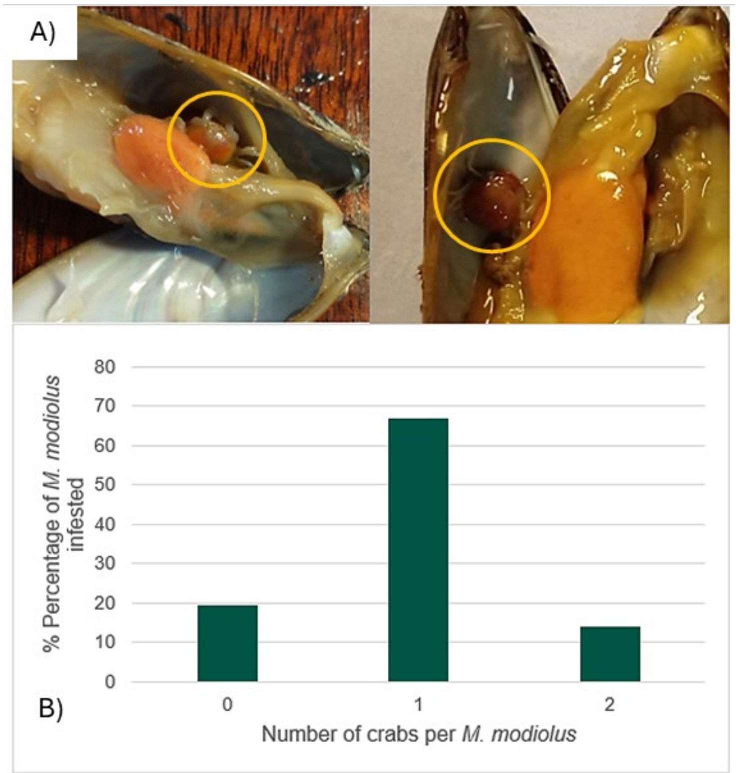


Figure 31: a) *Pinnotheres sp*. (pea crab) inside *Modiolus modiolus* shown by yellow circles; b) Percentage infestation of *M. modiolus* with none, 1 or 2 *Pinnotheres sp*. from the Pen Llŷn a'r Sarnau Special Area of Conservation reef.

In addition to these dissections, a small sample (n=19) of *M. modiolus* were screened for several potential bivalve pathogenic diseases by Bangor University. This was a preliminary study that aimed to establish a methodology to identify microbial pathogens in *M. modiolus* and screened the samples for several potential bivalve pathogenic diseases. The pathogens that were tested for were oyster herpes virus and some of the most important protozoan pathogens: *Haplosporidia*, *Urosporidium* and *Perkinsus* spp. These were tested for by extracting DNA and using quantitative Polymerase Chain Reaction (qPCR) analysis followed by family-specific PCR assays to detect the specific genera of parasites (Table 8).

Table 8: Results from the family-specific Polymerase Chain Reaction (PCR) analysis on *Modiolus modiolus* samples, from the Pen Llŷn a'r Sarnau Special Area of Conservation reef, showing seven samples were positive for oyster herpes virus, eight were positive for *Haplosporidia spp*, 12 for *Urosporidium spp* and five samples for *Perkinsus spp*. The bryozoan sample was taken from an encrusting bryozoan on a *M. modiolus* shell.

P: positive

N: negative

Sample ID	**Sample type**	**DNA concentration in extract (ng/µl)**	**Oyster herpes virus**	***Haplosporidia***	***Urosporidium***	***Perkinsus***
S1	*Modiolus*	288	N	P	P	N
S2	*Modiolus*	260	N	P	P	N
S3	*Modiolus*	436	N	N	P	P
S4	*Modiolus*	296	P	P	P	P
S5	*Modiolus*	170	N	P	P	N
S6	*Modiolus*	437	N	N	N	N
S7	*Modiolus*	506	P	P	N	P
S8	*Modiolus*	476	N	P	P	N
S9	*Modiolus*	322	N	N	N	N
S10	*Modiolus*	416	N	N	N	N
S11	*Modiolus*	288	P	P	P	P
S12	*Modiolus*	189	N	P	N	N
S13	*Modiolus*	918	P	N	N	N
S14	*Modiolus*	14.7	P	N	N	N
S15	*Modiolus*	210	P	N	P	P
S16	*Modiolus*	17.1	P	N	P	N
S17	*Modiolus*	198	N	N	P	N
S18	*Modiolus*	502	N	N	P	N
S19	*Modiolus*	552	N	N	P	N
S20	Bryozoan	120	N	N	N	N

PCR testing of *M. modiolus* found seven samples positive for oyster herpes virus, eight for *Haplosporidia* spp., 12 for *Urosporidium* spp., and five for *Perkinsus* spp. Sanger sequencing was then carried out on the strongest PCR products. Results were mixed, with some samples showing non-specific signals or high background noise, suggesting multiple species were present. However, *Minchinia* spp. was confirmed in four of six *Haplosporidia* samples, and the hyperparasite *Urosporidium crescens* was found in one of the two *Urosporidium* samples. Sequencing for *Perkinsus* was inconclusive, likely due to the presence of more than one species (Table 9)

Table 9: Sanger sequencing performed on the amplicons of the Polymerase Chain Reaction (PCR) reactions targeting *Haplosporidia*, *Urosporidium* and *Perkinsus spp*.

Sample ID	**DNA concentration (ng/µl)**	**Target family/genus**	**Sequencing quality**	**Genus/species (Identity)**
S1	18.9	*Haplosporidia*	Good quality	*Minchinia mytili/chitonis* (91.5%)
S2	9.06	*Haplosporidia*	Good quality	*Minchinia mytili/chitonis* (94%)
S4	16.7	*Haplosporidia*	Good quality	*Minchinia tapetis* (98%)
S8	14.9	*Haplosporidia*	Good quality	*Minchinia mytili/chitonis* (92-94%)
S11	14.9	*Haplosporidia*	Non-specific	*Haplosporidium* sp.
S17	3.02	*Urosporidium*	Non-specific	No significant similarity found
S18	1.93	*Urosporidium*	Good quality	*Urosporidium crescens* (84%)
S3	3.62	*Perkinsus*	Early termination	No significant similarity found
S4	2.76	*Perkinsus*	High background noise	No significant similarity found
S15	3.88	*Perkinsus*	Good quality	No significant similarity found

The preliminary data suggests this methodology is suitable for the identification of microbial pathogens in shellfish. However, the detection of the pathogens does not indicate infection. Further work would be needed to understand their pathogenicity to *M. modiolus*.

As described in Farkas et al. (2024, unpublished) *Minchinia* spp. mainly affects oysters and can cause up to 80% mortality in oysters (Bearham et al. 2008). It has been found in *M. edulis* and *Cerastoderma edule* but not *M. modiolus* (Ward et al. 2019; Lynch et al. 2020). *Urosporidium crescens*, a parasite of trematodes with a wide host range, could potentially infect *M. modiolus*, though this has not been observed (Couch 1974; Le et al. 2015). Bonamia, another genera of *Haplosporidia*, responsible for major oyster losses worldwide, was absent from *M. modiolus* but recorded in *M. edulis* in the nearby Menai Strait in 2011 (Lynch et al. 2014).

The only shellfish-associated bacterium found was *Mycobacterium* spp., which can cause severe disease and mass mortality in bivalves (Davidovich et al. 2020). Human-associated bacteria, including *Pseudomonas aeruginosa* and *Lactobacillus johnsonii*, were also present, suggesting possible sewage contamination. Most other microbes were likely harmless, free-living species.

Although *M. refringens* (mentioned previously) infects a wide range of bivalves, including mytilids, to date it has not been detected in animals in the Irish Sea (though is spreading northwards), and was not screened for in this study (Rowley et al. 2014).

Future analysis of samples over time is recommended to identify reoccurring genera and a subsequent typing using PCR/Sanger sequencing to assess bacterial diseases. Comparable disease screening at other *M. modiolus* sites, including beds that are not currently declining, would also help determine whether the North Llŷn population differs from patterns observed elsewhere. Further work is also needed to quantify and determine the pathogenicity of diseases to *M. modiolus*. Currently, evidence on the pathogenicity of common bivalve diseases on *M. modiolus* is limited. Although increases in seawater temperature have been linked to disease outbreaks in bivalves (Ward and Lafferty 2004; Malham et al. 2009; Carballal et al. 2020) it remains unclear whether these factors are contributing to the current decline of *M. modiolus* at the PLAS SAC. Climate change may increase disease prevalence, but targetted research is needed to understand the specific impacts of pathogens and parasites on *M. modiolus*, particularly under future climate scenarios.

Pressure assessment scores

The sensitivities and evidence described above were used to assess the impact of parasites/microbial pathogens on the PLAS SAC *M. modiolus* reef (Table 10). A timing score of 2 was assigned because this pressure would likely occur mostly outside the time period. Intensity was assigned 1 reflecting the current very low intensity impact of parasites/microbial pathogens. Frequency was assigned 2 to reflect the likely infrequent pressure during the time period and spatial scale was scored 2 since it would likely affect part of the site. A low sensitivity score (2) was given to reflect the low vulnerability to parasites/microbial pathogens. The confidence was low for this assessment due to the limited availability of supporting literature and data.

Table 10: Assessment for **parasites/microbial pathogens**. Scores range from 1 (low) to 4 (high). Timing = the likelihood that the pressure occurred during the decline period (2004 – 2023); intensity = the relative magnitude of the pressure; frequency = how often the pressure occurs; spatial scale = the proportion of the feature affected by the pressure; sensitivity = a feature's susceptibility to change and ability to recover under pressure. For detailed definitions, see Table 2.

Timing	Intensity	Frequency	Spatial scale	Sensitivity	Risk	Confidence
2	1	2	2	2	16	Low

Smothering and siltation rate changes (Light)

Definition of pressure: ‘Light’ (deposition of up to 5 cm) of fine material added to the seabed in a single, discrete event

Sensitivity of species

The sensitivity assessment (MarESA, Marlin.ac.uk) classified *M. modiolus* resistance to Smothering and siltation changes as "medium-high" with resilience rated as " medium-high" and overall sensitivity as " medium-high" (Tillin, H.M and Tyler-Walters, H. 2015).

Studies have shown *M. modiolus* as vulnerable to burial and the effects of suspended particulate matter (SPM). Following bottom trawling in Strangford Lough, mass accumulation rates of 0.63 ± 0.09 g cm^2 $year^{-1}$, were recorded and proposed as a possible driver of negative effects on the physiological health of the remaining *M. modiolus* populations (Strong and Service 2008). Hutchinson et al. (2016) showed that *M. modiolus* faces significant mortality under sediment burial, with survival rates decreasing dramatically as burial duration increases. In tank experiments they survived burial for up to 8 days but faced over 50% mortality after 16 days, particularly in finer sediments (i) Mortality of *M. modiolus* under sediment burial of variable durations (from Hutchinson et al. 2016) ii) (a) Mean and (b) maximum gape angle, and (c) proportion of time spent open for *M. modiolus* exposed to high (194 mg l-1), low (33 mg l-1) and control (5 mg l-1) levels of suspended particulate matter for a 6 hour period. Error bars represent 95 % confidence interval, means with different letters are significantly different (Tukey HSD: $p < 0.05$, from Clegg 2014).Figure 32). Unlike *Mytilus edulis*, *M. modiolus* had limited ability to emerge from burial, especially without hydrodynamic assistance, making it more susceptible to long-term sediment disturbances such as those caused by dredging and trawling activities. Temperature also exacerbated mortality, with higher temperatures leading to greater mortality rates (10% at 8°C to more than 60% from 14.5°C).

Exposure to varying concentrations of suspended particulate matter (SPM) also negatively impacts the behaviour of *M. modiolus*, reducing its shell gape and the time spent open (Clegg 2014) (Figure 32). The SPM concentrations used in Clegg, 2014, were determined using a sediment plume model simulating suspended sediments in the wake of a scallop dredge. This was adapted to environmental conditions on the North Llŷn Peninsula. Findings indicated that trawling at 10 m from the reef would have severe impacts on *M. modiolus*, causing complete shell closure for the duration of exposure. At 50 m varied responses were recorded with an overall negative effect observed. More research is needed to extend the duration of the study and increase understanding of the impacts to *M. modiolus* and how these sediments settle out.

The impacts of sediments on *M. modiolus* will be related to the hydrodynamics of the site. In areas with strong tidal flows where some *M. modiolus* beds are located, silt deposits can be cleared away relatively quickly, although some sediment will still become lodged in crevices and gaps. In contrast, in areas with weaker currents, such as in sheltered lochs where beds occur, sediment removal happens more slowly, and the resulting impacts can be more severe.

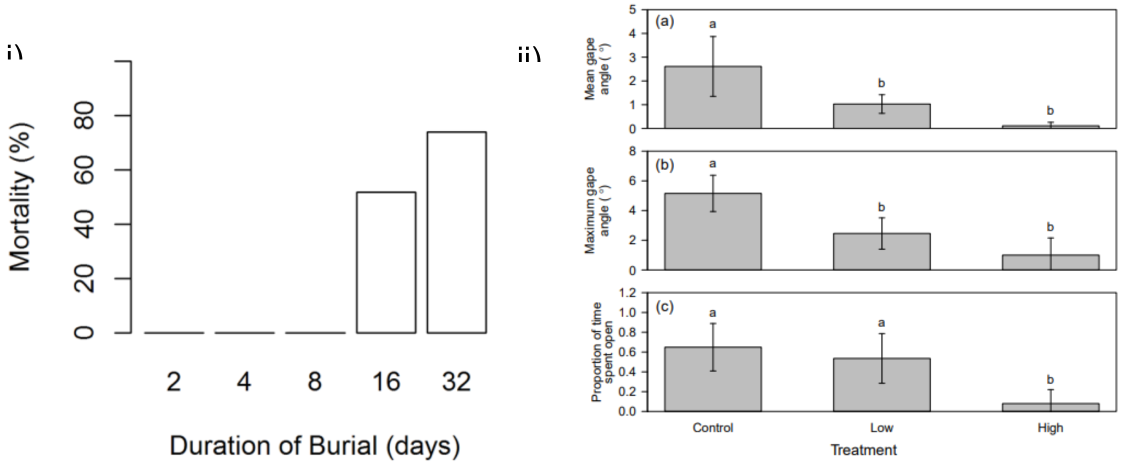


Figure 32: Effects of suspended materials on *Modiolus modiolus:* i) Mortality of *M. modiolus* under sediment burial of variable durations (from Hutchinson et al. 2016) ii) (a) Mean and (b) maximum gape angle, and (c) proportion of time spent open for *M. modiolus* exposed to high (194 mg l-1), low (33 mg l-1) and control (5 mg l-1) levels of suspended particulate matter for a 6 hour period. Error bars represent 95 % confidence interval, means with different letters are significantly different (Tukey HSD: $p < 0.05$, from Clegg 2014).

Evidence of smothering and siltation rate changes at the PLAS reef

The PLAS SAC reef is situated in an area with strong tidal flow (1.25 ms $^{-1}$), meaning silt deposits are likely removed rapidly, reducing sedimentation impacts. *M. modiolus* normally bind and stabilise sediments but in parts of the reef where losses have occurred, this stabilising effect has reduced. As a result, sediment and dead shells have become more mobile, and the abundance of reef-associated epibiota has declined, observed through diver-held and drop-down video footage and stills (Jackson-Bué et al. 2025). The stable hard substrata, created by the binding action of *M. modiolus* byssal-threads is no longer present, preventing reef-associated species from settling, as they are now scoured away by the movement of loose shells. The silty element of the reef, thought to be a combination of mussel pseudo-faeces and trapped silty sediments, has also greatly reduced removing the community it once supported. There is, however, no evidence that this sediment has smothered live *M. modiolus* or that sedimentation directly caused the observed decline. It is possible that a sedimentation event that lasted more than 8 days could have occurred and caused mortalities with the sediment subsequently being swept away, but there is no available data to determine this. In addition, a recent modelling study for the area suggests that sediment mobility is generally limited, indicating that smothering and siltation from natural processes are unlikely to be a significant pressure at this site (Coughlan et al. 2021).

Since 2012 a 350 m buffer zone was designated around the reef to prevent sedimentation from mobile fishing gears. It is therefore unlikely fishing activity related sedimentation could have occurred. There are no dredging or disposal grounds near the reef. If aggregate extraction were to occur within this potential resource area, it would require a marine licence application, which may include a Habitats Regulations Assessment (HRA) to ensure compliance with environmental protection requirements.

There is no available evidence to indicate that smothering and siltation changes caused the observed decline.

Pressure assessment scores

The sensitivities and evidence described above were used to assess the impact of smothering and siltation rate changes on the PLAS SAC *M. modiolus* reef (Table 11). A timing score of 1 was assigned because this pressure would have occurred outside the time period. Intensity was assigned 2 reflecting the low intensity impact of smothering and siltation rate changes. Frequency was assigned 1 to reflect the likely infrequent pressure during the time period and spatial scale was scored 2 since it would likely affect part of the site. A high sensitivity score (4) was given to reflect the high vulnerability to smothering and siltation rate changes. The confidence was medium for this assessment due to the limited availability of supporting literature and data.

Table 11: Assessment for **smothering and siltation rate changes**. Scores range from 1 (low) to 4 (high). Timing = the likelihood that the pressure occurred during the decline period (2004 – 2023); intensity = the relative magnitude of the pressure; frequency = how often the pressure occurs; spatial scale = the proportion of the feature affected by the pressure; sensitivity = a feature’s susceptibility to change and ability to recover under pressure. For detailed definitions, see Table 2.

Timing	Intensity	Frequency	Spatial scale	Sensitivity	Risk	Confidence
1	2	1	2	4	16	Medium

Introduction or spread of invasive non-native species (INNS)

Definition of pressure: The introduction of one of more invasive non-native species (INNS)

Sensitivity of species

The sensitivity assessment (MarESA, Marlin.ac.uk) classified *M. modiolus* resistance to introduction or spread of invasive non-indigenous species as "low" with resilience rated as "very low" and overall sensitivity as "high" (MarLin).

There are two high risk INNS present in Wales that could potentially impact the *M. modiolus* reef. The carpet sea squirt, *Didemnum vexillum* and the American slipper limpet, *Crepidula fornicata*.

D. vexillum is an invasive colonial ascidian that is present in Holyhead marina and Milford Haven in Wales. It is considered an "ecosystem engineer" due to its ability to alter habitats and biodiversity. There is no evidence of impacts to *M. modiolus*. However, in Strangford Lough and the Gulf of Maine, it has been observed overgrowing mussels. It can severely impact bivalves by smothering them, negatively affecting growth and shell thickness and causing mortality. There is also some evidence that overgrowth of *D. vexillum* on mussels can reduce predation risk (Auker 2010).

C. fornicata is an invasive mollusc present in the UK since the 1870s. There is no evidence of its impacts to *M. modiolus* though it can colonize a wide range of substrate and is an epibiont to several commercially important shellfish species including *M. edulis*. *C. fornicata* is highly fecund and has large larval dispersal distances suggesting even distant mussel beds can be at risk. It has been reported to reduce growth and survival in *M. edulis* *(*Thieltges 2005), modify benthic community structure (e.g. Preston et al. 2019) and change sediment composition, increasing fine sediments through production of pseudofaeces (Blanchard1997). Additionally, *C. fornicata* forms stacks which are thought to increase drag and energy requirements for attachment, which might result in clumps of mussels being removed in high water flow. High densities reduces space for other organisms to settle, increase competition for food, and consumes larvae of macrobenthic organisms, potentially impacting recruitment to the area (Blanchard 1997).

Evidence of introduction or spread of invasive non- native species (INNS) at the PLAS reef

In 2023, samples were collected from the reef to assess its health. A single *C. fornicata* (33 mm in length) was found in 5 cleared quadrats taken from a central area of the reef. This is the first record of *C. fornicata* at the PLAS *M. modiolus* reef. Fishers from nearby Porthdinllaen have also been finding *C. fornicata* stacks on *B. undatum* from the north Llŷn area (Figure 33). Records have been increasing locally in Caernarfon Bay and the Menai Strait in recent years, with a marked increase in reported occurrences since 2020. There is a now an established population in the western Menai Strait with intertidal records first being noted in 2020. There has also been a record near Holyhead though this was on a scallop shell which could have been discarded from a vessel and might not be resident in that area.

Figure 33: *Crepidula fornicata* stacks on *Buccinum undatum* collected near the Pen Llŷn a'r Sarnau Special Area of Conservation reef (images courtesy of Charlotte Colvin, Bangor University).

There have been no records of *D. vexillum* from the reef, despite its prevalence at Holyhead Marina (~50 km north of the PLAS reef).

The presence of *C. fornicata* within the *M. modiolus* reef is cause for concern for the future. Though there is no evidence of its impacts on *M. modiolus* it can have severe impacts on other bivalve reefs. Numbers are increasing rapidly in the area and future monitoring should include *C. fornicata* surveys. There is no evidence to suggest INNS as a cause for the current decline.

Pressure assessment scores

The sensitivities and evidence described above were used to assess the impact of introduction or spread of invasive non- native species (INNS) on the PLAS SAC *M. modiolus* reef (Table 12). A timing score of 2 was assigned because this pressure occurred mostly outside the time period. Intensity was assigned 1 reflecting the low intensity impact at this time. Frequency was assigned 1 to reflect the likely infrequent pressure during the time period and spatial scale was scored 1 since it would likely affect a small part of the site. A medium sensitivity score (3) was given to reflect the potential vulnerability to the introduction or spread of invasive non-native species (INNS). The confidence was medium for this assessment due to the limited availability of supporting literature and data.

Table 12: Assessment for **introduction or spread of invasive non- native species (INNS)**. Scores range from 1 (low) to 4 (high). Timing = the likelihood that the pressure occurred during the decline period (2004 – 2023); intensity = the relative magnitude of the pressure; frequency = how often the pressure occurs; spatial scale = the proportion of the feature affected by the pressure; sensitivity = a feature's susceptibility to change and ability to recover under pressure. For detailed definitions, see Table 2.

Timing	Intensity	Frequency	Spatial scale	Sensitivity	Risk	Confidence
2	1	1	1	3	6	Medium

Summary of pressures

Table 13: Pressures spreadsheet summary table. Pressures assessed in this report ranked from highest to lowest risk of causing the decline at the Pen Llŷn A'r Sarnau Special Area of Conservation (PLAS SAC) *M. modiolus* reef.

Pressure	Risk	Confidence
Ocean warming	256	High
Penetration and/or disturbance of the substrate below the surface of the seabed, including abrasion	192	High
Abrasion/disturbance of the substrate on the surface of the seabed	144	Medium
Predation	144	Low
Ocean acidification	48	Medium
Introduction of parasites/microbial pathogens	16	Low
Smothering and siltation rate changes (Light)	16	Medium
Introduction or spread of invasive non-native species (INNS)	6	Medium

Discussion

Importance of the PLAS *M. modiolus* reef and background

The PLAS SAC *M. modiolus* reef and the additional bed located off Porthdinllaen are Wales' most extensive *M. modiolus* beds, and represent the most southerly extent of reef formation within the species' range (Lindenbaum et al. 2008; Gormley et al. 2015a). These rare biogenic reef habitats support high biodiversity and provide essential habitats for species of ecological and commercial importance (Kent et al. 2017). Due to their sensitivity, slow recovery, and vulnerability to environmental and human pressures, *M. modiolus* reefs have declined across their range and are now conservation priorities protected under multiple national and international frameworks (Dinesen and Morton 2014; Brash et al. 2018).

The PLAS SAC reef, estimated to be over 150 years old and covering ~4 km², has shown signs of deterioration since monitoring began in 2004. Its designation as an SAC feature under the Conservation of Habitats and Species Regulations 2017 highlights its ecological value and the need for continued protection and management (Lindenbaum et al. 2008).

Connectivity studies suggest the PLAS SAC reef is part of a wider Irish Sea metapopulation, with genetic links to populations in Northern Ireland and the Isle of Man (Gormley et al. 2015a). Larval dispersal modelling indicated potential connectivity up to 150 km, though discrepancies between genetic and dispersal data highlight the need for further research. To address this, a new genetic study (NRW, ATU, Heriot-Watt) is underway including additional sites, to refine understanding of gene flow and identify source/sink populations, with results expected in 2026. This will support future restoration and management of the reef and associated MPAs.

Monitoring data and ongoing reef decline

Monitoring of the PLAS SAC *M. modiolus* reef since 2004 has identified a significant and ongoing decline in reef health and extent with the reef assessed as being in "unfavourable" condition in both the 2018 and 2025 SAC condition assessments (NRW 2018; Jackson-Bué et al. 2025). Live mussel densities have dropped sharply at the monitoring sites, and the internal structure has also reduced with the characteristic bioherm wave forms generally flattening out across the reef. Reef extent has declined by over 60% from 3.88 km² in 2005 to 1.47 km² in 2024, with fragmentation and central bed losses accelerating between 2015 and 2024. DDV surveys in 2022 and 2023 confirmed that areas with higher *M. modiolus* density still support greater biodiversity, but these areas are now more limited. Population analysis in 2023 showed limited juvenile recruitment and an aging population, shaped by three historic cohorts (1988, 1998, 2003). Although recent spat settlement was observed, recruitment success remains uncertain.

The lack of recovery and ongoing decline suggests that either the pressures are ongoing, for example, as the population is at its southern range and recruitment may be limited due to climate change, or that a tipping point was reached as a result of historic impacts with no recovery and continued decline observed.

Potential drivers of decline and ongoing pressures

Eight pressures relevant to the PLAS SAC *M. modiolus* reef were identified through the pressures assessment. These can be grouped into three categories, with the highest-risk pressures highlighted in bold:

1. Historic Pressures (from previous bottom towed fishing activity)
    - **Penetration/disturbance of the seabed below the surface (including abrasion)**
    - Smothering and siltation rate changes (light)
2. Ongoing and Potentially Increasing Pressures
    - **Ocean warming**
    - **Surface abrasion/disturbance**
    - **Predation**
3. Emerging Future Pressures
    - Ocean acidification
    - Introduction of parasites or microbial pathogens
    - Invasive non-native species (INNS)

Taken together, these pressures highlight a complex set of interacting factors likely contributing to the decline of the PLAS SAC *M. modiolus* reef. Long-term ocean warming is likely to be a major underlying driver, reducing resilience, recruitment, and structural integrity. Historic mobile-gear abrasion and penetration may also have left the reef weakened, making it more vulnerable to subsequent pressures. Ongoing low-intensity seabed-contacting activities, including static gears, and increased predation pressure may be contributing additional stressors on a reef that is already compromised. However, current evidence is insufficient to determine the relative contribution of each pressure, and it is probable that several have played a role in the observed decline.

Interactions and cumulative effects

The observed decline is likely the result of multiple interacting pressures, both historic and ongoing, which may have exceeded the reef's resilience threshold.

Historic fishing (towed gears) is recognised as a driver of *M. modiolus* reef degradation, likely causing physical damage and population fragmentation that reduced recruitment and connectivity (Strong et al. 2016; Fariñas-Franco et al. 2018b). Recovery is typically very slow (12–20 years) or absent. The decline at the PLAS SAC reef may reflect ongoing residual effects, with broader population losses across the Irish Sea likely limiting larval supply and connectivity (Gormley et al. 2015a; Mackenzie et al. 2022).

Climate change is an increasingly significant pressure, with clear mechanisms for rising sea temperatures to affect larval dispersal, settlement success, and survival of both juvenile and adult mussels. Temperature stress may also impair byssal thread production, weakening reef structure and increasing susceptibility to physical disturbance and predation. Reef breakdown further reduces recruitment potential by eliminating adult mussels that provide refuge for early life stages. It seems very likely that the rising sea temperatures since the 1990s are a major factor in the decline of the *M. modiolus* reefs. This decline is likely to continue, with modelling suggesting climatic conditions will become unsuitable for *M. modiolus* reefs in Wales within the next decade (Gormley et al., 2013)

Predation pressure may be intensifying due to climate-driven shifts in trophic dynamics. Anecdotal evidence suggests an increase in *M. brachydactyla* (spider crab), a known predator of *M. modiolus*, coinciding with the period of reef decline. Additionally, changes in plankton communities may be altering food web dynamics, increasing predation risk across life stages. It is also possible that declines in higher-level predators that typically regulate populations of benthic predators (e.g. whelk and spider crab) have reduced top-down control, further amplifying predation pressure on *M. modiolus*. However, confidence in this pressure as a cause of decline is lower.

The combined effects of warming, ongoing physical disturbance (e.g. static gears), and predation may be contributing to a cumulative impact that inhibits recovery and accelerates decline. These pressures may be acting on a reef already destabilised by historic mobile-gear abrasion and penetration prior to fisheries closures, with earlier structural damage potentially reducing resilience to subsequent stressors. These pressures may also interact with emerging threats such as disease outbreaks and invasive species, although current evidence for their role at the PLAS SAC *M. modiolus* reef remains limited.

Comparative data from Öresund, Sweden, a strait between Denmark and Sweden connecting the Baltic Sea to the Kattegat, suggests similar patterns of recruitment failure seen at the PLAS SAC reef. Since 2000, no *M. modiolus* individuals under 35 mm have been recorded (Stina Bertilsson Vuksan, pers. comm. 2024), indicating a long-term recruitment collapse. This may be linked to heavy seabed trawling in the adjacent Kattegat, which could have disrupted larval supply to Öresund, where direct fishing pressure is low. Temperature data from the region shows a 1.5°C increase between 1971 and 2009, with the most pronounced warming in the 2000s, coinciding with declines in Arctic-boreal species (Göransson 2017). These findings support the hypothesis that climate change and regional-scale disturbance can significantly affect recruitment and population persistence, even in areas with limited local impact

Broader trophic shifts in the North Atlantic, including the Irish Sea, have been linked to long-term fishing pressure and climate change (Bell et al. 2018; Hernvann et al. 2020). These shifts include reductions in fish biomass (e.g. cod and sole) and increases in crustacean populations (e.g. *Nephrops norvegicus*), which have become more dominant as traditional fish stocks declined (Bell et al. 2018; Hernvann et al. 2020). This reflects ecosystem-level changes, or regime shifts, that may influence benthic community dynamics and the resilience of biogenic habitats like *M. modiolus* reefs. Such changes can alter predator-prey relationships and competitive interactions, potentially increasing predation pressure on reef-forming species and reducing their capacity to recover following disturbance. These patterns warrant further investigation to understand their implications for reef conservation and management.

Management considerations

Achieving favourable conservation status presents considerable challenges in light of the ongoing pressures at the reef discussed above. Increasing sea temperatures represent a major long-term threat to the persistence of the *M. modiolus* reefs, and this climate-driven pressure extends beyond what can be managed solely within Wales. Management therefore needs to focus on protecting the remaining functioning parts of the reef, reducing local pressures that may inhibit resilience, and adopting a precautionary, adaptive approach in line with SAC obligations to maintain or restore feature condition. Studies (e.g. Gormley et al. 2013, 2015a; MCCIP 2018; Hoppit et al. 2022) have considered potential management strategies for *M. modiolus* reefs and the approaches outlined below appear to be the most relevant for managing the PLAS SAC reef:

- **Reducing or removing anthropogenic pressures** is considered the most effective way to increase reef resilience to ocean warming (MCCIP 2018). While the reef is an important fishing ground for local communities, particularly for whelk potting, the evidence regarding the impact of this activity on reef integrity remains inconclusive. Engagement with local fishers is essential to ensure that conservation measures are balanced with socio-economic needs and informed by local knowledge.

- **Maintaining and strengthening connectivity** between populations is critical for resilience and recovery of *M. modiolus* reefs. Studies suggest that remaining beds in the Irish Sea act as interconnected stepping-stones, meaning management should focus on strengthening links between sites through well-designed MPA networks and dispersal corridors (Gormley et al. 2013, 2015). The results of the ongoing genetic study (NRW–ATU–Heriot-Watt, expected 2026) will be particularly important for understanding source–sink relationships and will inform whether local recovery is feasible or if the PLAS SAC reef is dependent on external larval supply.

- **Adaptive management** is increasingly recognised as necessary in the face of climate-driven habitat shifts (Hoppit et al. 2022). Predictive modelling indicates that the PLAS SAC reef may become unsuitable for *M. modiolus* under future climate scenarios, making long term restoration potentially unfeasible. Management may therefore need to shift from maintaining historic baselines toward supporting ecological resilience and accommodating climate-driven change in situations where natural recovery is unlikely (Fariñas-Franco et al. 2018a). Previously, conservation aquaculture approaches for *M. modiolus*, as well as habitat-based methods such as the deployment of artificial substrates or cultch to provide settlement structure, have been trialled (e.g. Northern Ireland) (Roberts et al. 2011; Cook 2016; Fariñas-Franco and Roberts 2023), but success has been limited. Further research is needed to assess the feasibility of these methods, which are likely to be increasingly constrained by warming seas. As such, they would need to be considered alongside wider discussions about how best to maintain ecological function under changing conditions.

As climate change alters habitat suitability, future management may need to shift from trying to maintain current reef extent to supporting habitat transitions and species movement. This approach, managing habitats under changing conditions rather than preserving historical baselines, is not yet widely adopted but is becoming increasingly important for long-term ecosystem resilience (Gormley et al. 2015b; Hoppit et al. 2022). Any consideration of alternative habitat enhancement approaches (e.g. historically present reef-forming species) should be explored through research and wider discussion before any future management action is considered.

Ongoing monitoring

Continued monitoring is essential to assess the ongoing condition of the reef. Key actions include:

- **Temperature Monitoring**: Maintain logger deployments to track sea temperature trends at the reef.
- **Spat Collection & Recruitment monitoring**: Continue using spat collectors with improved lab protocols for storage, identification, and processing. Define a regular sampling schedule to assess recruitment success and population structure.
- **Reef Condition Assessment**: Continue surveys to monitor mussel density and detect invasive species such as *C. fornicata.* Use towed drop-down video (DDV) or other methods such as Remote Operated Vehicle (ROV). Surveys should be kept to a minimum to reduce potential physical disturbance to the reef, suggest no more than every four years (Morris 2015).
- **Habitat Extent**: Conduct annual side-scan sonar surveys to track reef extent.
- **Bathymetric Surveys**: Perform multibeam echosounder (MBES) surveys approximately every 5 years to monitor structural changes.

Knowledge gaps and research needs

Despite ongoing monitoring and research, several key knowledge gaps remain that limit effective management and conservation of the PLAS SAC *M. modiolus* reef. Filling these gaps will be essential for refining future management decisions and supporting an adaptive approach:

1. Impacts of Static Fishing Gear

- Most studies on fishing impacts have focused on mobile gear, with limited investigation into static gear. Recent long-term studies in Lyme Bay MPAs (Gall et al. 2020; Rees et al. 2021) suggest potting may be more damaging than previously assumed, particularly to reef-building species. There is a need to assess long-term potting intensity and its ecological thresholds in the PLAS SAC to inform management.

2. Temperature Stress and Climate Impacts

- The effects of rising sea temperatures on *M. modiolus* physiology, particularly during larval stages, remain poorly understood and more research is needed across multiple life stages to assess vulnerability and resilience under warming scenarios. In situ bio-monitoring of thermal stress (e.g. gill haemolymph sampling) would support early detection of physiological impacts.

3. Larval Connectivity and Source-Sink Dynamics

- Further larval modelling is required to determine whether the PLAS SAC reef acts as a source or sink. Multi-year modelling incorporating updated larval behaviour would help clarify annual variability in dispersal pathways and should include warming scenarios.

- Additional *M. modiolus* areas are known in the region, including off northeast Anglesey, though they are not currently protected. These areas are not well mapped and their condition remains uncertain. Identifying, mapping, and assessing these reefs is essential, as they may serve as important stepping stones for larval connectivity with the PLAS SAC reef. Understanding their role in regional population dynamics could inform future conservation efforts and support long-term resilience.

- Investigate improvements to spat collector design and expand deployment to additional sites to support future connectivity studies. Age spat and analyse larval pathways to better understand dispersal dynamics. Explore alternative, non-invasive methods such as eDNA and eRNA to enhance larval monitoring and complement physical sampling.

4. Pathogens and Disease Risk

- The impact of current and emerging pathogens on *M. modiolus* is unclear, particularly under warming conditions that may increase disease prevalence.

Research is needed to assess pathogen presence and potential effects on reef health.

5. Invasive Species

- The ecological impact of *C. fornicata* on *M. modiolus* reefs is not fully understood and warrants targeted investigation.

6. Historical Ecology and Potential Restoration Pathways

- The age and historical development of the PLAS SAC *M. modiolus* reef, including potential overlap with native oyster *(Ostrea edulis*) beds is unknown, limiting our understanding of long-term habitat changes. Understanding this context could clarify past habitat structure and whether other reef-forming species historically contributed to ecosystem function. This information would support research into alternative restoration approaches, including the potential role of historically present species to maintain ecological function if *M. modiolus* restoration and recovery are not feasible. Further work is also needed to evaluate the potential for habitat-based methods (e.g. substrate or cultch deployment) and conservation aquaculture techniques, building on trials undertaken elsewhere, to determine whether these could contribute to future ecosystem function under changing environmental conditions.

7. Parasitism

- The effects of *Pinnotheres* sp. infestation on *M. modiolus* are unknown and require further study to assess potential health and reproductive impacts.

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Appendix

A. Table of all monitoring carried out at the Pen Llŷn A'r Sarnau (PLAS) Special Area of Conservation (SAC) *M. modiolus* reefs

Year	Survey type	Undertaken by	Purpose
1960s	Dredge	Ivor Rees	Exploratory benthic surveys
1994-1997	RoxAnn^{TM} acoustic seabed discrimination system Drop Down Video (DDV) Side-scan sonar (herafter Sidescan) Sediment samples Modiolus samples	North Wales & North West Sea Fisheries Committee (NW&NWSFC) with Research Vessel (RV) Prince Madog & University of Wales (UW) Bangor (Ivor Rees)	Ground truth & mapping
1998	Sidescan	Countryside Council for Wales (CCW) & RV Prince Madog/UW Bangor	Trials to determine use as monitoring tool
1999	Diver DDV Sidescan Sub-bottom profiling RoxAnn^{TM} surveys	CCW & RV Prince Madog/UW Bangor	Complete side-scan survey of reef, ground truthing & establishing monitoring station at site 1 (including taking infaunal and modiolus samples, deploying pyramid beacon)
2003	Diver	CCW	Temperature logger in place

Year	Survey type	Undertaken by	Purpose
2004	Diver	CCW	Set up site 1 with spat collector, temperature loggers, fauna quadrats, video quadrats & genetic samples taken
2005	Diver Multibeam echosounder survey (MBES) & DDV & grab sampling & Sediment Profile Imaging (SPI)	CCW Interreg IIIa HABMAP project	Set up site 2 (deploy smaller pyramid beacon), first yr in-situ counts at both sites, video quadrats, replace spat collectors Mapping & habitat survey
2006	Sidescan	CCW	Extent mapping
2007	Dive survey Sidescan	CCW	Video quadrats and in-situ counts site 1. Replace spat collectors & loggers, install t-pod. Extent mapping
2008	Dive survey Sidescan Multibeam	CCW British Geological Survey (BGS) & School of Ocean Science (SOS)	Video quadrats and in-situ counts site 1 & 2. Replace spat collectors & loggers, remove t-pod. Extent mapping

Year	Survey type	Undertaken by	Purpose
2009	Dive survey Sidescan	CCW CCW	Video quadrats and in-situ counts site 1 & 2. Replace spat collectors & loggers. 4/5 new sites (A-E) visited and 2 quadrats filmed. Infaunal and modiolus samples collected at Site 1. Extent mapping
2010	Dive survey	CCW	Video quadrats and in-situ counts new sites 4 & 5
2011	Dive survey Sidescan	CCW	Video quadrats and in-situ counts site 1, and new sites X & Y. Replace spat collectors & loggers. Extent mapping
2012	Dive survey Sidescan	CCW	Video quadrats and in-situ counts site 1, and site A Extent mapping
2013	Dive survey Sidescan	CCW	Replace temperature loggers site 1 Extent mapping
2014	Dive survey Sidescan	Natural Resources Wales (NRW)	Site 1 + 2 visit – quadrats and maintenance Extent mapping
2015	MBES	UK Hydrographic Office (UKHO)	Survey of Caernarfon Bay

Year	Survey type	Undertaken by	Purpose
2022	Towed DDV Sidescan	NRW	Assessing wider reef condition Extent mapping
2023	Diver Towed DDV	Bangor University	Whelk potting impact study Infaunal and modiolus samples collected in the centre of the reef
2024	MBES survey	NRW/Hydrofix	Extent mapping

Data Archive Appendix

Metadata for this project is publicly accessible through Natural Resources Wales' Data Discovery Service https://metadata.naturalresources.wales/geonetwork/srv (English version) and https://metadata.cyfoethnaturiol.cymru/geonetwork/cym/ (Welsh Version).

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