Exploring Marine Restoration Opportunities in the Cleddau Estuary

Desk Based Research into the Opportunities, Constraints, and Environmental Nutrient Thresholds for Seagrass, Saltmarsh, and Native Oysters

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Executive Summary

Milford Haven, along with the estuary of the Cleddau rivers in West Wales, is a protected area within the Pembrokeshire Marine Special Area of Conservation and is home to seagrass, saltmarsh and native oysters. However, as none of these protected and designated features are in good environmental status there is a desire to support recovery and restoration.

This review and data analysis considers opportunities, constraints, and environmental nutrient thresholds for seagrass (*Zostera marina* & *Zostera noltii*), saltmarsh, and native oysters (Ostrea edulis). It focusses on identifying what is currently 'known' and 'unknown' through desk-based research and stakeholder interviews to support future restoration efforts. Recommended future research is also suggested to address important 'unknowns'.

Seagrass - both *Zostera marina;* and *Zostera noltii* (recently reclassified as Nanozostera noltii); are found within the study area, with the greatest threat to these species being excess nutrients, with nitrogen being of particular concern. Excess nutrients impact both species throughout the waterway as a result of lower light to photosynthesise, algal overgrowth, physiological stressors, and direct physical responses with the greater impacts in the upper estuary furthest from the sea. Nutrient levels are three times higher at sites in the upper estuary than found at sites near the mouth of the estuary. There are other anthropogenic pressures such as physical disturbance through moorings, coastal developments, and anchoring, but these are seen as less significant than nutrients. Dredging and sediments from the catchments are likely an impact on the seagrass, but their action is poorly understood and monitored. To date, there has been regular seagrass and water quality monitoring of intertidal meadows, including some sampling of seagrass tissue nutrients which has enabled some understanding of the effects of nutrients in different areas of the waterway and the varying levels of nutrients to the health of seagrass. This has enabled the creation of an hypothesised extreme nutrient threshold of 0.75mg/L total nitrogen for intertidal seagrass (mixed *Zostera noltii* and *Zostera marina*). Our analysis indicates that areas of intertidal seagrass with concentrations of total nitrogen higher than 0.75mg/L have seagrass at lower densities. This doesn't mean that the seagrass at concentrations lower aren't under stress, merely that they aren't in decline. Such a threshold is unlikely to be within the safe operating space for sub-tidal seagrass, as this analysis does not apply to those environments, where long-term loss and decline has been happening over the course of multiple decades. A much lower concentrations is likely. A threshold for phosphorus could not be proposed because of a lack of data due to less monitoring in the marine environment.

The proposed extreme threshold of 0.75mg/L of total nitrogen is reached further upstream between the middle and upper reaches of the waterway near the Cleddau bridge. These are the areas in which opportunistic macroalgae is well established and extensive, often covering large areas of seagrass.

Levels of nutrients within the tissue samples of the seagrass indicate levels higher than what is understood for healthy seagrass in most other areas of the UK. Although intertidal seagrass remains extensive throughout the waterway (though in a state of stress.) the excess nutrients may well be altering the ecosystem function of this habitat.

Some areas of intertidal seagrass (dominated by *Zostera noltii*) have been increasing in both cover and density in recent years, even in areas of elevated nutrients, the reason for such expansion we hypothesise is from increased sea surface temperatures associated to the local power station outfall. In sheltered areas close to the mouth of the estuary subtidal *Zostera marina* is subjected to lower nutrient concentrations and remains healthy. This is the site of an existing *Zostera marina* restoration project near to the village of Dale.

Opportunities for seagrass restoration within the Milford Haven Waterway remain mostly within the lower reaches close to the estuary mouth where water quality is high. This is particularly the case for subtidal *Zostera marina*. Additional opportunities may also exist in the saline lagoons and in some of the intertidal areas in the lower to middle estuary. The beds of expanding and healthier *Zostera noltii* potentially provide the opportunity to be donor beds of mature seagrass to be transplanted to other areas to aid coverage or density.

Saltmarsh (Atlantic Salt Meadow) is a designated feature of the Pembrokeshire Marine SAC and are found throughout the Milford Haven Waterway and the Cleddau Estuary. While their distribution and current extent have been deemed favourable, its highly likely that with long-term land reclamation throughout the Milford Haven Waterway salt marsh has declined in area. The structure and functional component of Saltmarshes in the Waterway like seagrasses have been assessed as being in an unfavourable state due to elevated levels of dissolved inorganic nitrogen (DIN) and the presence of macroalgae, which can suffocate saltmarsh species. Many examples of such suffocation are readily observed in locations such as Sandy Haven and the Pembroke River. Saltmarsh plant species can benefit from and cycle nutrients, ultimately leading to the sequestration of these nutrients. Unfortunately, at elevated concentrations of nutrients, especially of nitrogen, the growth of saltmarsh plants can become negatively impacted. Reduced root growth typical of high nitrogen leaves saltmarshes susceptible to erosion, and this risk becomes more significant when natural inland advancement is restricted by coastal squeeze. Some saltmarsh species are more tolerant of excessive nutrients, leading to reduced species diversity, especially in the mid to upper marsh areas. Nutrients are known to have both positive and negative effects on the growth of saltmarshes however we are not aware of a specific threshold or level of nutrients identified that would threaten saltmarsh species and communities. It is understood that opportunistic macroalgae can outcompete pioneer saltmarsh species at a crucial stage of saltmarsh development. Despite this knowledge that macroalgae can outcompete pioneer saltmarsh, it is not known what level of nutrient concentration causes the proliferation of opportunistic algal mats at a specific location from year to year. Locations of algal mats are well known and monitored by NRW, and in the absence of a known specific nutrient level in the water column that poses a threat to saltmarsh or triggers opportunistic macroalgae, the density and extent of macroalgae should be considered which is monitored through SAC condition assessment and is available on request from NRW.

No constraints or a nutrient threshold were identified by the available data or by stakeholders interviewed that would prevent saltmarsh restoration, aside from having suitable land available and consideration of appropriate nutrient tolerant species. Through this research, no specific areas within the Cleddau Estuary have previously been identified for saltmarsh restoration through any formal report or project. Though there is recent broad ‘opportunity’ and ‘future flood risk’ mapping that provide general areas to consider and can be built upon through a recommended more detailed feasibility study. Consideration could also be given to how the water quality regulation functions of increased and improved saltmarsh might benefit the health of adjacent seagrass.

The native oyster (Ostrea edulis) was once considered plentiful in Milford Haven and the Cleddau Estuary, with records as early as 1600, but by 1870 populations had sharply declined due to overfishing. Although oysters are still present, the lack of sufficient density of mature breeding specimens, combined with the widespread presence of invasive slipper limpets, the oyster disease Bonamia, and the lack of suitable settlement substrates, means Oyster reef formation is highly constrained. These constraints are not unique to the Milford Haven Waterway, as such problems are limiting recovery across Northern Europe. Many of the constraints on the reproduction and growth of native oysters such as available substrate could be due to their current low numbers, as a preferred substrate for new larval settlement is existing oyster shells, and to a lesser extent other bivalves and hard clean rock. Additionally, obtaining oysters for restoration efforts is a challenge throughout the UK due to limited aquaculture facilities for their growth. Native oysters are generally not considered sensitive to high levels of nutrient enrichment, water clarity, or suspended solids (unless the levels are extremely high). Therefore, nutrient thresholds and environmental factors resulting from nutrient enrichment are probably not of major importance for successful restoration efforts. The presence of a sufficient number of mature oysters, without high levels of Bomania, to ensure adequate larval production and provide a suitable substrate for further reef formation seems to be a more crucial threshold to consider than nutrient levels in the water column, or the environmental factors associated with nutrient enrichment. Oysters as filter feeders have been shown to provide significant regulatory water quality improvements. Native oysters still exist on historic beds, and this is a positive as it shows environmental conditions are still suitable. Upstream of the Cleddau bridge is protected from oyster dredging due to designated SAC reef features. There is an existing native oyster restoration project and a commercial oyster farm that produces native oysters within Milford Haven and the Cleddau Estuary. Both are modern data-driven initiatives, and the restoration effort is a funded initiative that is constrained by both delivery timescales and resource coming to completion in 2026. This provides the opportunity to build on restoration work with a strong foundation and knowledge base.

There are a variety of constraints to restoration of seagrass, saltmarsh and native oysters, and nutrients have different levels of impact on each species, with seagrass having the most understood nutrient threshold. None of the constraints including nutrients would prevent restoration being pursued, though consideration of the elevating level of nutrients when navigating up the estuary should guide decision making for nutrient-sensitive species, alongside the co-designing of nutrient mitigation in terrestrial and coastal environments.

Introduction

Milford Haven, and the estuary of the Cleddau Rivers located in West Wales and within the Pembrokeshire Marine Special Area of Conservation is a beautiful and highly designated part of Wales. Many marine and coastal habitats within Milford Haven and fed by the Cleddau River are not in good environmental status, though there is a desire to support recovery and restoration.

There are a variety of pressures from the terrestrial environment that pose challenges to restoration. Excess nutrients for example contribute to eutrophication and can lead to major disruptions of aquatic ecosystems, making conditions for recovery or restoration less than optimal.

By adopting a 'wholescape ' approach, WWF are looking at land, rivers, and seas to create models for how these ecosystems can be managed holistically, because they are all intimately connected. To support this ‘wholescape’ approach WWF asked Pembrokeshire Coastal Forum & Project Seagrass to identify the spatial opportunity, constraints, and environmental nutrient thresholds for marine restoration in the Cleddau, to benefit coastal communities, our climate, and collective futures. This desk-based review of research bringing together the available data on marine restoration opportunities, identifying constraints, and environmental nutrient threat thresholds within the Cleddau Estuary. With a focus on seagrass, saltmarsh and native oyster species and habitats and the known pressure of excess nutrients the work aims to bring together what is ‘known’, identify what is ‘not known’, and make recommendations on how to address what is ‘not known’. This work was completed between November 2023 and July 2024.

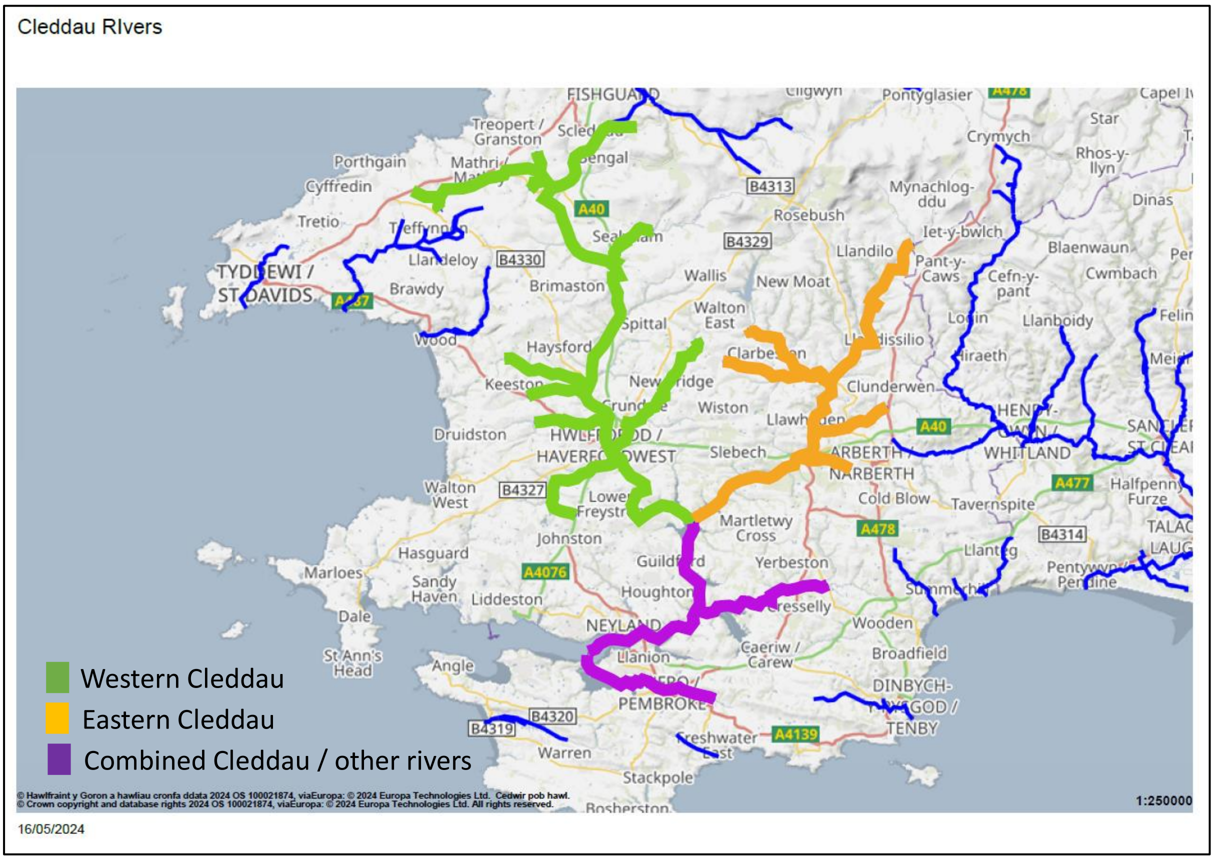
This report was completed through a combination of stakeholder interviews to highlight issues or data and desk-based research. Below is a list of the stakeholder organisations interviewed and a summary of the stakeholder interviews can be viewed in appendix 2.

- Pembrokeshire Local Nature Partnership
- Pembrokeshire County Council (Ecology Team)
- Pembrokeshire Coast National Park (Conservation Team)
- Milford Haven Waterway Environmental Surveillance Group
- Native Oyster Network / Wild Oyster Project
- Natural Resources Wales (Marine Team)
- Centre for Ecology & Hydrology
- Wetland & Wildfowl Trust
- Pembrokeshire Marine SAC (Management Officer)
- Nature Am Byth (Project Officer)

Background on study area

Milford Haven Waterway (MHW) is a large estuary in Wales and its catchment area comprises a great proportion of Pembrokeshire. It is a ria estuary (drowned river valley), representing 34% of the UK's resources of this estuary type. Of its 55 km^2 area, over 30% is inter-tidal habitat [1] that contains an abundance of seagrass [2].

The Cleddau Rivers (Eastern and Western) are both Special Areas of Conservation (SAC) and arise at fairly low altitude and are a predominantly lowland catchment with moderate to low gradient in the Pembrokeshire peninsula (https://sac.jncc.gov.uk/site/UK0030074).


Cleddau RIvers

🟩 Western Cleddau
🟨 Eastern Cleddau
🟪 Combined Cleddau / other rivers

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Figure 1 - Major rivers of Pembrokeshire with the eastern, western and combined tidal areas of the Cleddau emphasised by colour.

The Eastern Cleddau originates in the foothills of the Preseli mountains and spans approximately 34 kilometres. About 7 kilometres of its length is influenced by tides. It converges with the Western Cleddau at Picton Point. The Western Cleddau has two main branches. The eastern branch begins at Llygad Cleddau, situated 4 kilometres southeast of Fishguard. It flows southwest, passing Scleddau, and joins with the western branch at Priskilly. The western branch originates at Penysgwarne, flowing eastward to Priskilly. The combined stream then flows south to Haverfordwest, where it becomes tidal (Natural Resources Wales, 2020).

The tidal estuary widens into a deep ria, merging with the Eastern Cleddau Estuary at Picton Point to form the Daugleddau estuary. The Western Cleddau from Penysgwarne to Picton Point spans approximately 40 kilometres, with about 9 kilometres influenced by tides. The catchment area is defined by intensive agricultural activity, predominantly focused on dairy farming. However, sheep rearing and early potato cultivation also hold significance locally. Dairy farming, in particular, is a key driver of the local economy (Natural Resources Wales, 2020).

The MHW comprises a central waterway with numerous shallow embayments, tributaries and pills. As a major and deep water estuary, it creates one of the deepest natural harbours in the World, making it a historically significant location for maritime commerce, shipping and more recently, the petrochemical industry [3]. In the last few decades, the waterway has also been transformed again by the construction and operation of two large liquefied natural gas (LNG) plants (Dragon LNG and

South Hook LNG) and one of the largest combined cycle gas-turbine power plants in Europe (RWE npower). Renewable energy technologies are also rapidly becoming part of the port operations [4].

Within Milford Haven and the Daugleddau estuary, as well as smaller estuaries that feed into the Milford Haven waterway like the Pembroke River, Cosheston Pill, Carew and Cresswell Rivers, Garron Pill, Sprinkle Pill, and Millin Pill, there are regular sightings of nationally significant numbers of wildfowl during their winter migration. These birds make essential stops in these areas for refuelling. The intertidal mudflats and associated habitats that drain into the main waterway provide a habitat for diverse and thriving communities of shellfish and worms that are excellent foraging for species such as Curlew.. In the upper reaches of the Daugleddau, underwater features such as bedrock, boulder slopes, and areas with shells and cobbles are home to vibrant anemones, an impressive variety of sponges swept by currents, and patches of sea squirts. Native oysters and migratory fish also inhabit these waters. The Daugleddau estuary and the Milford Haven Waterway fall within the Pembrokeshire Marine SAC, which is one of the largest marine SACs in the UK, covering an area of 138,069 ha. (www.pembrokeshiremarinesac.org.uk/).

Due to the extensive industrial activity of MHW, the biodiversity present within it remain at risk from anthropogenic impacts. For example, Milford Haven has been subjected to a number of oil spills since 1960, the biggest being the Sea Empress in 1996 in which approximately 72 000 tonnes of light crude oil (Forties Blend) and 480 tonnes of heavy fuel oil were released into the surrounding waters of MHW, resulting in the contamination of 200 km of the Pembrokeshire coastline [5]. More recently, the anthropogenic risk caused by excess nutrients draining into the waterway has been highlighted as a cause for concern, with multiple indicators suggesting that MHW could be close to being defined as being eutrophic [6]. The vast majority of the Dissolved Inorganic Nitrogen (DIN) entering the waterway from the catchment area comes from agricultural land, whereas continuous point sources (typical of industry and sewage treatment) supply a higher proportion of the dissolved inorganic phosphorus (DIP) load (~42%) into MHW [6].

The river and the estuary areas of the Cleddau rivers are highly designated, and recognised national and internationally as home to unique and special habitats and wildlife. The majority of both the Eastern and Western Cleddau River SACs are not meeting their good ecological status as part of the 2021 Cycle 3 of the Water Framework Directive (WFD), with most stretches or sub catchments of these rivers classed as ‘moderate’ with two instances of ‘poor’ and a handful of ‘good’ areas in the Eastern Cleddau. The Daugleddau estuary and the Milford Haven Waterway areas of the Pembrokeshire Marine SAC are both also classified as moderate under the Water Framework Directive (https://waterwatchwales.naturalresourceswales.gov.uk/en/). The status of these designated areas are an indication of the existence of unique and special habitats and species, though not functioning at their full potential, and possibly provides opportunities to restore these areas to increase the benefits these habitats provide. Though this piece of work will focus on the marine environment, it is important to make the connection between terrestrial environments and the potential pressures they place on marine areas.

Water quality status

Inputs into the MHW

In the Cleddau River’s catchment area, dairy farming, sheep rearing, and potato cultivation are prevalent. The main concerns regarding water quality include tackling nitrate, phosphorus, and sediment pollution originating from various sources, both point and diffuse. Additionally, there are issues related to alterations in river channels and banks, such as historical channel adjustments, the presence of in-channel structures, and disconnecting floodplains creating barriers to fish movement and disturbing or removing natural habitats. Other challenges include grazing, trampling, and cultivation along riverbanks, leading to the loss of wildlife corridors, as well as the widespread occurrence of invasive species. Nutrient impacts stemming from wastewater, industrial emissions, and agricultural activities flow into the marine environment from the surrounding catchment area, affecting the overall environmental status of the water body (Natural Resources Wales, 2022).

Agriculture stands as the primary land use within the catchment, emphasising the crucial role of sustainable land management for farmers, the environment, and the local economy. Both agriculture and tourism serve as indispensable pillars for local communities and the economy. The tourism sector depends heavily upon high-quality natural resources and an unspoilt landscape (Natural Resources Wales, 2022).

A report produced by NRW in 2016 titled "Evidence Review of the Trophic Status of the Milford Haven Waterway" concluded that the Milford Haven Waterway was hypernutrified with the upper reaches above the Cleddau Bridge seeing more acute effects of this eutrophication (Haines & Edwards, 2016).

Data on opportunistic macroalgae, phytoplankton, and nutrient levels have been examined through research conducted for the Nitrates, Urban Waste Water Treatment, and Water Framework Directives (WFD). The Milford Haven Waterway is currently classified as having a Moderate status and is hypernutrified compared to WFD nutrient standards. While phytoplankton blooms do not occur in the waterway itself, sheltered bays and inlets experience widespread and often dense growth of opportunistic macroalgae species, primarily Ulva sp. Monitoring under the WFD in the Milford Haven Inner water body reveals moderate levels of dissolved inorganic nitrogen (DIN), which align with the Moderate status classification of opportunistic macroalgae (Haines & Edwards, 2016).

An opportunistic algal species is considered to be able to take advantage of conditions in which other species often struggle to survive or compete. Due to high rates of nutrient uptake and enhanced reproductive capability, they can prevent or stunt growth of perennial algae by excessive abundance and competition for space (Abbott &Hollenberg, 1976, cited in Haines & Edwards, 2016). Mats of opportunistic macro algae can be found throughout the Milford Haven waterway and the Cleddau Estuary within bays and narrow inlets from rivers. These mats change in intensity of coverage seasonally and can outcompete or smother other species.

Figure 2 - Opportunistic macroalgae at Cosheston Pill, 2012, the most impacted inlet within the Inner water body, during peak growth, this photograph demonstrates opportunistic macroalgal growth at its most prolific. *(Haines & Edwards, 2016)*

Figure 3 - Opportunistic Macroalgae cover within the Milford Haven waterway, 2014 (Haines & Edwards, 2016)

The total nitrogen and phosphorus loads to the Daugleddau estuary and the Milford Haven Waterway were calculated to be 2508 tonnes N/year and 48.5 tonnes P/year by a study in 2012

(ADAS 2012, cited in Haines & Edwards, 2016). The same study indicated that there is no evidence of an increasing trend in nutrient (DIN or DIP) loads entering the waterway or nutrient concentrations within the waterway. However, a review of more recent Natural Resources Wales, SEACAMS (Swansea University) data, which is discussed in detail later in this section of our report, indicates an upward trend of nutrient inputs and ***that the highest concentrations ever recorded in the MHW have all been recorded since 2020.***

The majority of the Dissolved Inorganic Nitrogen (DIN) entering the waterway originates from agricultural land within the catchment area. Approximately 8% of the DIN load can be traced back to consistent point sources like sewage treatment plants and industrial discharges. Other sources such as occasional discharges and urban runoff are considered to have minimal impact (Haines & Edwards, 2016).

A larger share of the Dissolved Inorganic Phosphorus (DIP) load, approximately 42%, originates from consistent point sources. Previous modelling investigations have suggested that both nitrogen and phosphorus levels might play a significant role in regulating algal proliferation, depending on the location within the waterway, season, weather conditions, and tidal conditions. However, analysis of observational data has indicated that nitrogen limitation is likely more prevalent influence overall (Haines & Edwards, 2016). More recent SAGIS modelling on Phosphorus input into the Afonydd Cleddau conducted by Natural Resource Wales and Dŵr Cymru / Welsh Water indicate that in the Eastern Cleddau, effluent from sewage treatment works accounts for 11% of the average daily load of phosphorus(kg/d) with rural land use contributing 84%, storm overflows contributing 2% and a further 3% from other sources including septic tanks and urban run-off. In the Western Cleddau, rural land use accounts for 65%, WwTWs 22%, storm overflows 5% and other sources 8% of phosphorus loading (Dwr Cymru & Natural Resources Wales, 2023).

Water quality in the MHW

The majority of the water quality data used in the present report has been obtained from external sources, principally Natural Resources Wales, SEACAMS (Swansea University) and the review of the historic extent of seagrass in Wales by Quentin Kay [7]. Additional seagrass nutrient data has been provided by the team at Project Seagrass and Swansea University.

Water chemistry at 12 sites in the Milford Haven Waterway has been assessed annually since 2000 (see figure 4). This assessment includes analysis of the different forms of nitrogen (as Total N) as well as chlorophyll as two of the most consistently available parameters. This monitoring is done under what was formerly the Urban Waste Water Treatment Directive (91/271/EEC) ('the Directive') and the Water Framework Directive. A statement of the exact methods of sample collection and analysis from Natural Resources Wales is not available. An additional detailed dataset on water quality is available specifically for the period 2013 to 2014 and conducted by the SEACAMS project at Swansea University [8]. This is based on combined seabed and surface water sampling monthly over 12 months at four locations throughout the Milford Haven waterway. Although a whole range of parameters were assessed, here we focus on the Dissolved Inorganic Phosphate (DIP), Nitrate and Chlorophyll A. Full methods are contained within the report [8].

In addition to the traditional water chemistry-style water quality data, we include data collected over time on the nutrient content of seagrass leaves, specifically the seagrass Zostera marina, at sites in Gelliswick Bay, Longoar Bay, and Dale. This data includes the elemental C, N, and P values of the seagrass leaves, alongside the isotope values of N15 and C13.

Assessment of the nutrient content of seagrass leaves provides a better cumulative assessment of the nutrient content and conditions of marine and coastal waters. This creates a time-integrated measure of water quality and differs from ‘in-water samples’ that aren’t always collected at times of storm overflow and tend to hide the true nature of the conditions. This data also differs from loggers that record all events but are not placed in shallow water environments and are not extensive in number due to their high capital and maintenance costs.

By measuring seagrass plant tissue nutrients, we see an indication of what the actual biota is being subjected to. This is because any concentration of nutrient recorded in the water column will have a different impact on the ecosystem dependent upon many other factors such as tidal flushing and may or may not be available to the biota present. By examining different ratios of particular elements in the seagrass tissue, we’re also able to estimate the amount of light available to the seagrass; this is particularly important as seagrasses are flowering plants that require light to photosynthesise. Disturbance and excessive pollution can increase the turbidity of the water reducing the amount of light available for photosynthesis.

The method used has previously been used in the UK [9] but is more widely known for its role in helping marine park authorities understand the impacts of catchment degradation on the Great Barrier Reef in Queensland Australia.

Detailed water quality monitoring (Only available from 2013-14)

Water quality was assessed in 2013-2014 at four locations throughout the MHW. This is the most detailed dataset available, as sites were assessed on the seabed and at the surface of the water each month as opposed to the annual monitoring of water quality conducted by the Water Framework Directive monitoring. Addition monitoring of phosphate, salinity and range of parameters was conducted during that time.

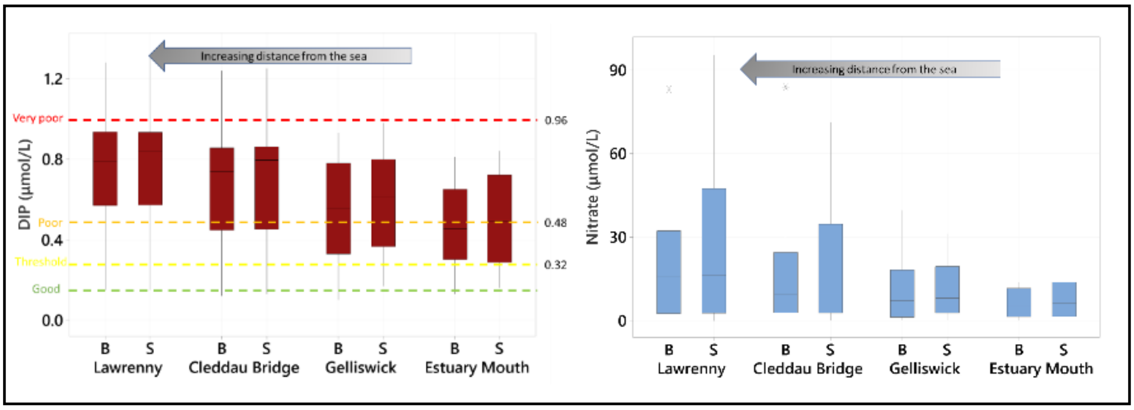

Figure 4a & 4b - Mean total Dissolved Inorganic Phosphate (DIP) and Nitrate at four locations across a gradient of estuarine influence within the Milford Haven waterway. Sites were assessed each month over 12 months from 2013-2014 on the seabed and at the surface (Lowe et al., 2014).

A similar pattern of increasing DIP and Nitrate was found with increasing distance up the estuary during this period of 2013-2014. DIP values were high relative to values found to be considered thresholds for seagrass health [10]. Salinity ranged between 34.4 and 8.7 ppt over the sampling period, with by far the greatest variation at Landshipping of between 33.1 and 8.7ppt. This compares to the more marine station at Thorn Island which varied between 34.4 and 30.0 ppt. Water temperature ranged between 20°C and 8.2°C, with higher temperatures in spring/summer and minimum values during winter. There were only slight differences between the different stations and with depth.

Long-term water quality monitoring (2000-2023)

In 2023, the mean Total Nitrogen (TN) concentration in the MHW was 0.57 ± 0.32 mg/L. Values have fluctuated quite highly between years with the maximum value recorded in 2020 of 1.1+-0.52 and the minimum value recorded in 2003 of 0.26 ± 0.15. The trend over time is for an increasing concentration, with the four highest annual mean values all being recorded in the last 5 years (2019-2024).

On average across the years (2000-2023) of assessment, TN was highest in Landshipping and at the village of Hook, where values were 1.1 ± 0.36mg/L and 1.2 ± 0.44mg/L, respectively. These two sites are the furthest up the estuary of all the sites sampled. The lowest values were recorded at Thorn Island, close to the mouth of the Estuary. There is a general trend of decreasing values towards the mouth of the estuary.

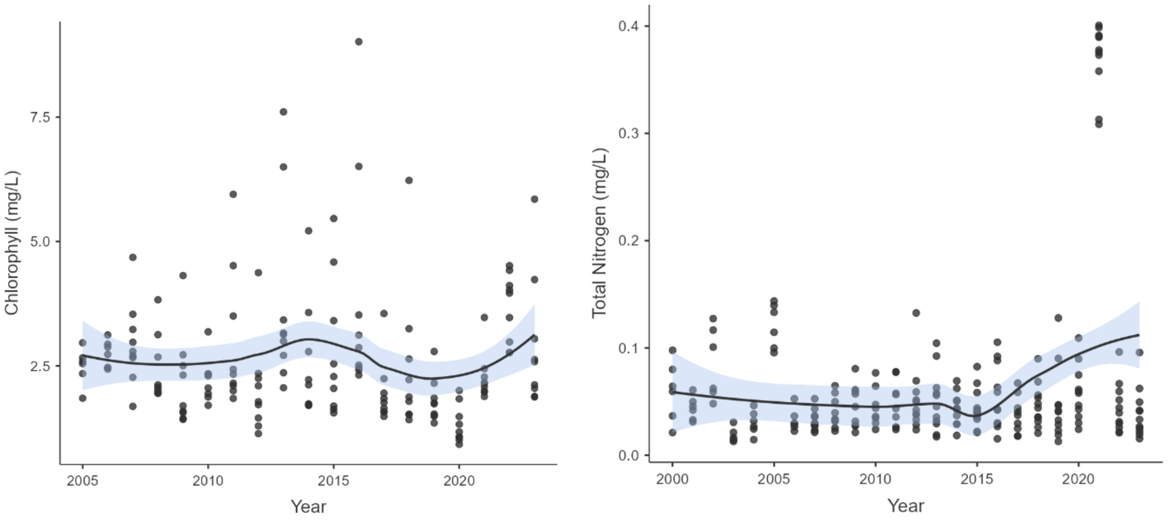

Figure 5 – Scatter plot of Total Nitrogen (TN) and Chlorophyll a in the water column across 12 locations spanning the Milford Haven Waterway from 2000 to 2023.

Of the 12 sites assessed, the highest values for total nitrogen were all recorded since 2020 except for Thorn Island (closest to the mouth of the estuary) where there has been little change over time and the highest value was recorded in 2002. Sites near the mouth (Thorn Island, Texaco Jetty, Depot Jetty and Pennar Mouth) all had largely stable levels of nitrogen up until 2019, when concentrations increased drastically to levels over the double background. Sites in the middle of the estuary (Pembroke River, Cleddau Bridge, Mill Bay, Cosheston Pill) had on average over double the Total nitrogen concentration of the outer estuary (Outer: 0.28 ± 0.12, Mid: 0.58 ± 0.20). At Cosheston Pill there was a general increasing trend over time of the Total nitrogen, however the other mid estuary sites had high variability between years.

Upper estuary sites had TN levels with an average of 0.91 ± 0.37mg/L (over three times the concentration at the estuary mouth) (Figure 6). The sites at Carew and Beggars Reach were highly variable between years, with some minimal increasing trend over time; however, the sites at Landshipping and Hook exhibited trends of increasing values over time.

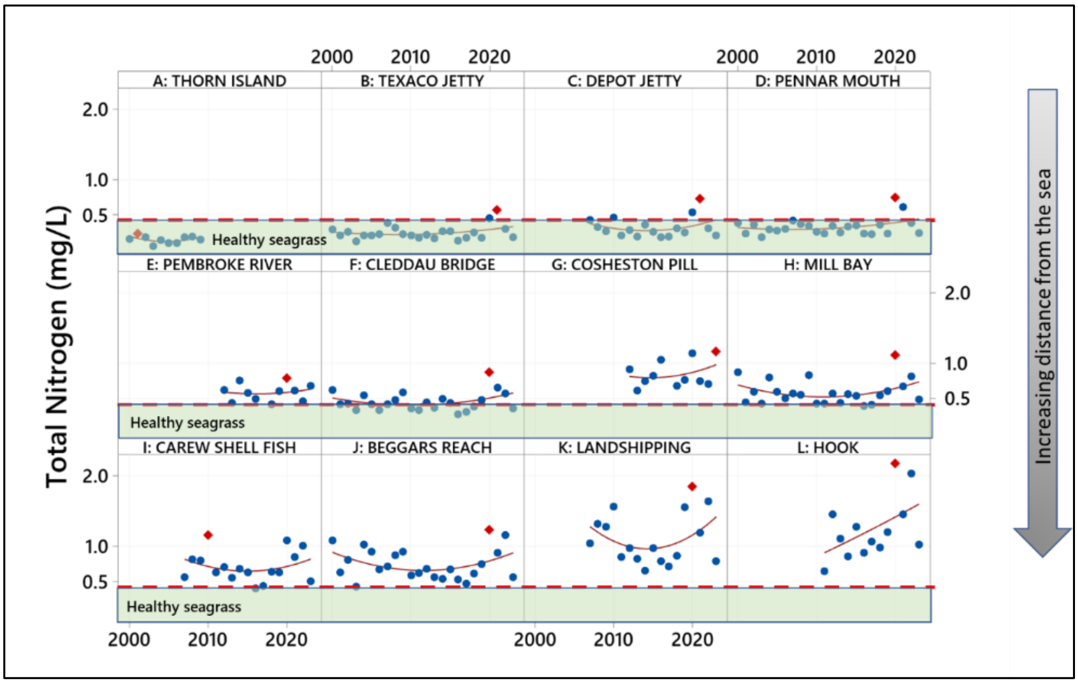

Figure 6 - Mean annual Total Nitrogen (TN) concentrations within the water column at 12 sites within the Milford Haven Waterway from 2010 to 2023. Points labelled red are the highest mean values within each site dataset. The green shaded areas at the bottom of each figure show the area within which research has previously found such concentrations to be reflective of healthy seagrass (Benson et al., 2013).

Chlorophyll levels were found to exhibit broadly similar trends to those found for Total Nitrogen (TN) (Figure 7), however there was more variability between years and a less of a marked pattern of increasing values within the most recent period. The highest values were recorded in 2013 and 2016. On average chlorophyll was 2.07 ± 0.71 µg/L in the outer estuary, 2.26 ± 0.76 µg/L in the mid estuary and 3.30 ± 1.54 µg/L in the upper estuary. Values are low relative to those recorded in healthy seagrass meadows within Cape Cod in the US [11].

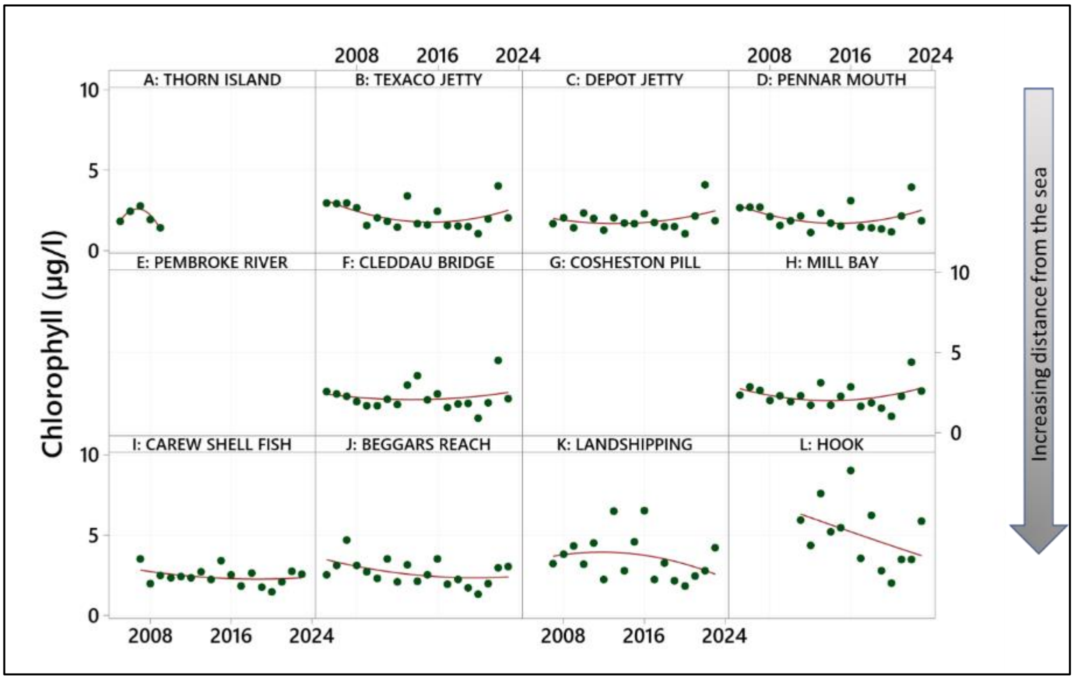

Figure 7 - Mean annual Chlorophyll (µg/L) concentrations within the water column at 12 sites within the Milford Haven Waterway from 2007 to 2023.

Seagrass leaf tissue nutrients

Elemental Nitrogen in seagrass leaf tissue was found to be on average 3.74 ± 0.85 %, this is above the global average of 2.7%. In addition, the elemental phosphorus was 0.33 ± 0.06 %, also above the global average of 0.27% [12]. Mean C:N ratio as an indicator of light availability finds the seagrass to have adequate light at 14.3 ± 2.5.

Nitrogen isotopic signatures in seagrass leaf tissue have been widely used as indicators of anthropogenic impacts, as effluents and different sources of matter have different isotopic footprints [13, 14]. Values in the range -7 to +1 ‰ indicate inputs from precipitation; 0‰ biologically fixed N, as well as synthetic / artificial fertilisers, due to the use of atmospherically fixed N, with an upper and lower range of -3 to +3 ‰. 4 - 6 ‰ indicates urban sewage or effluent, whilst > 10 is most likely caused by human sources [15-17]. The high values of δ15N at Gelliswick from 2012 to 2016 strongly suggest that these sites received elevated levels of organic nitrogen from human sources. Values in 2019 were exclusively collected from Dale rather than Gelliswick, and these provide a much lower N15 signature, suggesting the nitrogen to be predominantly of inorganic fertiliser origin.

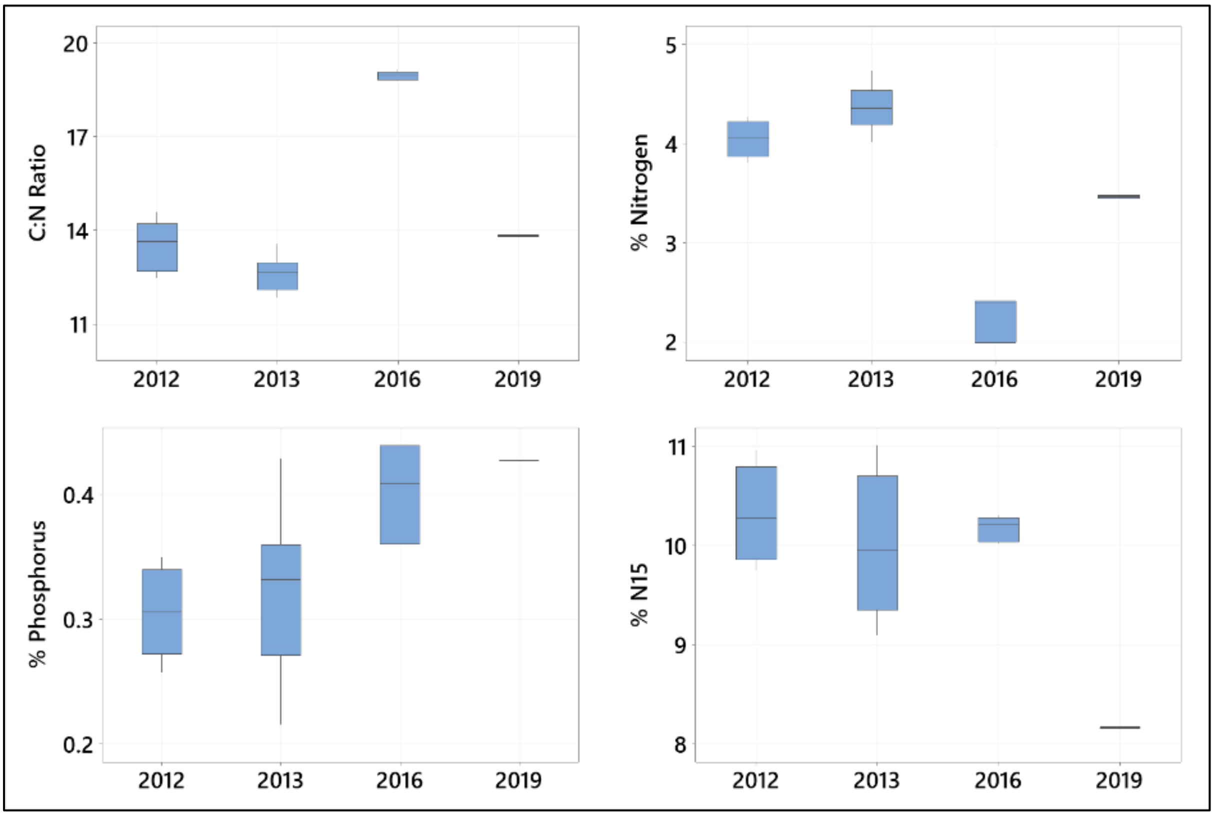

Figure 8 - Seagrass leaf tissue elemental nutrient concentrations recorded at Gelliswick and Dale within the Milford Haven Waterway from 2012 to 2019.

Seagrass

Seagrass meadows are habitats comprised of flowering plants adapted to life in a saline environment, where their distribution is restricted to intertidal to shallow subtidal areas of abundant light, soft sediments, sufficient nutrients and high shelter [18]. The extensive meadows formed by seagrass are created by the plants bioengineering their own environment [19]. They stabilise sediments with their roots, trap particles to improve light and oxygenate sediments to reduce toxic sulphide, leading to an affable environment for dense seagrass and, consequently, high biodiversity. Dense, tall seagrass shoots create a complex habitat where algae can grow, where small snails and crustaceans can graze, where animals can hide, and ultimately where complex food webs can develop. It's these key ecological functions that lead to seagrass being of high interest for the ecosystem services they provide. Seagrasses are known for their ability to lock carbon into marine sediments [20], their support for biodiversity [21], their role in support of global fisheries [22], and ability to cycle nutrients and capacity to reduce coastal erosion [23].

The location of these productive meadows in near-shore sheltered environments creates problems as they are sensitive to anthropogenic pressures, such as eutrophication, overfishing, habitat fragmentation and destruction, and forestry and commercial developments [24]. The loss and degradation of seagrasses has led to a range of negative impacts such as carbon loss, fisheries decline and sediment instability. This loss then leads to positive feedback mechanisms in many locations, hindering the potential recovery of these ecosystems [25].

In this section of this report focusing on seagrass the majority of the data used has been obtained from external sources, principally Natural Resources Wales (through FOI requests), SEACAMS (Swansea University), Project Seagrass and the review of the historic extent of seagrass in Wales by Quentin Kay [7].

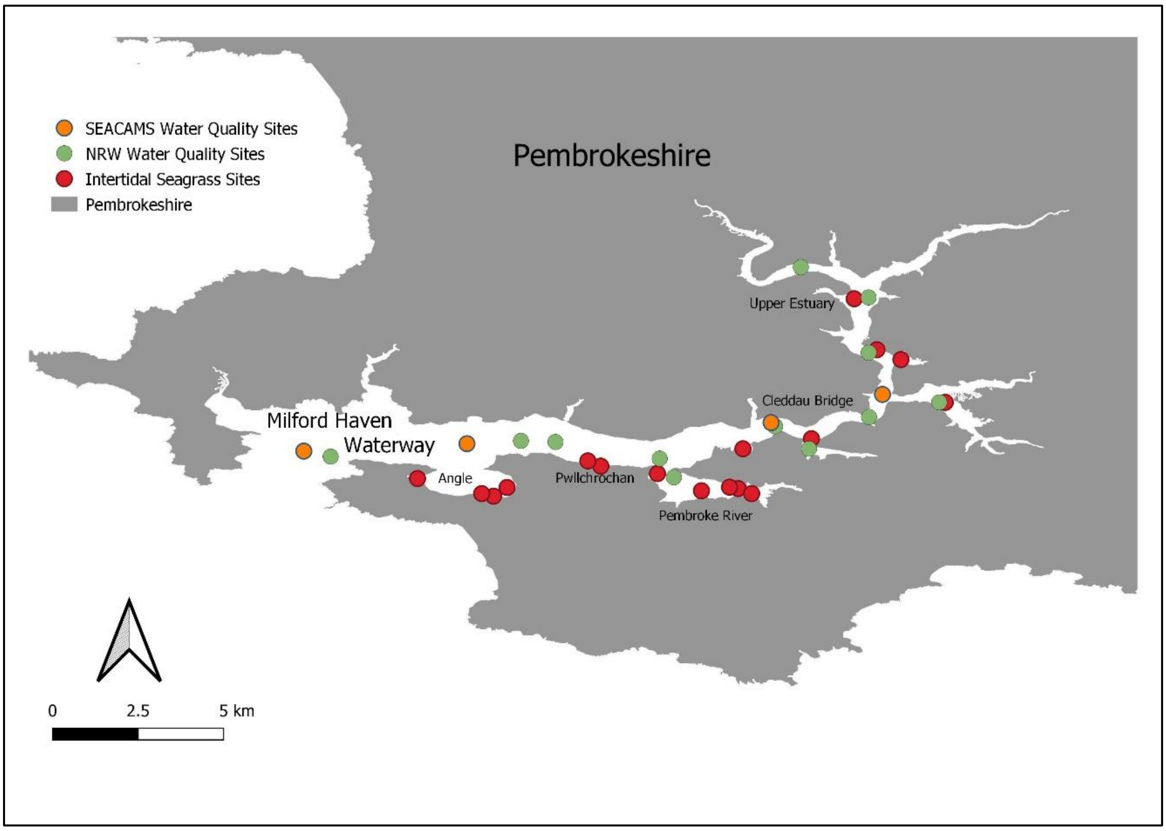

Figure 9 - Locations of the water quality and seagrass sampling sites used in the present study.

Seagrass Constraints

Seagrasses are susceptible to low light and algal overgrowth, therefore changes in seagrass distribution, abundance and condition can be related to environmental conditions [26, 27]. It is for this reason they are commonly referred to as 'coastal canaries' and the ongoing monitoring and assessment of their populations is a critical part of understanding the health of coastal waters [28, 29].

In the UK, seagrasses are in a perilous state, principally due to poor water quality, principally excess nutrients creating eutrophic conditions [9, 12, 17]. It is thought seagrasses no longer exist in 50% of UK estuaries, and recent estimates of loss are at least 50% – possibly as high as 92% [30]. Causes for these losses are many: early industrialisation of the UK, its historic mining past, coastal land reclamation and water quality problems are likely causes of the decline [30], with limited evidence that disease caused this large-scale loss. Many subtidal seagrass meadows remain in a stressed state [9, 17] and are subject to a range of cumulative stressors that are often poorly understood. In some places, optimism exists, as some intertidal meadows, however, are increasing in area and health, possibly as a result of reduced disturbances and improved water quality [31].

Of particular concern for seagrass are elevated nutrient levels in coastal and estuarine waters mostly due to nitrogen enrichment, but also as a result of elevated phosphate. Nutrients are problematic for seagrass plants because they result in less light becoming available for seagrass to photosynthesise. Light reduction happens through stimulation of high-biomass algal overgrowth as epiphytes and macroalgae in shallow coastal areas and as phytoplankton in deeper coastal waters (Figure 10). Direct physiological responses such as ammonium toxicity and water-column nitrate inhibition through internal carbon limitation may also contribute to the impacts of eutrophication.

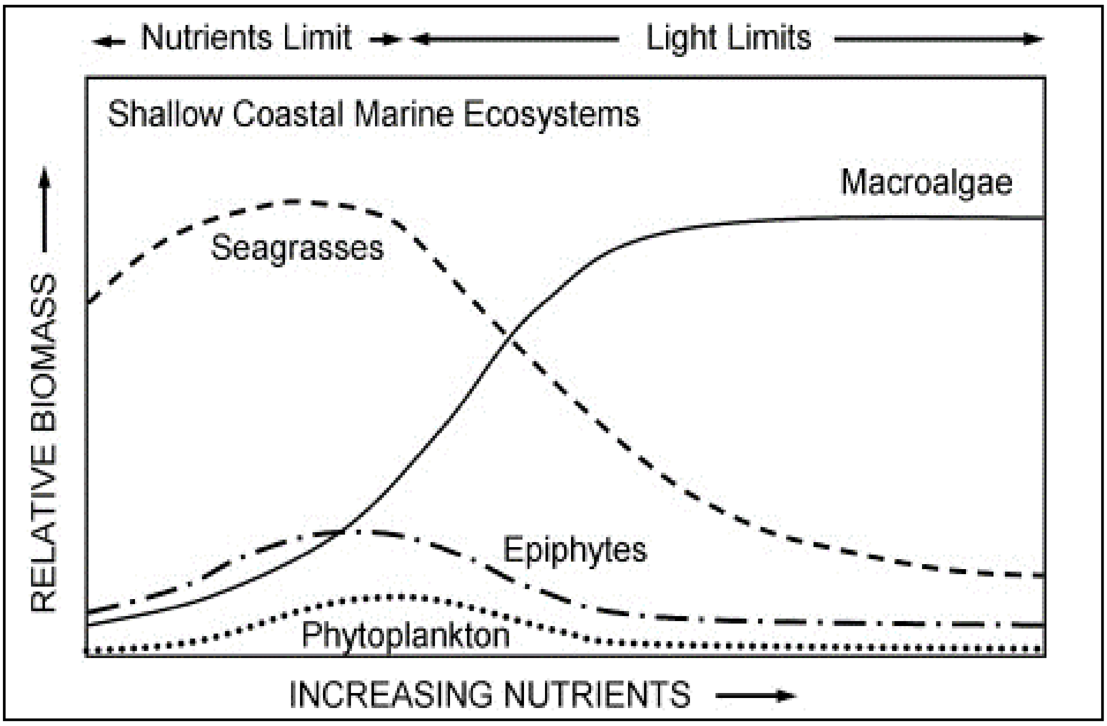

Figure 10 - Conceptualised relationship between increasing levels of nutrients in the coastal environment with the amount of seagrass and macroalgae (from (Burkholder et al., 2007))

Nitrogen is generally the most problematic nutrient impacting seagrass and is available in coastal and estuarine waters in a range of forms (Nitrate, Nitrite and Ammonium) (see Figure 11). Processes of nitrogen fixation, nitrification and denitrification are all present in the ocean and therefore, nitrogen is continually in a state of flux. Most data reported for N in coastal waters are for inorganic nitrate. This is logical in that nitrate is the thermodynamically stable form of N under toxic conditions and so has been assumed to typically dominate the species of N present in the estuarine water column, and it is the nitrate load that is most frequently associated with eutrophication issues [32].

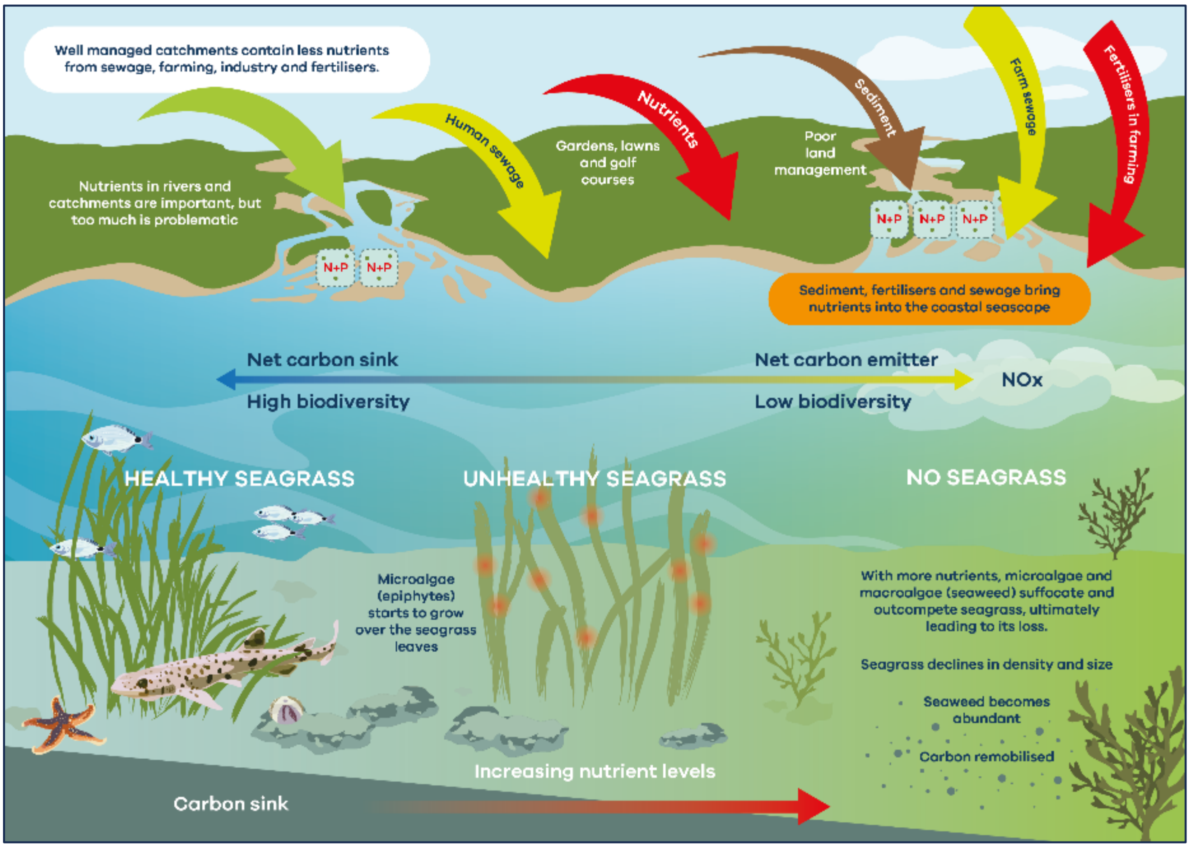

Figure 11 - Potential sources of nutrients in coastal waters and their impacts upon shallow water seagrass.

Seagrasses derive N from sediment pore water (especially ammonium) and the water column (most nitrate). The importance of leaves versus roots in nutrient acquisition depends, in part, on the enrichment conditions. For example, a shift from reliance on sediment pore water to increased reliance on the overlying water for N and P supplies has been observed under progressive water-column nutrient enrichment [33].

Although nitrogen levels may appear to be relatively high in a particular setting, the actual nitrogen available for seagrasses (particularly within the pore water) may be substantially lower leading to a range of studies finding that nitrogen enhancement leads to increased seagrass growth, even in locations thought to be awash with nutrients [34, 35]. These challenges in understanding the impact of nutrient levels on seagrasses highlight how little we understand of the key dynamics of this relationship. Given the potential and known negative impacts on seagrasses globally, it's vital we have a better understanding of these processes.

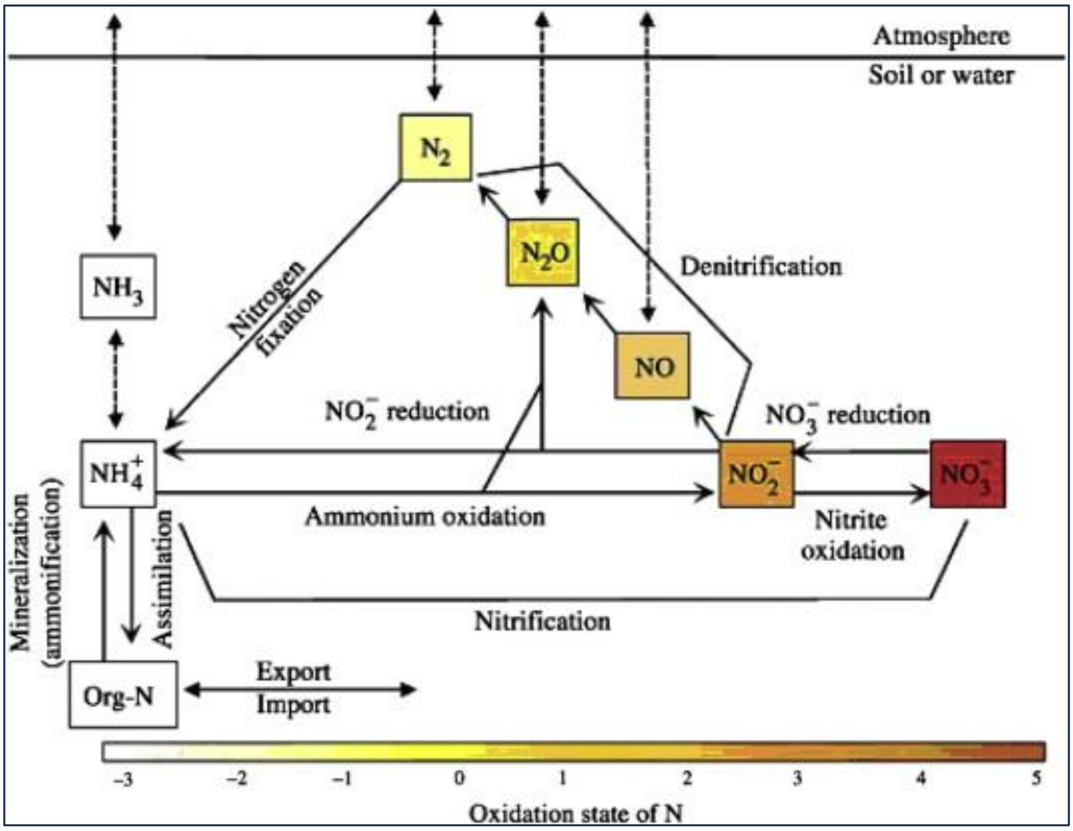

Figure 12 - Principal inter-conversion routes for nitrogen in the biosphere (From (Statham, 2012).

Seagrass Status in the MHW

Seagrass has been assessed within the MHW since the 1970's with records spanning back as far as the 1960's [7]. Early records are likely less accurate as methods are unclear and available technology (e.g. GPS units) limited; however, good descriptions exist within this data including some estimates of the amount of aerial coverage. Seagrass was first assessed and monitored quantitively in 1987 [36] and until the late 2000's a series of adhoc assessments were undertaken. In 2007 intertidal seagrass was first monitored within the Pembroke River as part of the management of the power station and has continued annually since. In addition, Natural Resources Wales (formerly as CCW) commenced intertidal seagrass monitoring (% cover and area) across a range of meadows in the MHW at a series of sites (see Map 1) that have mostly continued annually, creating over 10 years of data for a range of sites. These intertidal meadows have mostly been dominated by Zostera noltii with some limited coverage of *Zostera marina* (referred to in those historic data as Zostera angustifolia). Assessment of *Zostera marina* in the MHW has been less consistent and detailed over time. The recent report by [37] contains a summary of this and the data is included in the present report.

Intertidal Zostera noltii

The area coverage of intertidal seagrass (predominantly comprised of *Zostera noltii*) in the Milford Haven waterway is showing long-term sustained increases (Figure 9). This is predominantly being driven by increases in the Pembroke River populations that in 2022 were over 128ha. Other sites such as Pwllchrochan have also observed increases such that in 2022 this meadow was found to cover >6 hectares, yet in 1992 there was no seagrass found at all. Recent increases in Angle have also occurred, bringing coverage back to levels estimated to have been observed in the early 1970's.

Although the spatial extent of many of these seagrass meadows has increased, the density of the seagrass (% cover) has been highly variable throughout the period of monitoring from 2007 to 2022 with an average of 53.5 ± 15.5%. However, geographic differences are present. In line with the spatial increase at Pwllchrochan, seagrass density has also increased to values upwards of 80% cover; however, at Pembroke River, where seagrass has also increased in coverage, there is a variable but generally negative trend in the density of the seagrass. Sites within the Upper Estuary are also showing long-term declines in seagrass density. Although the data at these sites is extensive both spatially and temporally it doesn't provide much detail in terms of the health of the system in terms of its nutrient enrichment.

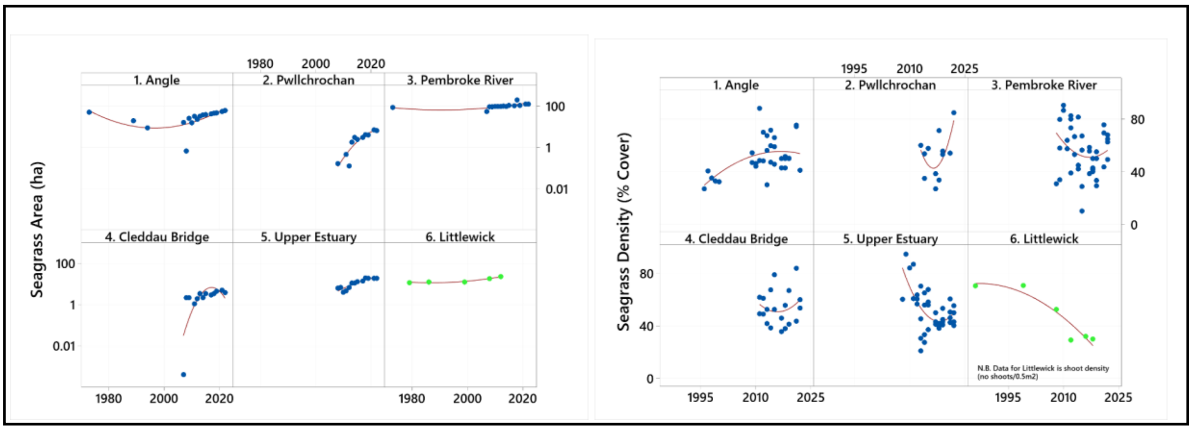

Figure 4a & 13b - Total seagrass coverage (hectares) and density (% cover) within the five broad intertidal (Zostera noltii) areas of the Milford Haven Waterway from the 1970's to 2022. Additional data is also included from the Littlewick Bay meadow of subtidal Zostera marina.

Subtidal Zostera marina

The largest *Z. marina* meadow within the Milford Haven waterway is found at Littlewick, west of Milford Haven and Gelliswick Bay, with smaller meadows or patches found at Longoar Bay, Angle Point, Castle Beach Bay Hakin Point and Dale. There have also been historic records of *Z. marina* at Sandy Haven and a few other locations within the inner Haven where populations are no longer present. The seagrass meadow at Littlewick is the only meadow that has been monitored in the long-term and was first assesssed in 1979 (F. Bunker). Six detailed diving and video based assessment surveys have since been conducted with the most recent in 2018 [26, 36-39]. Seagrass area coverage (hectares) has over time increased and almost doubled to 2018, however this is in contrast to a clear long term decline in seagrass shoot density that has halved since 1986. In addition, the canopy height of the seagrass has also decreased significantly [26].

The seagrass in Longoar Bay is first described in 1989 [40] to cover an area of approximately 35 hectares. In the review by Quentin Kay in 1998, he dismissed this conclusion. However, data from a survey in 1999 finds remnant patches across much of the area outlined by Howard, suggesting his estimate may be more accurate than first thought. When investigated in 1999, the meadow at Longoar was found to be generally patchy (Irving and Worley, 2000), but in 2000, volunteer divers [41] conducted a thorough survey, collecting shoot densities and providing baseline data. (Surveys by NRW in 2018 collected more data for Longoar Bay.) Recent surveys have also confirmed a more detailed understanding of populations of subtidal *Zostera marina* near the Angle RNLI station, Castle Beach Bay, and recently restored meadows in Dale; however, detailed area estimates are not available at present.

Zostera angustifolia is described in many previous intertidal seagrass data and reports from the Milford Haven Waterway. It is now clear that this is an ecotype of *Zostera marina* and not a distinct species [42]. Within more contemporary surveys and reports there appears to be less reference to this species in an intertidal context. A 1995 survey of the intertidal populations found less presence of this species in locations previously known to contain it. Pembroke River and Angle Bay are two localities where there is now less reference to the species, however this has never been fully quantified. Any decline in *Zostera marina* within intertidal meadows relative to abundant *Zostera noltii* would likely reflect the declining light availability given the high light requirements of this species relative to the smaller Dwarf Eelgrass.

Zostera marina is the dominant seagrass species present in the subtidal environment. This species is far bigger than the 'Dwarf Eelgrass' *Nanozostera noltii* that lives in the upper-intertidal. It is also a perennial species, whereas Dwarf eelgrass tends to have a far bigger winter senescence and is often an annual. These two species although nominally both seagrasses fill different ecological niche and with it provide very different foundational species roles. As a permanently flooded environment, the subtidal *Zostera marina* is a key fish habitat, whereas the intertidal distribution of *Nanozostera noltii* creates a key foraging habitat for coastal wading birds [43]. It is likely that the permanent habitat also has a far greater capacity to accumulate carbon, cycle nutrients and baffle wave action.

Seagrass Thresholds

Although the scientific literature on seagrass is rich in information about the decline of its health and coverage in the context of elevated nutrients, we still do not have clear findings as to what is the safe operating space for seagrass. We do not have any certainty as to threshold values beyond which certain species will cease to survive.

Thresholds for nitrogen loading into seagrass have been determined for other localities [44-46]. However, our analysis of data on water quality and nitrogen loading in the MHW (2508 tonnes N/year, or 57.2/km2/year)) indicate that these values have been surpassed [47], yet seagrass remains extensive. This indicates they don't apply, probably due to the environmental conditions of the waterway (i.e. the high rates of tidal flushing)[48].

What can be observed from the intertidal monitoring programme relative to the available linked data on nitrogen is that above a total nitrogen concentration of 0.75mg/L, seagrass is far less abundant; we hypothesise this is a potential tipping point or threshold for nitrogen impacts on intertidal seagrass. We emphasise that this remains only an hypothesised threshold, but is the first such analysis of seagrass data relative to nutrients that we're aware of in the UK. Developing certainty on this threshold would need further investigation to improve the confidence of this number and to create a value that reflects a safe operating space (a healthy and productive system) rather than just a threshold [49]. A threshold for phosphorus could not be proposed because of a lack of data due to less monitoring in the marine environment.

This hypothesised threshold of a total nitrogen concentration of 0.75mg/L, does not consider the needs of the subtidal seagrass that is dominated by *Zostera marina*. Sub-tidal plants are far more sensitive to light reduction brought about by phytoplankton and suspended sediments that interact with nutrients in the water column, such concerns mean that a threshold is much likely a lot less, an argument backed up by strong evidence of long-term seagrass decline in Littlewick Bay.

Although we document that *Zostera noltii* exists in areas of higher nutrient concentration than 0.75mg/L of total nitrogen concentration, it is not healthy and could be near the point of collapse. In many areas below that point it is also likely to be unhealthy given the concerns about macroalgal smothering of the intertidal. Although speculative given poor data, some studies have found that with increasing levels of eutrophication in the coastal environment, nitrous oxide (NoX) production (a potent Greenhouse Gas 300 times more powerful than Carbon Dioxide) can be significant. In mangrove systems, seawater nitrogen concentrations above 0.31mg/L resulted in significant NoX emissions [50]. In the MHW we're well above that point, suggesting that the waterway could be a significant emitter of NoX.

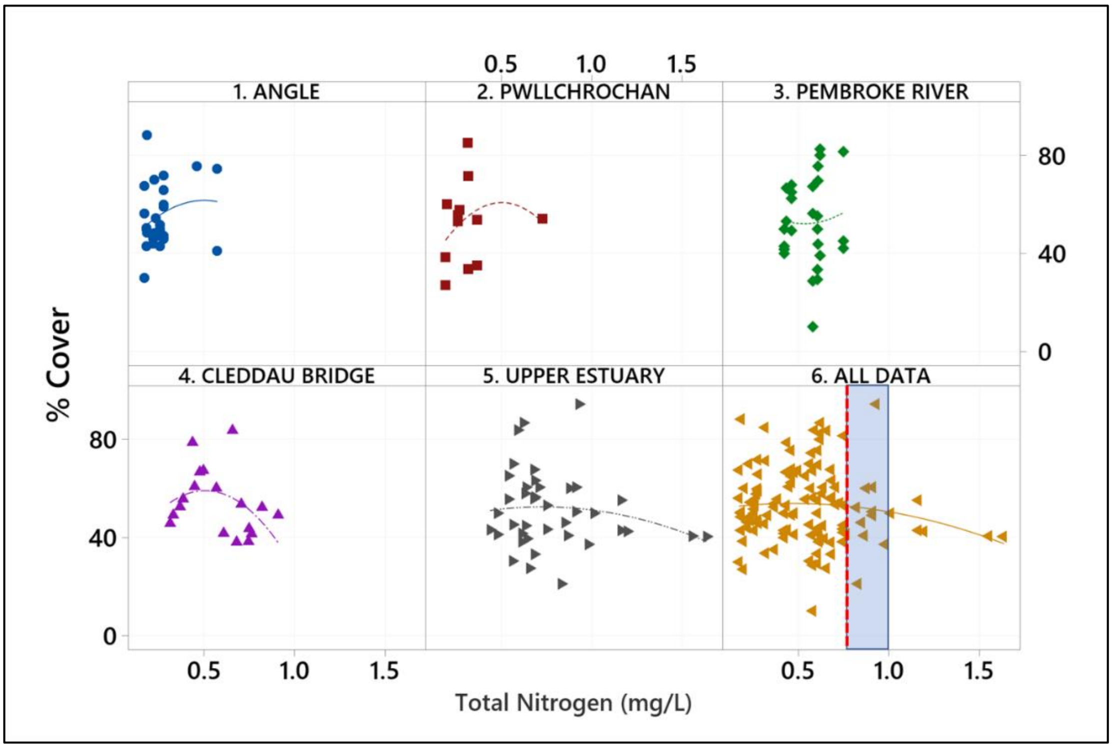

Figure 14 - Seagrass coverage within the five broad intertidal (Zostera noltii) areas in the Milford Haven Waterway relative to the average Total Nitrogen content of the water. Within a sixth figure showing the relationship between all seagrass % cover data and Total Nitrogen we hypothesise a potential management trigger point and water quality threshold that may reflect the point (>0.75mg/L) beyond which seagrass in the Milford Haven Waterway begins to degrade.

Seagrass Opportunities

Intertidal and subtidal areas of seagrass in the MHW are under stress, principally due to water quality concerns from excess nutrients, mostly nitrogen, but also phosphate as well as suspended sediments. Whilst we have long-term data on nitrogen (namely nitrate and ammonium) we have a limited understanding of present phosphate levels and next to no knowledge of suspended and accumulating sediments and the impact they are having on seagrass habitats. In addition, the long-industrialised nature of the MHW and many dredging and construction programmes has left sediments rich in many contaminants, whose influence on seagrass is likely significant but not understood in any detail [4].

Although most of the seagrass in the MHW is under some level of stress, there is explicitly clear evidence of increasing extent of intertidal seagrass, and declining state of subtidal seagrass. In order to improve seagrass health throughout the MHW, the evidence of increasing eutrophication suggests that water quality improvement schemes have to be a major component of any level of recovery package for seagrass. Although water quality is highly problematic within the inner reaches of the MHW, areas closer to mouth of the estuary have clearer water, less suspended sediments and nutrients are much lower suggesting recovery is possible. This creates opportunities for action that can improve the biodiversity and habitats of the MHW.

A number of disturbances are also present on seagrass habitats throughout MHW that are poorly quantified. Bait digging is a key disturbance, and remains prevalent in places such as the Gann where seagrass recovery has commenced but remains limited by persistent digging. In addition, boating impacts remain on seagrass and poor mapping of seagrass mean that even the most environmentally conscious boaters might inadvertently anchor in seagrass. Active recovery of seagrass is already happening within the lower reaches of the MHW. These include *Zostera marina* restoration efforts in Dale by Swansea University, Project Seagrass, WWF, Pembs Marine SAC and Pembrokeshire Coastal Forum. These programmes although slow to develop into improved areas of seagrass are now showing significant promise with extended habitat now largely visible.

Opportunities for long-term recovery of seagrass in the MHW have to be driven by improvements in catchment wide water quality, as well as better management of sediments, however a number of actions can be taken to facilitate improved rates of recovery. Within the lower reaches of the MHW active restoration could potentially be expanded, this could be as an addition to the work ongoing in Dale. Removal of stressors such as bait digging would open up opportunities for increased restoration work in the Gann and further discussions and engagement with local communities might facilitate expanded restoration within the Dale Roads area. In addition, investments in more sustainable mooring systems to relieve stressors could also open up restorative opportunities.

Project Seagrass in collaboration with partners are investigating new potential areas for restoration within the MHW (Dale, Angle, Castle Beach Bay) and within the wider area beyond the heads of the Waterway (Saundersfoot, Freshwater East, Caldey Island and Lydstep).

Saltmarsh

Saltmarshes are near-horizontal platforms identified by largely continuous cover of salt-tolerant (halophytic) vascular plants (grasses, rushes and shrubs). In the transition zones between the lower mudflats and the upper terrestrial areas of the salt marsh, annual plant species may prevail in the marsh canopy, while perennials dominate the upper regions. Adjacent tidal flats often harbour a wealth of invertebrates with highly specialised adaptations. Within the vegetated salt marsh, the richness of invertebrate species varies greatly and is sensitive to localised conditions. Saltmarshes serve as vital habitats for breeding, feeding, and roosting birds, many of which are migratory, as well as for fish and aquatic/marine invertebrate species [51].

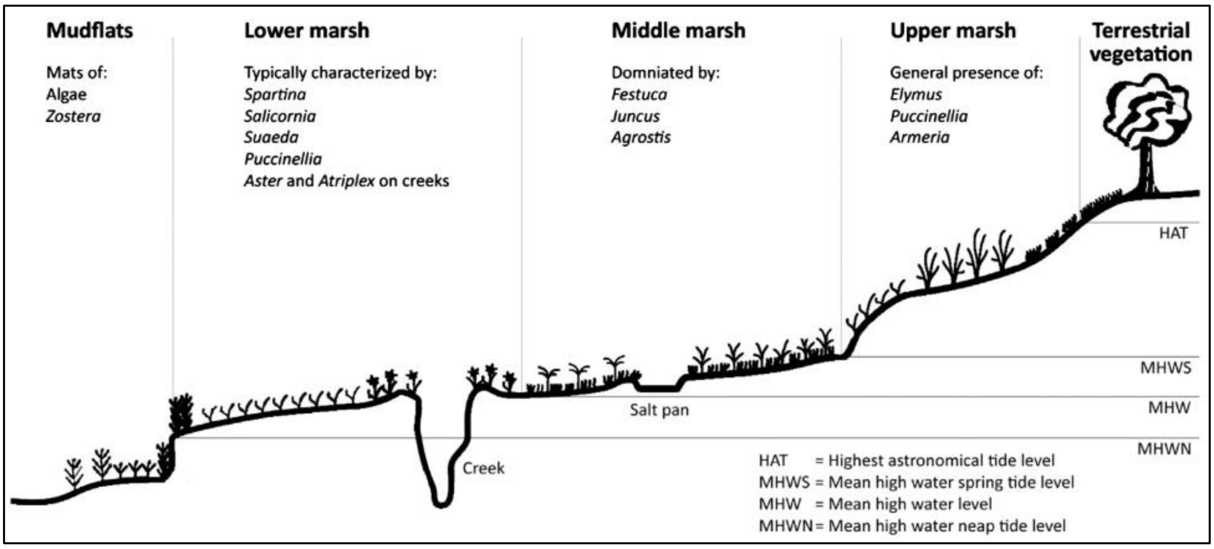

Figure 15 Generalised separation of intertidal habitats of Saltmarsh based on elevation in relation to tidal height (Davis et al., 2018)

Large portions of the Milford Haven waterway feature vast stretches of salt marshes and Atlantic salt meadows. These meadows border both sides of the waterway and reach into the expansive shallow bays of Dale, Angle Bay, Sandy Haven, Pembroke River, and extend further upstream into the Carew and Cresswell Rivers, as well as the Western and Eastern Cleddau (www.pembrokeshiremarinesac.org.uk/).

Salt marshes and mudflats are included in Annex I of the Habitats Directive and are listed as 'habitats of principal importance' under Section 7 of the Environment (Wales) Act 2016. Additionally, these habitats often play a significant role within broader 'habitat' features such as 'estuaries' and 'large shallow inlets and bays'. Many mudflats and salt marshes in Wales are further safeguarded as features of Ramsar sites, Special Areas of Conservation (SACs), or Sites of Special Scientific Interest (SSSIs), and/or serve as supporting habitats for the bird interest features of numerous Special Protection Areas (SPAs)(Armstrong, Pearson, Williamson, Frost, Scott 2021). Atlantic Saltmarsh is a designated feature of the Pembrokeshire Marine SAC.

Nationally and globally, there have been significant losses of these intertidal habitats, primarily as a result of human activities, particularly land reclamation and the development of sea defences, ports, and harbours. It is estimated that around 100,000 hectares of British salt marshes were lost between 1600 and 1900, mainly to create more land for agricultural purposes [52]

Saltmarsh Constraints

Saltmarsh (Atlantic Salt Meadow) as a designated feature of the Pembrokeshire Marine SAC is found in both the inner (upstream of the Cleddau Bridge) and the outer water body (Cleddau Bridge to Mid Channel Rock) of Milford Haven. While their distribution and extent have been deemed favourable, the structure and function component has been assessed as unfavourable due to elevated levels of dissolved inorganic nitrogen (DIN) and the presence of macroalgae, which can suffocate saltmarsh species. In 2018, NRW provided the overall indicative assessment of unfavourable with an overall confidence level of medium, while citing relevant activities directly impacting condition of the designated feature as water pollution point sources, diffuse pollution, and sediment pollution (Natural Resources Wales, 2018).

In addition to existing pollution inputs that put pressure on saltmarsh habitats, it is important to consider the wider constraints of coastal processes and geomorphology that can create challenges to effectively restore or create sustainable new saltmarsh in areas that have insufficient supply of fine sediment or lack of accommodation space at suitable elevations, or high wave exposure which can erode fine sediment [51].

There are also challenges to obtaining permission to undertake restoration efforts that should be accounted for, such as marine licensing with NRW, planning permission with Pembrokeshire County Council, foreshore and seabed leases (landowner permission) with the Pembrokeshire Coast National Park Authority , impacts on protected areas/features/wildlife as the site falls within the Pembrokeshire Marine SAC, and impacts on flood and coastal protections [51]. These constraints are not touched on in detail in this report but should be a part of wider consideration of feasibility of saltmarsh restoration.

When saltmarshes are situated in sheltered water bodies like estuaries, coastal embayments, or back barrier settings, saltmarshes can fulfil a significant function in regulating water quality. For instance, they can mitigate high nutrient levels by absorbing inorganic nutrients such as phosphates and nitrates. However, excessive nutrient levels can also have adverse effects and diminish the future resilience of salt marshes [51]

An evidence review published in 2016 by Natural Resources Wales of the trophic status of the Milford Haven Waterway found the entire body of water is hyper nutrified with areas upstream of the Cleddau Bridge of Milford Haven with more evidence of impacts of eutrophication on water use [6].

Eutrophication, characterised by excessive nutrient loading, has been demonstrated to diminish root growth in certain instances among salt marsh plants, thereby decreasing sediment stability and heightening erosion risks [53]. This erosion risk can be more pertinent if the area of saltmarsh is also facing higher sea level / wave action, due to climate change and in areas facing coastal squeeze preventing the saltmarsh from naturally advancing inland.

Coastal squeeze refers to the loss or degradation of natural habitats due to human-made structures or activities that obstruct the inland movement of these habitats in response to sea level rise (SLR) and other coastal processes. This phenomenon particularly impacts habitats located seaward of existing structures. Coastal squeeze when combined with sea level rise leaves saltmarsh exposed to erosion at the seaward edges through increased wave exposure. In addition, coastal squeeze prevents saltmarsh from advancing inland and can lead to increased inundation by seawater which can alter habitat zonation potentially leading to high marsh species being progressively replaced by lower marsh species [51].

The Shoreline Management Plan (SMP) which covers the outer haven up to Pembroke Dock and Neyland does indicate that there will be effects of coastal squeeze (www.southwalescoastalgroup.cymru/the-smp20-area). The upper estuary is not covered by the SMP, though NRW is currently undertaking a report on deterioration due to coastal squeeze using best available data for all MPAs across Wales. Preliminary data shows that the upper estuary will have future coastal squeeze predicted of a similar order of magnitude to the outer estuary. There is also additional ‘natural squeeze’ where habitat is squeezed against natural features or high ground rather than structures. Both aspects are relevant in terms of context for restoration activities.

There has not been a study in the Milford Haven Watery on the effects of nutrients and density of root growth. It could be possible to speculate locations where the diminished root growth would be possible or likely to occur due to excessive nutrient loading, by relating extent or distance to identified areas of regular opportunistic algal mats in existence within the Milford Haven Waterway (See Figure 3). This diminished root growth, combined with lowered resilience to wave exposure and sea level rise can both potentially lead to increased erosion risk and loss of existing habitat, possibly constraining suitable locations for restoration efforts.

Approximately 40 different species of plants have been found in UK saltmarsh, with each individual saltmarsh typically harbouring between 10 and 20 species. However, when considering the broader spectrum, a greater number of plant species can be found in the upper and transitional zones [54]. Multiple peer-reviewed sources provided strong evidence indicating that nutrients, particularly nitrogen (N), influenced the species composition of various marsh zones within the European context, resulting in the presence of both “winner” and “looser” species [76].

Typical species diversity of upper to mid-marsh tend to decrease with additional N, while combined high N and P addition sped up succession through increased biomass of late successional species [76]. However, the specific species involved may vary depending on both abiotic and biotic factors, such as sediment type, salinity, deposition/accretion, temperature, pH, and existence of grazing animals. Overall, there was strong evidence suggesting that a lower marsh species Atriplex portulacoides (Sea Purslane) and an upper marsh species Elymus athericus (Sea Couch) tended to exhibit positive or at least neutral responses to higher nutrient availability [76]. This suggests that in areas affected by high levels of nutrients a saltmarsh may be present or feasible through restoration, but it is likely not to contain many species and thus not overall as biodiverse, though it could be sequestering carbon well alongside playing a role in nitrogen removal.

Within Milford Haven and the identified constraints of the geography, geomorphology, nutrient loads, and existence of coastal squeeze, it would be important to set the right restoration goals and objectives. A goal or a measurement of success of the ability for saltmarsh to sequester carbon and the removal of nutrients is likely to be more achievable than setting a goal of a saltmarsh with high levels of biodiversity. Clearly defining targets for the restored saltmarsh is essential while considering the desired size, species, habitat types, and functions as the project's outcomes. During this process, it is important to recognize that it takes time for saltmarsh plants and animals to become established, the area may not develop exactly as a natural saltmarsh would, and that saltmarshes naturally undergo succession, meaning interim habitats are valuable although they may not be aesthetically pleasing to all stakeholders [77].

Current saltmarshes have been assessed in an unfavourable status and excess nitrogen levels, and the existence of macro algae have been cited as contributing factors. Nutrients can benefit saltmarsh plant species, at excessive levels nutrient, particularly nitrogen, can have adverse effects through diminished root growth. This diminished root growth can leave saltmarshes vulnerable to erosion, and this erosion risk can be a larger issue when an area is prevented from natural advancement inland by coastal squeeze. Some saltmarsh species are more tolerant to excessive nutrients, and this may lead to less diversity of species particularly in the mid to upper marsh. Constraints were not found that would prevent saltmarsh restoration beyond having the suitable land and the practical site selection factors that are outlined in the Natural England produced ‘Saltmarsh Restoration Handbook- UK & Ireland’.

Saltmarsh Thresholds

There is some evidence that different forms of nutrients can have both positive and negative impacts on saltmarsh species’ establishment and development [76]. However, the literature review did not yield definitive evidence on how specific nutrient forms, at particular concentrations in marine environments, pose a threat to UK saltmarsh plant species or communities. The challenge lies in integrating diverse metrics of impacts (biotic and abiotic) into a comprehensive measure. Within a “Rapid evidence assessment of impact of nutrient on saltmarsh” commissioned in 2023 by Natural England, there was a lack of data within studies with the majority not reporting nutrient additions, forms, and or background availabilities, and or had conflicting results for particular species [76]. Without all relevant metrics, it's difficult to assess the total nutrient pressure affecting a species or vegetation community. These challenges prevent quantifying the threshold at which a species is lost from a saltmarsh or the point at which species’ gain or loss triggers vegetation changes impacting saltmarsh integrity [76]

Nutrients, once at high enough levels, can contribute to growth of opportunistic macro algae which can compete with species in the low and mid zone of saltmarsh. Nutrients combine with several other factors such as water temperature, salinity, and light availability, and makes determining a specific level of nutrients that trigger macro algae proliferation a challenge. It is generally accepted across several studies that the opportunistic macro algae competes with the species within the pioneer saltmarsh zone, as shown in Figure 16 below. There does not seem to be a specific known level of nutrients that triggers this growth.

Figure 16 Opportunistic macroalgae growing over Salicornia spp. (pioneer saltmarsh) at Angle, 2014. (Haines & Edwards, 2016)

The importance of this lack of understanding of the nature of nutrient loading and the effects on current saltmarsh habitats and future restoration efforts is known. The UK Hydrographic Office is funding further research by academia into the dynamic of nutrients and saltmarsh species and is currently in recruitment for a researcher.

It is known that nutrients can have both positive and negative effects on the growth of saltmarsh, there is also not a known threshold or particular level of nutrients that would pose a threat to saltmarsh species and communities. It is understood that opportunistic macro algae can out-compete with pioneer saltmarsh at a key stage of saltmarsh evolution. It is not known at a specific location from year to year what level of nutrient concentration causes the proliferation of opportunistic algal mats. It is known where these mats regularly form within the Cleddau Estuary, though intensity of the algae can change each year. With the absence of a known specific level of nutrients in the water column that is a threat to saltmarsh or a known level of nutrients that triggers opportunistic macro algae, the density and extent of macroalgae should be considered which is monitored through SAC condition assessment and is available on request from NRW.

Saltmarsh Opportunities

There have been several mapping exercises of saltmarsh extent within Milford Haven over the past 20 years, though fewer detailed investigation of opportunities or feasibility studies for restoration purposes have been conducted. This is potentially due to the geomorphology of Milford Haven being a ria with deep water near shore and quick rising sides limiting the spatial opportunities beyond existing extent. This aspect of being a natural safe haven for shipping has led to extensive industry in the outer haven and the quick rising ground has allowed development (housing and agriculture) right up to the edge of the mean high water in many places.

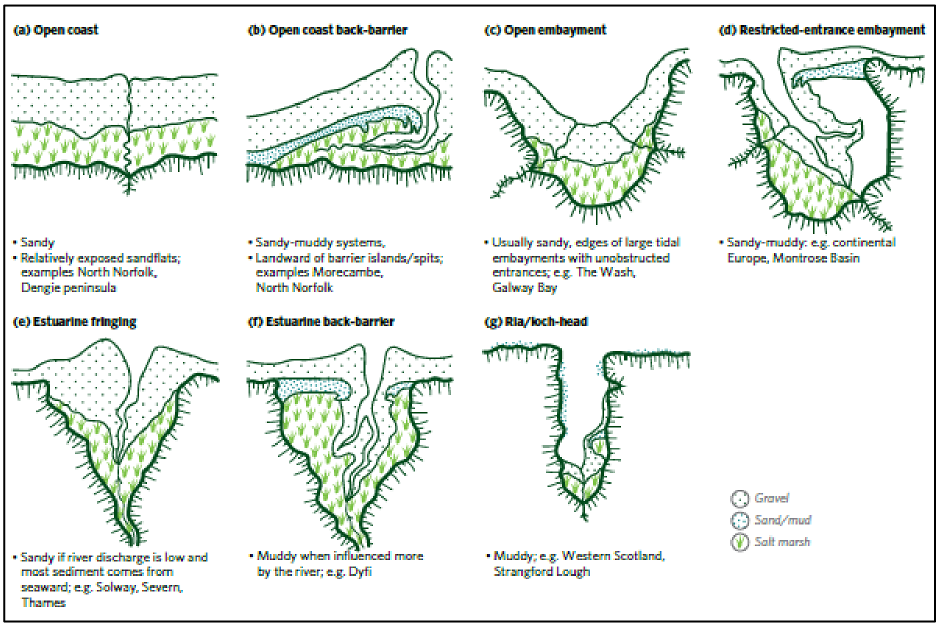

Figure 17 Seven distinct saltmarsh context identified by Allen (2000) citied in [77] Illustrating the natural constraints of saltmarsh extent within a ria(g) compared to other types of coastal environments

Recent opportunity mapping for saltmarsh Wales-wide conducted by NRW (Restoring marine and coastal habitats in Wales: identifying spatial opportunities and benefits, May 2021), show areas throughout the Milford Haven and Cleddau Estuary. This data is viewable & downloadable through DataMapWales here (Salt Marsh Opportunity Map Wales 2021). Though when considering these opportunities presented in the 2021 NRW mapping, which are based on methodologies that were designed as an initial search rather than a tool for identifying a suitable site, there are numerous areas that are not practical to pursue for restoration. This is due to no land use filtering being undertaken prior to the mapping, so existing urban areas, smaller settlements, industrial units and areas with international or national conservation designations reside within the opportunity mapping. Below are examples of where the opportunity mapping overlays with existing uses that are unlikely to align with restoration work. Shown through Figure 18 are 'opportunities' in or near Pembroke Dock with existing heavy industrial, residential and commercial uses.

🟩 Saltmarsh Extents ⬜ Saltmarsh Opportunities

Figure 18 Salt Marsh extent in green, opportunity mapping in grey which highlights the RWE power station and areas of residential and commercial use as opportunities for saltmarsh restoration

There are also areas of the current extent of saltmarsh within the opportunities which might be able to be considered for restoration actions to remove pressures aiding recovery to a higher functioning ecological system rather than large scale habitat creation restoration work. Below are examples of where the opportunity mapping overlays with existing extent of surveyed saltmarsh. Figure 19 illustrates this overlap of extent and opportunity in an area in the upper Western Cleddau Estuary just outside Haverfordwest near the farm of Lower Haroldston and the village of Uzmaston.

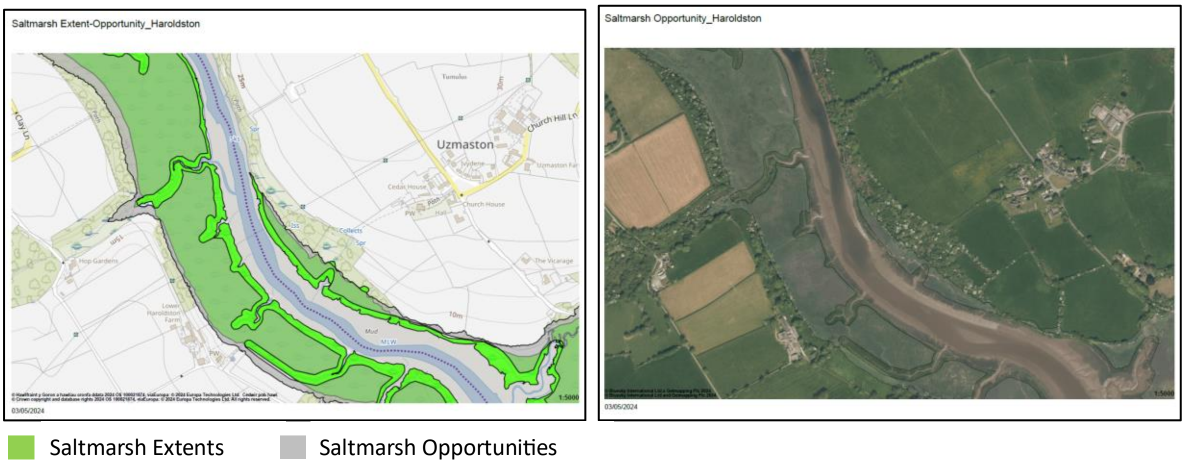

Figure 19 Highlight existing saltmarsh which is within saltmarsh opportunity mapping just outside of Haverfordwest on the Western Cleddau Estuary.

Even with limited spatial opportunities due to the natural geomorphology of the area being a ria, and the aspects of coastal squeeze due to the developed nature of the area, it is important to keep in mind that even small areas of saltmarsh can provide great benefits due to their high levels of unique biodiversity and the range of functions they provide. Particularly the services of provisioning resources and habitat structures needed for bird breeding, wintering and migratory staging, as well as important fish nursery grounds [77]. Through this research no existing efforts could be found beyond the NRW mapping in 2021 to identify sites for saltmarsh restoration within Milford Haven or the Cleddau Estuary.

There were no managed realignment opportunities found through the Shoreline Management Plan (SMP) which do not cover the upper estuary and stops at the Cleddau bridge between Neyland and Pembroke Dock.

However, there are potential opportunities when considering areas within Flood Risk Zones identified by NRW. NRW have identified coastal areas that are at a chance of flooding from the sea in a given year. These areas are shown in two zones - Natural Resources Wales / Flood Map for Planning / Development Advice Map

- 'Sea – Flood Zone 2' - Areas with 0.1% to 0.5% (1 in 1000 to 1 in 200) chance of flooding from the sea in a given year, including the effects of climate change.
- 'Sea – Flood Zone 3' - Areas with more than 0.5% (1 in 200) chance of flooding from the sea in a given year, including the effects of climate change.

If we consider areas within current Flood Risk zones 2 & 3 along the Cleddau where the habitat is not currently saltmarsh, 'natural' transitions could potentially be created/restored where there is currently intensive agricultural management. This could be done by establishing positive conservation management within these areas and removal of/or modifying constraints to tidal inundation. This will also facilitate saltmarsh establishment with sea level rise as these areas become inundated more regularly. There could also be a consideration of how the water quality regulating functions of greater and improved saltmarsh-adjacent seagrass could benefit seagrass health. There are areas in both the inner and outer estuary that warrant consideration of flood risk zones and natural transitioning. Below in Figure 20 A & B is an example using Garron Pill in the upper estuary where both saltmarsh and seagrass currently exist, and there is adjoining agricultural land and coastal flood risk.

Figure 20 A & B - Garron Pill in the upper Cleddau Estuary saltmarsh and seagrass extent shown with flood risk zones over agriculture land with positive conservation management and removal of/or modifying constraints to tidal inundation could allow natural transitions and expansion of saltmarsh.

There have not been specific areas identified for saltmarsh restoration within the Cleddau Estuary through a formal report or project. It is recommended that an initial step to any saltmarsh restoration would be a detailed feasibility study building on previous habitat and opportunity mapping to identify priority sites for restoration efforts. There should be consideration of future flood risk, the ability to create natural transitions, and adjacent intensively farmed land. This feasibility study should include both biotic and abiotic factors which can affect saltmarsh health and development as touched on briefly within the saltmarsh constraints section of this document.

Native oysters

The native oyster (*Ostrea edulis*) has a rounded, rough shell, typically displaying a pale yellow or green hue, and is often adorned with light brown or blue concentric bands, though shell coloration may vary. Oysters function as filter feeders, employing their valves to propel water across fine, hair-like gill structures, thereby filtering microscopic algae and small organic particles from the surrounding water [55].

Native oysters are listed as a species of primary significance pursuant to Section 7 of the Environment (Wales) Act 2016. Additionally, oyster beds are listed as a habitat facing threats and decline under OSPAR [55]. Among European marine habitats, native oyster reefs rank among the most threatened, with populations in the UK and Ireland plummeting by 95%. This decline has resulted in the loss of vital ecosystem services and functions formerly provided by these habitats [55].

In Milford Haven and the Cleddau Estuary, oysters were once considered plentiful, with historical records indicating fishing and trade activities dating back to the 1600s [79]. During the first half of the 1800s, peak catches exceeded 1000 oysters per boat within a 3-to-4-hour fishing window. However, by 1870, catches had sharply declined, making it increasingly challenging for remaining fishers to sustain their livelihoods [79].

There are a small number of active restoration efforts currently ongoing in Wales, namely The Wales Native Oyster Restoration Project (WNORP) in Milford Haven, Natur am Byth! Native Oyster Project in Milford Haven, The Wild Oysters project in Conwy Bay, and work by the Mumbles Oyster Company Ltd. in Swansea Bay [79].

Native Oyster Constraints

While Native Oysters are still found within the Cleddau Estuary, surveys of the historical Native Oyster beds show them to be found patchily distributed and at low densities [79]. A study conducted Milford Haven Native Oyster Regeneration project in 2017, [82]identified several factors contributing to the low oyster densities in the Milford Haven Waterway (MHW).

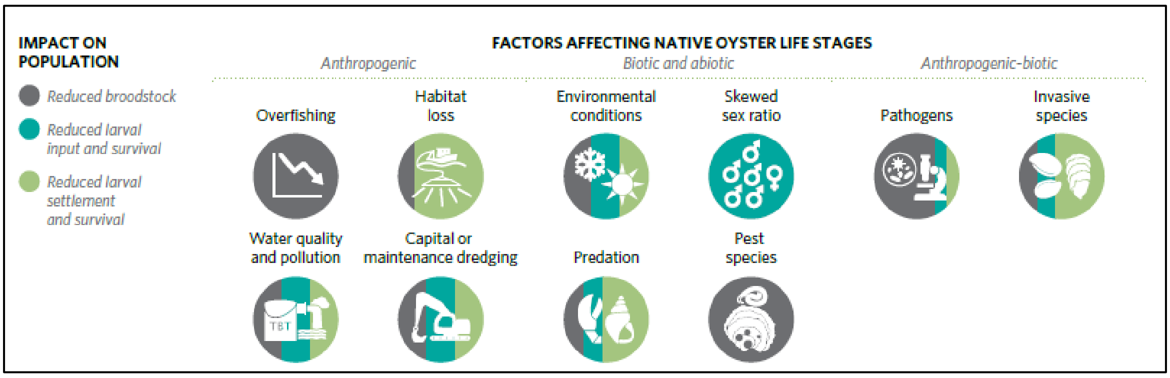

Figure 21 Factors affecting native oysters at different life stages (adapted from Helmer et al. 2019 citied in Preston J., Gamble, C., Debney, A., Helmer, L., Hancock, B. and zu Ermgassen, 2020)

These factors encompassed the absence of broodstock, the presence of Bonamia, and the inadequate quality of cultch. Furthermore, the prevalence of the American slipper limpet in certain areas was recognised as a factor to consider when evaluating potential restoration sites.

The invasive American slipper limpet Crepidula fornicata first recorded in the Milford Haven Waterway in 1953 [79]. The American slipper limpet (*Crepidula fornicata*) has been shown to negatively affect oyster populations when present in large numbers. It can outcompete oyster larvae for food (Blanchard et al., 2008; Preston et al., 2020a) and compete with the Native Oyster for settlement substrate (Preston et al., 2020a). Additionally, high densities of American slipper limpets reduce the biodiversity benefits associated with Native Oyster presence [81], thereby impacting both ecosystem function and recovery potential. Slipper limpets have locally reached very high abundances in the MHW, and was its original location of introduction to Wales [81]. Significant anecdotal evidence now indicates that these limpets cover vast areas of the hard substratum of the Waterway within thick beds, although limited spatial data on their extent is available. Efforts to remove or reduce these Limpets in other parts of Europe have largely failed indicating that they are now a long-term part of the ecosystem.

The pathogen *Bonamia ostreae* was detected in the Milford Haven Waterway in 2006 (Laing et al. 2014). The disease can cause mortality rates as high as 80% in affected oysters, the prevalence of Bonamia in the UK is relatively low, typically ranging from 10-20%, with correspondingly low mortality levels (https://www.gov.uk/government/publications/bonamia-exitiosa/bonamia-exitiosa).

In general, native oyster beds aren't regarded as greatly affected by alterations in water clarity, shading, deoxygenation, nutrient/organic enrichment, or smothering/siltation rate changes. However, they do exhibit a moderate sensitivity to localized reductions in salinity [83].

The European Native Oyster habitat restoration handbook identifies the formation of a robust native oyster reef that relies on four key life-history processes: survival, growth, reproduction, and recruitment [55].

These 4 processes are shaped by various abiotic factors, including seabed dynamics, water depth, salinity, temperature, oxygen content, current velocity, and the concentration of suspended particles in the water column, as well as by biotic factors such as adequate phytoplankton levels, predation, diseases, and population density [55]. Excess nutrients have not been identified amongst these abiotic and biotic factors that limit the formation of native oyster reefs.

Native Oyster larvae need a clean, preferably carbonate substrate to settle on. While they prefer settling on the shells of other living native oysters ,they can also settle on various other mollusc shells and carbonate surfaces [79]. The choice and availability of cultch is crucial for optimizing restoration, with settlement rates on blue mussel (Mytilus edulis) shells being nearly three times higher than on scallop (Pecten maximus) shells under laboratory conditions [79].

In addition to there being suitable substrate present, the substrate also has to be accessible to the oyster larvae. Fine sediment deposition on suitable cultch impairs settlement and recruitment of Native Oysters, so areas with high sedimentation should be avoided [79].

The availability of oysters is a major hold-up in European Native Oyster restoration efforts [80]. This bottleneck in supply is exacerbated by the specific needs of many restoration efforts. For example, restoration efforts might wish to consider introducing only stock bred from local broodstock, in order to maintain any current genetic structure [79]. The disease status of imported oysters must also be considered. For the Milford Haven Waterway, although importing oysters from areas affected by Bonamia is allowed, it is not advisable to introduce additional stock from Bonamia-positive regions due to the currently low incidence of the disease [79].

Though oyster still exist, it has been identified that the absence of enough density of mature breeding specimen along with the existence of slipper limpets, the oyster disease Bonamia, and suitable settlement substrate constrain oyster reef formation. The existing density of mature breeding specimens prevents enough larvae to be produced for appropriate levels of reproduction. The existence of high levels of slipper limpets which compete for food with native oysters during the larval stage add to this challenge of appropriate levels of reproduction. It is also known that the preferred substrate for settlement, i.e. other oysters were lost through overfishing long ago, this increases the challenge of successful reproduction of existing oysters. Many of the constraints for native oysters' reproduction and growth of extent relate to not having enough oysters currently. It is also known that the availability of oysters for restoration efforts is a challenge across the UK. Bomania is a disease affecting native oysters that has been known to cause up to 80% mortality in European waters and is present in the Cleddau Estuary, though at low levels and generally across the UK mortality rates of 10-20% are seen from Bonamia. Nutrient enrichment even at high levels, changes in water clarity, or siltation were not found to be constraints to native oyster populations.

Native Oyster Thresholds

There is some evidence that native oysters are not highly sensitive to changes in water clarity or shading, deoxygenation, nutrient / organic enrichment or smothering / changes in siltation rate (MarLIN, 2020). Though it is suggested to consider areas where potential high sedimentation loads are possible such as areas near dredging activities, as the deposition of fine sediments on suitable underlying cultch impairs settlement and ultimately recruitment of Native Oysters to the population, therefore areas of high sedimentation should be avoided [79].

In a report produced by the Milford Haven Waterway Environmental Surveillance Group on 'Bioaccumulation surveillance in the Milford Haven Waterway' in 2010, it is recognised that Tributyltin (TBT) and heavy metals are known to be fatal to oysters and their larvae [79]. Both are monitored within the Milford Haven Waterway. TBT levels in the MHW are highest in the lower reaches, near the port. In the lower estuary, TBT levels in mussels were above the lower Environmental Assessment criteria for mussels, meaning that sublethal effects are possible, but levels are below those which would be lethal [79].

It seems that research indicates that there are a variety of abiotic factors and biotic factors that are important in site feasibility of a restoration site that are more significant than excess nutrients. These abiotic and biotic factors are processes such as seabed dynamics, water depth, salinity, water temperature, water oxygen content, current velocity, concentration of suspended particles in the water column, substrate, sufficient levels of phytoplankton, predation, diseases, and population density of existing native oysters [55].

The existence of native oysters due to the ability to provide substrate and the highly gregarious nature of the species appeared across several sources of key importance. Providing or placing young oysters on suitable substrate in the absence of existing extent or in low density areas is also seen to be of key importance, alongside the protection from physical disturbance by high levels of sedimentation.

Native oysters are not reported to be sensitive to high levels of nutrient enrichment, water clarity, or suspended solids (unless extremely high) so a nutrient threshold and the environmental factors caused by nutrient enrichment is likely not the greatest importance to successful restoration efforts. The existence of mature oysters in sufficient numbers without levels of Bomania high enough to enable enough production of larvae and provide suitable substrate for further reef formation appears from the evidence to be a more important threshold to consider than nutrients in the water column or the associated environmental factors caused by nutrient enrichment.

Native Oyster Opportunities

Native Oyster habitats in Wales are extremely scarce, with only 0.01 km^2 identified through mapping efforts [83]. Native Oysters are still found within the Cleddau Estuary, with several surveys of the historical native oyster beds having been undertaken in between 2002 and 2021. Throughout this recent time period, oysters have been found patchily distributed and at low densities [79]. Native oysters are highly gregarious, meaning that oyster larvae prefer to settle where other oysters are present, so having even limited existing presence can be interpreted as a positive for current and future restoration efforts [80].

Restoration is recommended in areas that historically supported native oyster populations. However, several environmental, biological, ecological, and logistical factors must be considered to determine if restoration is feasible or realistic at a given location [80].

Oysters need a firm substrate, like shell material, for settlement, enabling them to create structured habitats. These habitats, known as oyster reefs, are created as vast numbers of living oysters and accumulated dead shells combine to establish an expansive habitat on the seafloor [80].

Since 2010, there has been no commercial oyster fishing in the Milford Haven waterway, following the Welsh Government's taking over of fisheries responsibilities following to the Marine and Coastal Access Act 2009. Prior to this change, commercial oyster fishing interest was primarily concentrated upstream of the Cleddau Bridge. Preliminary guidance from Natural Resources Wales (NRW) indicated that such activity was likely to impact the reef feature within the Pembrokeshire Marine Special Area of Conservation and without a Habitats Regulations Assessment demonstrating that the activity does not adversely affect the Special Area of Conservation, the Welsh Government cannot issue permits for oyster fishing [79]. There is however a commercial oyster farm (Atlantic Edge Oysters) within Angle Bay that alongside pacific oysters also produces native oysters and is potentially a source for broodstock for restoration efforts. This oyster farm uses modern raised off the seabed oyster bag system to grow their product, which avoids the detrimental effect to the environment that are associated with oyster dredging. Many of the beneficial provisioning services associated with oysters both native and pacific (*magallana gigas*) such as removal of nitrogen and phosphate, and improved water clarity are still delivered in a farmed environment. There is the potential for a growing commercial oyster farming or bivalve aquaculture sector to play a role in improving water quality while being a part of a low carbon food production.

Setting goals early in the restoration planning process is important and can determine locations, engagement priorities, and measures of success. For example, a restoration project for solely conservation objectives verses a project with fishery objectives would potentially differ greatly. Consideration of native oyster restoration is not a new concept, as early as 1953 there were proposals for a project within Milford Haven, as identified by report from the South Wales Sea Fisheries District Committee ‘Possibilities of reviving oyster culture in Milford Haven’ proposed areas in Dale and Angle Bays alongside Pennar Gut for supporting commercial fishing [84]. More recent restoration efforts have had a more conservation focus and being located upstream of the Cleddau Bridge, where there is now protection from commercial fishing.

Historical oyster beds surveys have been analysed through the Nature am Byth project considering the opportunities and barriers for restoration within the historical footprint of these oyster beds. Five sites were a part of this analysis with the majority of the sites being upstream of the Cleddau Bridge, and sites being identified for availability of suitable substrate, presence of invasive species, siltation rates and presence of native oysters [79]. Further drop-down and diver surveys at 4 sites were undertaken through a second phase of the Nature am Byth, with all sites upstream of the Cleddau Bridge between the bridge and Llangwm with detailed site selections analysis carried out and described in the interim project report “Natur am Byth! Native Oyster Project: February 2023” [78]. The Nature am Byth project has followed this survey and analysis work with deploying a batch of 20,000 native oysters across the identified suitable locations in May 2024 (Facebook, May 7th available at https://www.facebook.com/reel/1506673569887978). The scope of Nature am Byth is limited to a four-year timeframe between September 2023 and September 2027, and with the work being only a part of a wider project, resources are limited, and activity needs to deliver effective public engagement alongside species restoration. It is about involving people in species recovery and encouraging a wider range of people to benefit from nature in Wales and contribute to caring for it [78]. There is potential for the progress of native oyster restoration delivered through Nature am Byth to be furthered, from a foundation data driven and well monitored project.

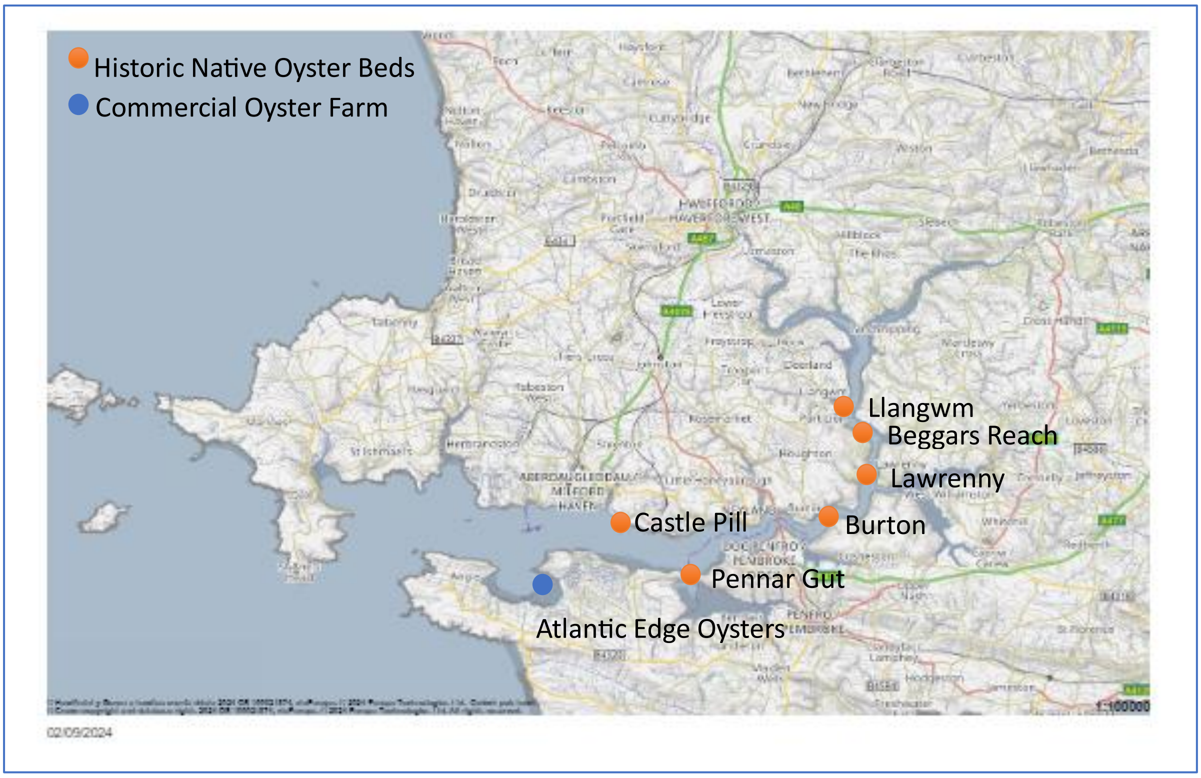

Figure 22 Locations of historic native oyster beds and commercial oyster farms

Historic native oyster beds are known within the Cleddau Estuary with some of these still home to native oysters at low densities. This is a positive opportunity as it shows environmental conditions are still viable and there is some suitable substrate for settlement. Upstream of the Cleddau bridge is protected from oyster dredging due to the reef features of the Pembrokeshire Marine SAC. This would protect restoration efforts from commercial fishing in this area. There is a commercial oyster farm within the outer haven at Angle Bay that produces both pacific and native oysters and could be a source of broodstock for restoration efforts. There are also the existing regulating ecosystem services of this low environmental impact production of oysters and expansion of this type of oyster farming could benefit water quality/clarity for other habitats and species. There is currently a data driven and well monitored native oyster restoration project that has deployed over 20,000 oysters in four historic oyster beds that have low densities of existing oysters. This native oyster restoration project, Nature am Byth is limited by funding and delivery timescale and there is opportunity to continue and build on this existing restoration effort.

Discussion

Seagrass is well known to be highly susceptible to declines in water quality, namely excess nutrients that lead to these productive plants becoming out-competed by macro and micro algae [56]. Places such as Denmark [57] and the Chesapeake Bay [58, 59] have been through long-term processes of degradation and eventual recovery that highlight how managing these problems is key to facilitating a productive marine environment. Here we draw on over 40 years of data on seagrass and over 20 years of data on water quality to examine the trends of a changing long-term environment in the Milford Haven Waterway that reveal some stories of optimism and resilience for intertidal seagrass, but also highlight the rapidly degrading water quality that is pushing the marine systems of the Waterway closer and closer to a point of collapse.

Saltmarsh area limited but beneficial

Saltmarsh within the Milford Haven Waterway exists throughout at a limited extent due to both natural geomorphology of the area and habitat loss due to coastal squeeze. Existing saltmarsh meadows are not in a favourable condition with both point and diffuse sources of water pollution cited as relevant activities causing this status. At excessive levels, nutrients have been identified as causing an imbalance of biomass above ground and diminished root growth leaving saltmarsh less resilient to dynamic current or wave action [76]. Though saltmarsh extent is not massive within the waterway, it is important to not overlook the magnitude of the regulatory and provisioning ecosystem service functions that even small areas of saltmarsh can provide in reducing sedimentation and increasing biodiversity [77]. The regulatory functions of resilient saltmarsh should be considered in enabling better environmental conditions for other species more sensitive to nutrients and loss of light through turbidity such as seagrass, particularly subtidal populations of *Zostera marina*.

The Outer Milford Haven Waterway

There is strong evidence that the intertidal seagrass and the water quality within the outer reaches of the Milford Haven Waterbody (MHW) are in a much better state than the inner waterway. Seagrasses in this area are expanding, whether this is an early response to stress or they're in an a healthy state remains to be seen, with the density and extent of the seagrass undergoing long-term increases, shown through figure 13a&b. At Pwllchrochan, seagrass (*Nanozostera noltii)* is also expanding very rapidly, and Pembroke River is close to its maximum intertidal potential, meanwhile data on nitrogen and phosphorus show levels well within values acceptable for health-recovering seagrass [10, 11]. There is no indication that water quality has improved over time in these areas, so the drivers for this are unclear, but we hypothesise that this is possibly as a result of an interaction with the warm water outflow from the power station, as *Nanozostera noltii* has a far higher temperature tolerance (relative to *Zostera marina*) at up to 37°C [60]. Alternative explanations could be changes in shipping or dredging activities reducing intertidal disturbance and sedimentation, or alternatively long-term climatic and environmental changes influencing the populations [61]. A recent analysis of long-term data on intertidal seagrass in the Thames [62] found that summertime seagrass density levels were highly correlated with wintertime freshwater inputs and low terrestrial temperatures, possibly due to the effect of these conditions upon seed germination. We have very little understanding of these relationships in the MHW. The subtidal seagrasses in this area are mostly in an abundant and healthy state, although they do have elevated leaf tissue nutrients relative to background. Although challenges have existed with subtidal seagrass restoration projects running near to the mouth of the estuary at Dale, they're generally on a strong pathway to long-term success due to the environmental conditions being generally affable for seagrass [63, 64]. Although not considered within the scope of this report, the remnants of the Mearl Beds impacted in the 2000's by major dredging are still present in the outer estuary area and remain protected under a range of fisheries orders, however low light availability from poor water quality (nutrients and sediments) is likley a major impact upon their long-term viability.

The Inner Milford Haven

Further up the estuary the story of the Inner Milford Haven waterbody is somewhat more complex and provides an increasing picture of an eutrophied estuary. Water quality, namely excess nitrogen and phosphorus is a significant threat to the environment and marine biodiversity of the middle and upper reaches of the Milford Haven Waterway. The data we present here only re-emphasises these points in more detail given previous Natural Resources Wales' reports highlighting the waterway's eutrophied status. High resolution temporal data collected in 2013-14 alongside detailed spatial long-term monitoring until 2023 finds nitrogen levels to be excessively high and impacting the trophic status of the Waterway.

Haines and Edwards [65] calculated that the annual nitrogen load into the Milford Haven Waterway is approximately 2193 tonnes/year, with a total area of 2192 hectares, which equates to a loading of 21.92 Mg/Km2/year. This is above the point at which previous research has found estuarine systems to flip from seagrass to algal dominance [66]. Since that loading calculation, background values of Total Nitrogen in the water column have increased further and are over one-third higher, further putting the estuary's trophic balance in doubt.

Since 2000, 92% of water quality assessment sites have recorded their highest ever values throughout the 23 years of monitoring and have shown trends of increasing nitrogen (nitrate and nitrite) availability, suggesting that not only is the trophic status of the estuary already in peril, but is getting worse. These concerns are particularly acute further up the estuary at sites such as Carew, Beggars Reach, Landshipping and Hook, as well as in the Pembroke River that have nitrogen concentrations well above 0.5mg/L.

High Levels of nitrogen concentrations within the waterway are also evidenced through the regular occurrence of opportunistic macro algae which outcompetes pioneer saltmarsh smothering these species (Natural Resources Wales, 2018). Areas prone to smothering macro algae are well known, mapped and shown on Figure 3, as is the relationship to excess nitrogen. The agriculture sector is the largest source of these nutrients (Haines & Edwards, 2016). What is less known, is what proportions of excess nutrients within the agriculture sector are arising from what land management actions.

Although seagrass at many sites has increased in area, and in some cases density at sites near the middle point the estuary, there is a clear trend of decreasing density in the upper reaches over time, suggesting that the seagrass in those areas is at or above a threshold of degradation and loss. This aligns with evidence that those sites further up the Estuary are increasingly covered with large areas of opportunistic macroalgae. Loss of those meadows at places such as Garron Pill could lead to the loss of sediment and the nitrogen held within them, reducing the nitrogen cycling and burial of the seagrass. Analysis of the data on Total Nitrogen relative to the seagrass area and seagrass % cover data doesn't show any strong relationships, however in a general sense, within outer estuary sites where nitrogen is low, increases in concentration have led to increases in density and area. However, within the upper reaches, this is not the case, and slight negative relationships can be observed.

Using data collected on nitrogen burial rates from the same species in other locations[67, 68], we calculated the amount of annual nitrogen burial that may occur as a result of the intertidal seagrass area known to be present in the waterway (219 hectares of *Zostera noltii*. We find that *Zostera noltii* is likely to be burying between 17.5 and 30.7 tonnes of nitrogen permanently into marine sediments. Based on previous estimates of the costs of nitrogen removal with other means [69], we apply these costs to the estimates of the amount of burial in the Haven and find the *Zostera noltii* meadows to have an annual economic value of between £0.35 to 0.61 million per year. The less abundant subtidal *Zostera marina* meadows have a lower confidence in the spatial extent and therefore confident numbers of nitrogen burial rates were not able to be calculated.

Difference between *Zostera marina* and *Zostera notlii*

Subtidal seagrass comprised of Zostera *marina* is far less abundant in Milford Haven waterway relative to the intertidal Zostera *noltii* and anecdotal evidence suggests that it used to be far more extensive. This lesser abundance of Zostera *marina* is likely the result of increasing turbidity and reduced light availability brought about by increasing degradation of the integrity of the waterway and the increasingly eutrophied catchments. The biggest subtidal meadow is that at Gelliswick, that in common with some of the intertidal meadows further up the Waterway, is showing increasing long-term signs of stress and degradation including the canopy becoming smaller, increasing coverage of epiphytes and the density of shoots falling by over a half [26]. This meadow at Gelliswick, along with other areas of Zostera *marina* assessed for their tissue nutrients, also paints a picture of very high levels of nitrogen and phosphorus in the water column relative to global levels and rank amongst the highest values recorded across the British Isles [12].

The potentially major impacts of excess nutrients present in the Milford Haven Waterway have, for a number of years, been masked by high levels of inter-annual variation, weak data and intertidal seagrass meadows increasing in area. In the present report, we for the first time highlight the whole picture of how seagrasses as 'canaries of the sea', together with data on water quality are increasingly showing a system within the mid to upper reaches of the estuary undergoing severe eutrophication. *Zostera marina* is showing severe signs of stress, nitrogen and phosphorus levels are extremely high and indicative of levels known to lead to a collapse in similar systems, and the intertidal *Zostera noltii* is increasingly smothered by opportunistic marine algae.

Inconvenient truth: seagrass remains extensive

When presented relative to other studies globally about seagrass responses to water quality, nutrient conditions in the Milford Haven Waterway appear severe. Nitrogen loading is beyond levels likely to support seagrass, concentrations of nitrogen in the water are well above those of healthy systems, and the elemental levels of nutrients are well in excess of global averages, but the inconvenient truth here is that seagrass remains extensive in the Milford Haven Waterway. Although we can't be certain as to the reason for this, we hypothesise that the residence time in the Waterway is short, and therefore, the nitrogen has less of a biological impact [70]. Given the Milford Haven Waterway's large tidal range of approximately 6.3m, the tidal flushing is likely high. However, this is influenced by the freshwater dilution, which will change between years and seasons.

Although the seagrass is still extensive and relatively dense throughout the Milford Haven Waterway, we don't know enough about its actual condition. Not only does this limit our ability to understand status, but it also limits our ability to predict whether changes such as the density declines in locations such as Garron Pill are indicative of a more widespread problem and are perhaps early indicators of the system being close to a water quality state that would cause collapse. Where detailed data exists on shoot density, canopy height, elemental nutrients and leaf condition at Gellsiwick, we see evidence of meadows in a poor state of health and potentially very close to collapse. The intertidal monitoring programme, whilst hugely successful in collecting large-scale annual data, does not quantify metrics likely to be indicative of sub-lethal nutrient impacts such as changes in canopy height, micro and macro algal overgrowth, and changes in elemental C, N, and P. What we can see from the intertidal monitoring programme relative to the available linked data on nitrogen is that above a Total Nitrogen concentration of 0.75mg/L, seagrass is far less abundant; we suggest this as a nutrient level threshold.

Seagrass in state of stress in mid and upper Estuary

Evidence of marine habitat collapse from other parts of the world indicates that habitats and ecosystems largely don't slowly degrade, they usually reach thresholds beyond which total collapse rapidly occurs. Sometimes, this can be brought about by a gradual change to a parameter, but it may also be brought about by a natural perturbation in the system when it is vulnerable and has a lack of ability to resist stressors. When the system is already in a state of stress, its resilience is likely compromised, restricting its ability to resist that perturbation and, importantly, recover from it. Here we see an environment in the mid and upper Milford Haven Waterway that is in a state of stress, awash with nutrients that ultimately limit the light available to seagrass and place its resilience in doubt, meaning that energy stores may be low, and the meadow may even have become fragmented. Having a resilient seagrass meadow is as much about the ability of the system to recover from stressors as it is resisting those stressors [71]. A system where resilience is low may have seedling development that is compromised by factors such as algal overgrowth and sediments whose resuspension following seagrass collapse would restrict recovery [72].

Oysters less affected by nutrients

Native Oysters seem to be less affected by the presence of excess nutrients and more affected by other biotic and abiotic factors. An important factor is getting oyster extent and habitat to densities high enough to enable natural settlement of spat on suitable substrate. Recent restoration efforts through Natur am Byth have been focused upstream of the Cleddau Bridge in areas of higher nutrient concentrations, and if proven successful could provide regulatory ecosystem services for other species and habitats. A single oyster can filter up to 200 litres of seawater per day, which can significantly improve water quality and clarity. Oysters can also assimilate excess nutrients and promote microbial activity in the underlying sediments to denitrify nitrates and nitrites, thus removing them from the water body [80].

A commercial oyster farm (Atlantic Edge Oysters) based in Angle Bay within the outer Milford Haven has had success in growing oysters in a modern raised off the seabed oyster bag system and has measured both carbon reduction and nutrient removal. Atlantic Edge oysters have reported a sequestration of 2.4 tonnes of carbon per annum, while also removing between 400-600kg of nitrogen and 100-200kg of phosphate from the waterway. These numbers were calculated by considering ~12% of an oyster shell is accounted for by carbon which is locked up for the long-term, and that oysters contain approximately 2-3% nitrogen and 0.5-1% phosphate by weight.

Increasingly, coastal restoration efforts are looking to understand the potential mutual benefits or even enhanced success that may arise from such “integrated restoration” including seagrass, saltmarsh and oyster habitats across a wider area [79]. There is potential for oysters and saltmarsh to play a role in reducing the pressure that seagrass is under due to the elevated levels of nutrients within the Milford Haven Waterway and the Cleddau Estuary.

Although we often think of habitat in a binary sense, particularly when we consider habitat area and ecosystem services, there is very good evidence that there is at least a linear relationship between seagrass habitat health and ecosystem functioning and services. Increasing eutrophication of seagrass globally has been found to significantly alter the associated food web at a range of different levels of the food web [73], including the fish assemblages that are seen as one of the most financially valuable ecosystem services provided by seagrass [74].

Summary of Findings

Fortunately, the Milford Haven Waterway and the Cleddau estuary still contains biodiverse and productive habitats such as seagrass and saltmarsh, and although these remain fairly plentiful, they are very much the remnants of a formerly productive and biodiverse seascape. The oyster reefs that once supported vast fisheries are long gone left only with a few oysters on historic beds (Select

Committee, 1876 cited in Zu Ermgassen P.S.E. 2022). Seagrasses are becoming atrophied, and so unfortunately are the saltmarshes that are suffocated by increasing levels of macroalgae in a body of water that is understood to be hyper-nutrified (Haines & Edwards, 2016). We also understand that many areas once known to contain seagrass and saltmarsh no longer do so, and areas likely to have previously done so have had their shallow water intertidal areas built upon for coastal infrastructure [75].

The existence of these special habitats even in a stressed state due a variety of factors can be seen as a positive, but it indicates urgent action is needed if there is desire for them to remain and ultimately thrive. In this research we have looked at what is 'known' 'and 'unknown' related to the opportunities, constraints and nutrient environmental thresholds to inform future marine restoration efforts in Milford Haven and the Cleddau Estuary.

Seagrass

Seagrasses are susceptible to low light and algal overgrowth, therefore changes in seagrass distribution, abundance and condition can be related to environmental conditions (McMahon et al., 2013; Bertelli et al., 2021). Seagrasses are in a perilous state, principally due to poor water quality, and excess nutrients creating eutrophic conditions (Jones & Unsworth, 2016; Jones et al., 2018; Unsworth et al., 2024b). Nutrients are problematic for seagrass plants because they result in less light becoming available for seagrass to photosynthesise. Light reduction happens through stimulation of high-biomass algal overgrowth as epiphytes and macroalgae in shallow coastal areas and as phytoplankton in deeper coastal waters. Nitrogen is generally the most problematic nutrient impacting seagrass and is available in coastal and estuarine waters in a range of forms (Nitrate, Nitrite and Ammonium).

A pattern of increasing nutrients (N & P) was found with increasing distance up the estuary nearer the river and further from the sea. Sites in the outer estuary (Thorn Island, Texaco Jetty, Depot Jetty and Pennar Mouth) with concentrations of 0.28 ± 0.12 mg/L, middle of the estuary (Pembroke River, Cleddau Bridge, Mill Bay, Cosheston Pill) had on average over double the total nitrogen concentration of the outer estuary at 0.58 ± 0.20mg/L. Cosheston Pill was a noticeable anomaly with nearly 3 time the outer estuary. The upper estuary sites (Carew, Beggars Reach, Landshipping, Hook) had total nitrogen levels with an average of 0.91 ± 0.37mg/L over three times the concentration at the estuary mouth. This was found with consideration of both traditional water quality monitoring and through analysis of seagrass tissue. Previous research has shown that concentrations of 0.5mg/L and below reflect areas home to healthy seagrass (Benson et al., 2013). Total seagrass coverage (hectares) and density (% cover) was analysed and with a noticeable and defined decline in density of coverage could be seen at sites with total nitrogen of (>0.75mg/L) beyond which seagrass in the Milford Haven Waterway begins to degrade. This point at (>0.75mg/L) of total nitrogen which happens at sites in the transition between the middle and upper estuary is hypothesise a management trigger point and water quality threshold.

There is an existing *Zostera marina* restoration project in Dale which is beginning to become an established bed of seagrass. There are opportunities to support the expansion of this seagrass bed in both coverage and density, and there are potentially other sites in the outer haven with lower nutrient pressures that would be suitable for restoration. There are also opportunities to reduce the impact of anthropogenic disturbance of *Zostera marina* caused through anchoring and moorings by engaging and supporting change within recreational users. There are beds of *Zostera noltii* that are doing well, growing in both coverage and density in the mid and outer areas of Milford Haven, at Pwllcrochan and Pembroke River for example. There is potential for these beds to serve as donors of small areas of *Nanozostera noltii* to be transplanted to increase coverage and density of the donor meadow itself or other areas. There is also opportunity to increase the health of existing beds of *Zotera noltii* within inlets or bays where a significant proportion of nutrient loading is from smaller coastal sub catchments. This could be achieved through increasing the regulatory water quality functions of adjacent saltmarsh or oyster restoration, or direct reduction in the terrestrial environment.

Saltmarsh

Current assessments indicate that saltmarshes are in an unfavourable condition, with excess nitrogen levels and the presence of macroalgae identified as contributing factors. While nutrients can benefit saltmarsh plant species, excessive levels of nutrients, particularly nitrogen, can have adverse effects by reducing root growth. This reduction in root growth makes saltmarshes more susceptible to erosion. This erosion risk is exacerbated when natural inland advancement is blocked by coastal squeeze. Some saltmarsh species are more tolerant of excessive nutrients, leading to decreased species diversity, especially in the mid to upper marsh. No constraints were found that would prevent saltmarsh restoration, provided suitable land is available and practical site selection factors, as outlined in the Natural England 'Saltmarsh Restoration Handbook - UK & Ireland,' are considered.

Nutrients can have both positive and negative effects on saltmarsh growth, but there is no known threshold or specific nutrient level that poses a threat to saltmarsh species and communities. Opportunistic macroalgae can outcompete pioneer saltmarsh species at crucial stages of saltmarsh evolution. It is not clear at what nutrient concentration this proliferation occurs from year to year in specific locations. However, in the Cleddau Estuary these mats regularly form, though their intensity varies each year. Without a known specific nutrient level that threatens saltmarsh or triggers opportunistic macroalgae, an alternative measure to identify a threshold could be the density and extent of macroalgae. This could be determined by the percentage of ground cover by algae mats, assessed using aerial photos, though the validity of this method needs further investigation.

Specific areas for saltmarsh restoration within the Cleddau Estuary have not yet been identified through any formal report or project, though there seem to be opportunities in areas of agriculture land with future flood risk. Considering the regulating ecosystem service functions of even small areas of saltmarsh to intercept / remove sediment and nutrients, the proximity to other priority habitats such as seagrass should be contemplated. It is recommended that the initial step for any saltmarsh restoration should be a detailed feasibility study. This study should build on previous flood risk and saltmarsh opportunity mapping to identify priority sites for restoration. Consideration should be given to future flood risk, the ability to create natural transitions, and the presence of adjacent intensively farmed land. The feasibility study should include both biotic and abiotic factors that can affect saltmarsh health and development, as briefly discussed in the saltmarsh constraints section of this document.

Native Oyster

Although oysters still exist, the formation of oyster reefs is constrained by the low density of mature breeding specimens, the presence of slipper limpets, the oyster disease Bonamia, and a lack of suitable settlement substrates. The current low density of mature breeding oysters results in insufficient larval production for adequate reproduction. Additionally, high levels of slipper limpets, which compete with native oysters for food during the larval stage, further hinder reproduction. The loss of preferred settlement substrates, such as other oysters, due to overfishing, also poses a significant challenge to successful oyster reproduction.

Many of the constraints on native oyster reproduction and growth are due to the insufficient number of existing oysters. Furthermore, the availability of oysters for restoration efforts is a challenge across the UK. The disease Bonamia, which can cause up to 80% mortality in European waters, is present in the Cleddau Estuary at low levels, with UK mortality rates generally between 10-20%. Nutrient enrichment, even at high levels, along with changes in water clarity or siltation, have not been found to constrain native oyster populations.

Native oysters are not reported to be sensitive to high levels of nutrient enrichment, changes in water clarity, or suspended solids (unless at extremely high levels). Therefore, nutrient thresholds and the environmental factors caused by nutrient enrichment are likely not of the greatest importance for successful restoration efforts. Instead, having a sufficient number of mature oysters without high levels of Bonamia, to produce enough larvae and provide suitable substrate for further reef formation, appears to be a more crucial factor to consider than nutrient levels in the water column or the associated environmental factors.

Historic native oyster beds exist within the Cleddau Estuary, some of which still host native oysters at low densities. This presents a positive opportunity, as it indicates that environmental conditions remain viable and there is some suitable substrate for settlement. The area upstream of the Cleddau Bridge is protected from oyster dredging due to the reef features of the Pembrokeshire Marine SAC, safeguarding restoration efforts from commercial fishing. Additionally, a commercial oyster farm in the outer haven at Angle Bay produces both Pacific and native oysters, potentially serving as a broodstock source for restoration efforts. The low environmental impact of this oyster farming also provides regulating ecosystem services, and its expansion could benefit water quality and clarity for other habitats and species. Currently, a data-driven and well-monitored native oyster restoration project, Nature am Byth, has deployed over 20,000 oysters in four historic beds with low densities of existing oysters. However, this project is limited by funding and delivery timescale, presenting an opportunity to continue and build on the existing restoration efforts.

To create opportunities with high levels of success for restoration of seagrass, saltmarsh, and native oysters within the Milford Haven Waterway, action is needed at many levels. Principally, within the catchments this will require reducing the impact of the water quality crisis, but also the consideration of alternative schemes such as establishment of major bivalve and seaweed aquaculture. In addition, whilst the precautionary approach should be to take urgent action to reduce the eutrophic state, action is also required to better understand the tipping points and levels of stress to which the seagrass of the Waterway is under. This desk-based report has looked at what is ‘known’ and what is ‘not known’ related to opportunities, constraints, and nutrient environmental thresholds. The next section makes suggestions for further research to address those that are ‘not known’ that have been indicated as important to the success of restoration efforts.

Knowledge gaps and further research

Whilst seagrass remains abundant throughout the Milford Haven Waterway, there remain many knowledge gaps about its functioning that require filling in order to improve our management of these productive resources. The recent exercise to define 100 questions for seagrass conservation in Europe (Nordlund et al., 2024) highlighted the need to understand the tipping points for anthropogenic threats to seagrass ecosystems and the effects of land use change and other terrestrial activities on seagrass ecosystems. In the present report, we document unprecedented concentrations of nitrogen in the Milford Haven Waterway. Recommendations for further research include;

- What are tipping points and safe limits of nutrient pressures on seagrass species in lab setting? To inform data gathered in real world settings.
- Gather the current health status of meadows across the estuary and collect actual enrichment level of nutrients to verify effects on health.
- What are the effects of land use change and other terrestrial activities on seagrass ecosystems? Particularly change in small sub catchments verse the wider catchment?
- How do the method and spatial arrangement of transplant units affect seagrass restoration success?
- Define the actual role seagrass plays in Nitrogen cycling.
- What are the impacts of eutrophication on turning seagrass from a sink to a source of Green House Gas(GHG) emissions?
- How can Citizen Scientists be engaged to map and monitor seagrass meadows at sufficient scales to improve conservation?
- How can the public be involved and contribute to the conservation and restoration of seagrass habitats?

There is a lack of evidence on how saltmarsh condition, life-stage, and surrounding vegetation responds to nutrients. The Natural England report Impacts of nutrients on saltmarsh: A rapid evidence assessment, March 2023 made recommendations to address the known lack of knowledge on the effects of nutrients on saltmarsh habitats. [76] these would be useful for any saltmarsh restoration effort UK wide.

- Conduct experimental and survey studies in UK marshes at appropriate scales to understand how saltmarsh species and vegetation communities respond to various forms and amounts of nutrients. These studies should also examine the direct and indirect effects of increased nutrient availability on multiple trophic levels and marsh stability over both short and long timescales.
- Conduct research to quantify the nutrient drivers of change in saltmarsh ecosystems by considering all input pathways. This includes nutrient concentrations in the marine environment as well as fluxes from terrestrial habitats and the atmosphere.
- Linked to this quantification of nutrient driver, there is a need to develop a metric of nutrient pressure that can account for different nutrient inputs to saltmarsh plants and vegetation communities.

There is also not a relevant feasibility study on potential saltmarsh restoration sites in Milford Haven that goes beyond the opportunity mapping completed by NRW which has recognised limitations with the methodologies used. It is recommended that a study is completed to determine the practical area of restoration that is possible related to the ecosystem benefits, site specific constraints and the cost to deliver.

There is an active oyster restoration project (Natur am Byth) within the Milford Haven Waterway and the Cleddau Estuary, there is limitations on these efforts and the monitoring of the sites being used due to the resource and timescale of the funding. It is recommended that further monitoring would help understand how the oysters placed in these sites are confronting the pressures discussed in the report to mature into a functioning oyster reef. In the Aquatic Conservation: Marine and Freshwater Ecosystems Volume 30, Issue 11, a consortium of native oyster specialists highlighted “Forty questions of importance to the policy and practice of native oyster reef restoration in Europe” (zu Ermgassen PSE, Bonačić K, Boudry P, et al. 2020). Below is a selection of questions with relevance to Milford Haven and the Cleddau estuary.

- How does population density affect reproductive success in native oysters?
- What is the minimum oyster population size, density or area in order for an oyster reef to successfully regenerate?
- Which biotic and abiotic factors determine and limit flat oyster recruitment, with recruitment defined as settlement, growth and survival to age two years.
- How can Bonamia-challenged and Bonamia-free native oyster spat be produced and upscaled?
- What are the mechanisms behind Bonamia ‘resistance’ and ‘tolerance’?
- How does ecosystem service delivery benefits scale with oyster density?

The Milford Haven Watery has both Tributyltin (TBT) and heavy metals present with highest concentration down stream nearest the port of Milford Haven (Langston et al. 2012). Metal concentrations in the MHW tend to increase upstream. In the majority of samples, the metal concentration is in the lower-middle part of the UK range. It is not clear from the available research what this means with regards to oysters. High metal concentrations have been linked to larval failure in hatchery settings. There is little to indicate that levels within the MHW approach those which would lead to recruitment failure, however, in the event of continued recruitment failure within the Nature am Byth restoration work, future efforts should consider that a closer look at metal concentrations and their distribution within the waterway may be worthwhile [79].

Coastal restoration efforts are increasingly focusing on understanding the potential mutual benefits and enhanced success that may result from "integrated restoration" where integrating saltmarsh and oyster restoration results in greater restoration success and recovery of ecosystem services, such as the work ongoing by the University of Portsmouth in the River Hamble in the Solent. It could be useful learning from this research when findings are available, and to further this approach of considering land and seascape restoration. Research on how ecosystems function upstream from marine restoration interact and benefit marine restoration could be added to this integrated restoration approach.

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Appendix 2 Stakeholder interviews summary

Stakeholder discussions

Several stakeholder organizations in the Milford Haven Cleddau Estuary area were contacted by email, followed by online or face to face semi-structured informal interview meetings, to gather perspectives on the opportunities, constraints, and known information on environmental thresholds facing coastal and marine habitat restoration efforts in the region. Inquiries were made regarding the main threats or pressures affecting the focus species saltmarsh, seagrass, and native oysters' preferred sites for restoration, and recommended actions to alleviate significant pressures. Responses include a blend of evidence-based impact reports or data shared and anecdotal observations provided by different stakeholders.

In discussions with the **Milford Haven Waterway Environmental Surveillance Group,** challenges around marine licensing were highlighted across all of the habitat focuses. It was expressed saltmarsh within Milford Haven is well mapped and typically a narrow band at the back of inlets within the estuary with the Gan being a bit of an exception. This narrow band of saltmarsh is being constricted by the natural landscape or existing uses, this lowers the resilience of existing habitat and limits the opportunity for restoration though still highly valuable for biodiversity. Intertidal seagrass seems to be doing well in some areas, though subtidal is seeing more challenges. It was expressed existing subtidal seagrass could be supported to be thicker and healthier beds with better management such as reducing / preventing anchoring. It was felt that that the greatest constraints to native oysters are the general low density of current extent, and that restoration work needing oysters without or resistant to Bonamia could be a challenge to increasing numbers. Also, an oyster restoration project will need to define itself as for restoration of nature purpose or as a fisheries purpose as this will be needed to set the correct expectation of those involved. In discussion with two **local habitat / ecologist consultants** it was expressed that current saltmarsh extent is generally in ribbons, rather than full extent of habitat or patchy in coverage. Opportunity of new areas of saltmarsh depends on landowners as existing land use restricts the current extent. There are some small opportunities where removal of grazing on land or moving a fence back could provide suitable land for restoration, such as the top end of Garron Pill. Nutrients from nuisance macro algae that is smothering, rotting and producing extra nutrients has more of an effect on the species in the low to mid tidal range of saltmarsh, such as pioneer saltmarsh species. Reducing pressures and improving conditions of current extent should be a focus of efforts for saltmarsh. Lots of spatial opportunities for native oysters, though a conservation 'Several Order' would be useful to add protection from harvesting. Dredging activities could also be a potential issue, smothering or preventing settlement of spat, in addition high sediment loads from upstream has likely led to a loss of suitable substrate. Nitrates and how they are transported is the largest environmental factor affecting all species, and there is little knowledge of the inputs / impacts from the smaller rivers/tributaries entering the waterway, the SWEPT project has some data on these areas, but no long-term data set. Fringed woodland that could be made wider and extended could be a good focus of work to reduce a variety of pressures, with a focus on land used for high density cattle grazing.

The **Zoological Society of London** through representation from the native oyster network emphasised marine licensing can be time challenging alongside potentially securing a specialised vessel, viable culture material alongside the native oysters themselves. Availability of enough appropriate substrate is important for settlement. Nutrient loading from agriculture has not been seen as a constraint to restoration, though site selection near wastewater treatment outflows could prevent achieving food quality status. Site selection that avoids areas of potential high sedimentation events, such as dredging should be avoided due to the smothering effects. In a conversation with the **Centre for Ecology & Hydrology** it was stated that there is a need to recognise the abiotic factors such as sea level, wave action, and gradient of landscape rise to ensure the system can function correctly. Hard boundaries lead to coastal squeeze and less resilient habitats, and ideally saltmarsh should gradually change into scrub and then woodland rather than a hard fixed boundary. At certain levels, nutrients (not exactly known) can lead to less below-ground biomass which creates destabilisation, loss of structural integrity and high risk of erosion. Nutrients do not really affect germination, but the impacts come later in the assembly of species, and plant diversity as more robust species will be more dominant. So, setting the goal for the restoration project will be important as saltmarsh could be possible with excess nutrients, but potentially not a meadow with high biodiversity. It is possible once levels of nutrients reach the proliferation of mats of opportunistic algal blooms could restrict initial spread and germination. There is still a lot of unknowns on the impacts of nutrients, particularly the relationship to biodiversity and carbon storage. There is currently a pilot study on the de-nitrification rates of saltmarsh and what drives the difference. The Centre for Ecology & Hydrology will be hosting a PHD study into the effects of nutrients on saltmarsh which is being supported by Natural England.

Members of the **NRW Marine Team** conveyed nutrients do affect the upper saltmarsh though there is currently not enough monitoring the detail of these changes, and there is very little concern with the level of grazing in these areas within Milford Haven. There are likely opportunities to remove a hedge bank here or there to create restoration areas, though there are not a great deal of sea defences that could be reengineered. There could be monitoring related to root density to establish whether reduction of underground biomass is occurring within saltmarsh areas of Milford Haven. The **Wetland and Wildfowl Trust,** though not readily familiar with the area, stated that there generally are opportunities to expand existing saltmarsh inland when farmland borders and buffer strips can be created to allow the saltmarsh to advance inland. Physical constraints of the site is generally the largest challenge, though also highlighted was the tendency of upper saltmarsh subject to excessive nutrient loads to have lower below-ground biomass and are more susceptible to erosion. Though it was stated that more research into this effect is required as there is little evidence in the UK context. It was also highlighted that a saltmarsh code is under development and will be available in 2025. It was also emphasised that it would be better to do something that is potentially not going to be a 'perfect saltmarsh' than doing nothing at all and having no saltmarsh. The **Pembrokeshire Local Nature Partnership** when speaking about saltmarsh restoration, stated that opportunistic algal blooms are smothering saltmarsh and adds nutrients to lower and mid marsh species when it rots. Nutrients are an issue on mid and lower marsh while management is key to upper marsh, ideally with some grazing but not too much. Management in the upper marsh is undervalued with either abandonment or overgrazing.