Centre for Environment Fisheries & Aquaculture Science

Cefas

Pressures on forage fish in Welsh Waters

A literature review of known and potential pressures on forage fish

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1. Summary

This report is aimed at identifying the main anthropogenic pressures on forage fish in Welsh waters. These include pressures resulting from activities such as fisheries, renewable energy, aggregate extraction, water abstraction and aquaculture, and other pressures such as contaminants, plastic litter, noise and climate change. The possible processes through which they act, as well as their impacts at both individual and population level are reviewed. The forage fish populations inhabiting Welsh waters provide a key source of prey for many predators, such as marine mammal and seabird species. They typically feed on plankton and their generally short life span and high spawning activity make them sensitive to environmental changes, which is reflected in large fluctuations in population size. Thus, understanding the response of forage fish to pressures is important to the wider ecosystem and society. Despite a growing body of research, detailed information on pressures on forage fish is very limited. Related literature focussing on other marine organisms and ecosystem processes is used to infer possible implications for forage fish. Most anthropogenic activities are suggested to have adverse impacts on marine organisms although, compared to benthic organisms for which most literature is available, forage fish may be less affected by some localised pressures due to their higher mobility, short generation time and high reproductive strategy. Species like herring and sandeel are suggested to be most sensitive due to their dependence on specific seabed substrates during at least part of their life, including spawning. Gaps in knowledge are identified and recommendations for future work suggested. Incorporating forage fish as part of existing and new environmental monitoring programmes is seen as critical. The highest priority will be to address the gap in knowledge on the population structure and size of the forage fish community as that is required as a baseline to assess population-scale impacts.

Crynodeb

Nod yr adroddiad hwn yw adnabod y prif bwysau anthropogenig ar bysgod porthi yn nyfroedd Cymru. Mae'r rhain yn cynnwys pwysau sy'n deillio o weithgareddau fel pysgodfeydd, ynni adnewyddadwy, echdynnu agregau, tynnu dŵr a dyframaeth, a phwysau eraill fel halogyddion, sbwriel plastig, sŵn a newid hinsawdd. Adolygir y prosesau posibl y maent yn gweithredu drwyddynt, yn ogystal â'u heffeithiau ar lefel unigol ac o ran poblogaeth. Mae'r poblogaethau pysgod porthi sy'n byw yn nyfroedd Cymru yn ffynhonnell allweddol o ysglyfaeth i lawer o ysglyfaethwyr, megis mamaliaid môr a rhywogaethau adar môr. Maent fel arfer yn bwydo ar blancton, ac mae eu rhychwant bywyd, sy'n gyffredinol yn fyr, a'u gweithgarwch silio prysur yn eu gwneud yn sensitif i newidiadau amgylcheddol, sy'n cael ei adlewyrchu mewn amrywiadau mawr o ran maint y boblogaeth. Felly, mae deall ymateb pysgod porthi i bwysau o'r math yn bwysig i'r ecosystem a'r gymdeithas yn ehangach. Er gwaethaf corff cynyddol o ymchwil, mae gwybodaeth fanwl am y pwysau ar bysgod porthi yn gyfyngedig iawn. Defnyddir llenyddiaeth gysylltiedig sy'n canolbwyntio ar organebau morol eraill, a phrosesau ecosystem eraill, i ragweld y goblygiadau posibl ar gyfer pysgod porthi. Awgrymir bod y rhan fwyaf o weithgareddau anthropogenig yn cael

effaith andwyol ar organebau morol er, o'i gymharu ag organebau dyfnforol y mae'r rhan fwyaf o lenyddiaeth yn cyfeirio atynt, gall rhai amgylchiadau lleol o bwysau effeithio llai ar bysgod porthi oherwydd eu symudedd uwch, amser cynhyrchu byr a strategaeth atgenhedlu uchel. Awgrymir mai rhywogaethau fel y pennog a'r llymrïen yw'r mwyaf sensitif oherwydd eu dibyniaeth ar is-setiau gwely'r môr penodol yn ystod o leiaf ran o'u bywyd, gan gynnwys silio. Cydnabyddir bod bylchau yn ein gwybodaeth ac awgrymir argymhellion ar gyfer gwaith yn y dyfodol. Ystyrir bod ymgorffori pysgod porthi fel rhan o raglenni monitro amgylcheddol presennol a newydd yn hanfodol. Y flaenoriaeth uchaf fydd mynd i'r afael â'r bwlch mewn gwybodaeth am strwythur poblogaeth a maint y gymuned pysgod porthi, gan fod angen hynny fel llinell sylfaen i asesu effeithiau ar raddfa poblogaeth.

2. Introduction

Forage fish are small, often pelagic schooling fish that are a main pathway for energy to flow from plankton to higher predators in marine ecosystems. Particularly the Clupeiformes and sandeels exhibit short generation times and tight coupling to lower trophic levels, and populations may therefore display large boom-and-bust dynamics (Engelhard et al. 2014). Because they maintain this trophodynamic role throughout their life, their population fluctuations may produce notable ecological effects and, therefore, the sustainable management of forage fish populations is critical to maintaining ecosystem functioning (Peck et al., 2014).

The shelf waters inhabited by forage fish, support a wide range of anthropogenic activities, including fisheries, aquaculture, and mineral resources extraction, and they provide sites for offshore renewable energy, cable routes, shipping, etc. Coastal waters are also susceptible to local scale pressures including pollution from anthropogenic inputs such as contaminants and microplastics, which enter the ecosystem directly or via rivers, and to large scale pressure such as climate change, which act through e.g. rising temperatures and flooding. These wide-ranging demands and pressures on the marine environment may impact forage fish through complex interactions between the physical and biological environment, affecting them at individual-, group- and ultimately population level.

The most important forage fish species in Welsh waters, both in terms of prey for top predators and of abundance, were considered in this study. These included the key pelagic species, herring (*Clupea harengus*), sprat (*Sprattus sprattus*), sardine (*Sardina pilchardus*), anchovy (*Engraulis encrasicolus*), sandeels (Ammodytidae), horse mackerel (*Trachurus trachurus*), mackerel (*Scomber scombrus*) and garfish (*Belone belone*) as well as several gadoid species known to be important in top predators' diet: poor cod (*Trisopterus minutus*), and (as juveniles) whiting (*Merlangius merlangus*) and cod (*Gadus morhua*). Details on the ecology including up-to-date maps of spawning and nursery areas, and details on management are provided in Campanella and van der Kooij, (2021).

To ensure sustainable management of forage fish in the context of their typically variable population dynamics (Dickey-Collas et al, 2014) the possible effects of these anthropogenic sources need to be identified, monitored and they need to be managed in an integrated fashion, so that the environment is protected for the benefit of future generations: different activities may have negative or positive impacts at local as well as larger scales, which may exacerbate or counteract each other and these complex interactions need to be considered.

In this review, the main pressures on the forage fish community are identified. Each section discusses a particular pressure, the process through which it impacts forage fish with, where available, examples of case studies in Welsh waters and current research or monitoring of and, where possible, trends in the pressure. Given the potentially large number of pressures in the marine environment, only those that reportedly have a direct impact on forage fish are included. It is beyond the scope of this study to provide a detailed assessment of specific sites and areas but it is recommended that the pressures identified in this report are considered as part of future environmental impact assessments.

3. Activities

3.1. Fishing Industry

Commercial fisheries may act upon the forage fish community in multiple ways, both directly and indirectly. Fisheries can exert top-down pressure on fish populations (Engelhard et al., 2014); if not managed adequately, the removal of individuals from a population can have a significant effect on the future stock size through a reduction in spawning stock biomass and ultimately recruitment.

As discussed in Campanella & van der Kooij (2021), few of the commercial fisheries operating in the area are directed at small pelagic fish. A summary of the main fisheries (potentially) catching forage fish is provided here:

- The only significant targeted fishery for small pelagic fish in the study area is for herring, in the northern Irish Sea and in the Celtic Sea. The latter is currently restricted due to a low stock size. The Irish Sea herring stock biomass has been fairly stable in recent years with consistent landings (ICES, 2021a).
- Relatively small but increasing quantities of sprat are caught, predominantly by Irish vessels, in the Celtic Sea (ICES, 2021b). Landings are thought to be underestimates due to the difficulties quantifying those from vessels less than 10 m lengths. Most sprat vessels primarily target other species like herring and switch to sprat opportunistically and dependent on the availability of herring quota. Sprat in this area is not regulated by quota.
- Small-scale local fisheries operate along the Welsh coasts, some targeting herring using gears like driftnets, and others catch sandeels used as bait by recreational

fisheries. However, very limited information is available on the quantities of fish taken and on the possible impacts.

- Whiting (considered a forage fish in the juvenile stages) in the Irish Sea has mainly been caught as bycatch in the *Nephrops* fishery since the early 2000s. The stock size is extremely low, likely as a result of fishing pressure (ICES 2021c). Whiting in the Celtic Sea is mainly landed by targeted fisheries with reductions in bycatch of whiting over the last few years. Spawning stock biomass is at low levels (ICES 2021d).
- Cod (considered a forage fish in the juvenile stages) is targeted by demersal fisheries and is also a bycatch in fisheries targeting *Nephrops*, mainly in the Irish Sea, and other demersal fish. Irish Sea cod catches have declined over the last decades and the stock is data-limited and a precautionary approach is applied (ICES 2021e). Due to low yields, cod in the Celtic Sea (ICES 2021f) is no longer a target species but a bycatch in haddock and whiting dedicated fisheries (ICES 2021d).
- Small pelagic fish may be caught as bycatch during demersal fisheries which may have an impact on their populations. However, demersal fisheries generally use larger mesh sizes and pelagic fish may school away from the seabed, which suggests that bycatch is unlikely a major issue for the small pelagic fish community.

Indirect effects of commercial fisheries on forage fish include the disturbance of seabed by ground gear which has an adverse effect on benthic communities reducing biomass, production, and species richness (Hiddink et al., 2006). However, among the forage fish community, this is likely to only directly affect those species that depend on particular seabed substrates, such as sandeels and herring (see also section 3.3 Aggregate Extraction Industry).

Should new fisheries develop targeting forage fish, either for human consumption or to support possible future finfish farming initiatives (section 3.5 Aquaculture), sustainable management of the populations is critical. As discussed however (Campanella & van der Kooij, 2021) very few of the forage fish in Welsh waters are currently managed or monitored.

3.2. Renewable Energy Industry

The marine renewable energy sector has become an increasingly important industry in recent years. Due to the virtually untapped source of energy that the marine environment represents (Pelc and Fujita 2002) it is seen as a solution to climate change and rising costs of energy (Diaz and Soares, 2020; Gill et al., 2020). Marine Renewable Energy Installations (MREI) are classified into different types depending on the main source of energy they harvest. MREIs relevant to Welsh waters are offshore wind (OWF, Pelc and Fujita, 2002) and wave/tidal energy or osmotic power (Neill and Hashemi, 2018).

The impacts of Offshore Wind Farms (OWF) on the marine environment have been investigated in a growing number of studies. Generally, the impacts of OWF are considered separately for the construction, operation and decommissioning phases.

During construction, one of the main impacts on marine life, including pelagic fish (Debusschere et al., 2014; Mooney et al., 2020, Kok et al., 2021), is the high levels of noise from pile driving. Several studies have reported changes in behaviour of aquatic animals when exposed to ambient noise levels (Slabbekoorn et al., 2018). Effects of sound on behaviour range from local changes in water column use (Hawkins et al., 2014; Neo et al., 2014) to horizontal avoidance of noisy areas (e.g. Carstensen et al., 2006; Kok et al., 2018), and may include impairment of the ability to choose a mate, foraging behaviour, and anti-predator responses (Shafiei Sabet et al., 2015; De Jong et al., 2018). More details on the effects of noise are provided in section 4.3 (Noise).

During their operational phase the impacts of OWF are more complex and can be separated into different categories:

1. Artificial Reef Effect. OWF have been reported to attract fish and other biota by acting as artificial reef or production hotspots (Langhamer, 2012; Degraer et al., 2013). Boulders are often used to secure the foundations of turbines which have been demonstrated to enhance local species diversity and biomass production (Randall 1963, Davis et al. 1982, Coleman & Connell 2001, Gray 2006, Arena et al. 2007). While this has mainly been reported for benthic and demersal species, it is also true for pelagic species, which can be attracted due to food abundance in those areas (Kok et al., 2021). However, existing and planned OWFs are often located on sandy substrates that are inhabited by a species community very different from that of boulder reefs, which may have an adverse impact. The direct effects of the resulting habitat loss may impact forage fish species like sandeels and herring, which are reliant on specific seabed substrates e.g. for reproduction. No long-term impacts were observed for sandeels as a results of the introduction of an OWF in the North Sea (van Deurs et al., 2012), although impacts may vary depending on the local conditions. In addition, instances of colonisation by non-native species around turbine structures have been reported (De Mesel et al., 2015, Schulze et al., 2020), which have a negative impact on the entire ecosystem.
2. Marine Reserve Effect. Most OWFs operate an exclusion zone around the structure(s) which prevents active fishing methods (such as trawling) taking place because of liability and safety issues (Gusatu et al. 2020). The absence of fisheries could see these areas function in a similar way as marine protected areas (Ashley et al., 2014). However, again the impacts are complex: since they are not designed as conservation tools, the exclusion of fisheries could either have a positive effect, by reducing fishing mortality (Harrison et al., 2012); or a negative effect, by increasing predator risk on local ecosystems (Gaines et al., 2010). Furthermore, a reduction in commercial fishing activity inside OWFs could lead to a spatial redistribution in fishing effort (i.e., fisheries displacement effect) to areas outside the windfarm (Bergström et al., 2014; De Backer et al., 2019), increasing the pressures there.

3. OWFs (like other MREIs) also change the sensory environment for marine life due to electromagnetic fields associated with cables and by underwater sound. These may adversely impact fish reproduction, migration and/or distribution (Gill et al., 2020). The acoustic effects of OWFs on sensitive species may occur through sound emitted when the OWF is operational. However, the effect is likely restricted to masking animal communication and orientation signals, rather than causing physiological damage or permanent avoidance reactions (Popper and Hawkins, 2019), particularly in the case of forage fish. Changes to water currents and wind wakes due to the loss of kinetic energy leeward of the turbines, may alter hydrodynamic patterns including vertical stratification that might have consequences for transport of nutrients for primary producers (Carpenter et al., 2016; van Berkel et al., 2020). This effect on the primary producers could cascade to the higher tropic levels, including forage fish and top predators. Finally, changing currents as a result of OWF (and other MREI), can also impact fish larval dispersal and distribution (Barbut et al., 2020).

Tidal energy production is still a relatively small contributor to renewable energy. It is however a growing industry with multiple proposals also in Welsh waters. The predictability of tides provides a potentially reliable source of energy. There are currently different technical approaches to obtaining energy from tide: Tidal streams, which involves the installation of turbines in tidally driven marine streams (such as in straits); tidal barrages and (the similar) tidal lagoons, both of which are based on a principle that an artificial (barrage/dam) or natural (lagoon) semi-enclosed body of water lets water in as the tide rises, and turbines harvest the energy of the tide as it recedes.

Impacts of tidal energy structures on marine fauna have focussed primarily on marine mammals (Nuuttila, 2015 and references therein). One concern is the collision of animals (fish as well as the predators targeting them such as diving seabirds, marine mammals) with rotating turbine blades which has the potential to cause injury or mortality (Wilson et al., 2007). Monitoring initiatives around ecological impacts of tidal stream turbines in Scotland (Williamson et al., 2014) have found evidence of increased occurrence of fish schools around turbines (Williamson et al., 2019). This may improve predator foraging efficiency, although the attraction of predators has the potential to increase animal collision risk (Williamson et al., 2019).

By restricting access to coastal or estuarine areas, tidal barrages may locally impact fish migratory routes although this can be mitigated by the construction of (fish) passes that allow space for the fish to transit (Pelc and Fujita, 2002). Tidal barrages also alter the natural flow, potentially causing salinity fluctuations, sedimentation and accumulation of organic matter (Retiere, 1994). These are important ecological drivers and the resulting change in habitat will cause a shift in the faunal community including displacement. Those forage fish that favour specific seabed substrates like sandeels and herring are likely to be most at risk (Retiere, 1994).

Renewable energy sources have a huge potential in Wales. Although the anthropogenic impact to the ecosystem and living communities cannot be completely avoided when

constructing and installing an MREI, it can be significantly reduced if projects are sited and scaled to minimize negative environmental impacts appropriately and designed to act as facilitators of ecosystems restoration (Inger et al., 2009).

3.3. Aggregate Extraction Industry

The UK marine aggregate dredging sector produces sand and gravel (aggregate) from licensed extraction areas around the coast of England and Wales (Highley et al., 2007; Russell, 2011). Around 80% of all marine aggregate in England and Wales is used for concrete, which is the premium product of the sand and gravel industry. Marine aggregates are also used extensively for beach replenishment and other coastal protection schemes that are required to combat rising sea levels (Newell & Woodcock, 2013).

Licenced aggregate dredging areas in Welsh waters are found along the north coast, in Liverpool Bay, and in the Bristol Channel, which is the main source (80%) of sand for Welsh needs.

Primary impacts of aggregate dredging result from the direct removal of sediment and associated benthic fauna, leading to loss of species richness, abundance and biomass. In some locations impacts to the fauna are also observed outside the boundaries of the licensed area, as a consequence of the fallout of material from sediment plumes (Desprez, 2000; Boyd and Rees, 2003; Newell et al., 2004; Desprez et al., 2010; Pearce et al., 2011): finer sediments are transported by tidal currents away from licenced areas causing temporary turbidity and their disposition elsewhere may alter the composition of sediments with consequences for seabed macrofaunal communities (e.g. Desprez, 2000). The recovery of the benthic fauna from aggregate extraction is dependent on dredging intensity but has been estimated to be many years (Cooper et al., 2007, Waye-Barker et al., 2015).

Within the forage fish community, sandeels are the main group of species that could be impacted directly as they spend most of their life buried in the seabed. For example, the lesser sandeel (*Ammodytes marinus*) prefers oxygenated substrates like coarse sand and gravel (Wright et al., 2000), which are the same substrates targeted by aggregate extraction companies. This activity can therefore directly cause mortality of the adult and juvenile life stages of sandeels residing in the seabed. Sandeels only emerge into the water-column during the day time in spring and summer (returning to the seabed at night and in the autumn and winter) and there is therefore no suitable season during which extraction impacts can be minimised. Extraction is also likely to cause direct mortality of eggs of some species: both sandeels and herring deposit their eggs on coarse substrates like gravel. For both species, the loss of essential coarse substrate habitats due to persistent aggregate extraction, is therefore likely to have long term detrimental impacts on their population.

The forage fish species whose habitat is more strongly associated with the seabed, such as (demersal) gadoid species (poor cod, whiting and cod), will also be impacted by

aggregate activities. While direct mortality is not likely to be a major issue for adult and juvenile fish, it is likely to cause displacement. However, given the generally localised dredge activities, and all three species being widely distributed (Campanella & van der Kooij, 2021), this may not have a significant impact at population level. The remaining small pelagic fish species are generally not restricted in their distribution by seabed substrate so populations are likely to be less affected by aggregate extraction activities. However, localised effects by extraction and wider spatial impacts due to turbidity caused by finer sediments being released into the water column will displace these species locally. This is confirmed by avoidance behaviour observed in visual predators like mackerel, but also herring and cod (Westerberg et al., 1996). Increased silt levels have also been linked to mortality of herring and cod larvae (Westerberg et al., 1996). It is therefore necessary for each aggregate extraction site to conduct a specific environmental impact assessment to ensure potential impacts on the eggs and larvae of commercial fish species are minimised by avoidance of spawning and nursery areas and periods.

Increased turbidity may also have indirect impacts on forage fish. Reduction in light caused by suspended silt particles will adversely affect phytoplankton productivity (Capuzzo et al., 2015) which will have a cascading effect through the higher trophic levels, including forage fish. In addition, zooplankton feeding and respiration may be affected by silt. The details on the scale and significance of these impacts, as well as those that affect bentho-pelagic coupling are however poorly understood and require more work.

3.4. Water abstraction

Abstraction involves pumping (sea)water for an industrial purpose, such as cooling, desalination or hydrogen production, and returning it to sea. In Welsh and surrounding waters the main applications of abstraction are for cooling water in power stations such as Hinkley and Pembroke, but future applications may expand into other areas.

Impacts of abstraction on the forage fish community depend on the location at which water is abstracted and the flow and volume of the abstraction. Most abstraction takes place in coastal locations which represent important nursery areas for many fish species including forage fish. Mortality of various life-stages of invertebrates and fishes, particularly juveniles, is commonly reported as a result of impingement on intake screens or entrainment through cooling systems. The reduced swimming ability of juvenile fish and the aggregative behaviour of forage fish suggest they are particularly vulnerable to potentially significant mortality. Impacts of impingement can be quantified relatively easily as samples can be collected directly from traveling screens (Callaghan, 2004). To provide an accurate estimate of mortality, this would have to be done over 24 hours and during different seasons, to account for factors such as tide and phenology. Adverse effects may be mitigated by reducing the velocity of the water intake, allowing species to evade the inflow. In addition, deterrents such as acoustic systems, have successfully reduced the intake rates of herring and sprat by ~90% (Maes et al., 2004).

The other main pressure caused by abstraction, particularly for cooling purposes, is the local increase in temperature due to the discharge of abstracted water. Thermal loading related to cooling water discharges directly interferes with physiological processes of the biota, such as enzyme activity, feeding, reproduction, respiration, growth and photosynthesis (Hadderingh et al., 1983). This may therefore cause behavioural changes (attraction or avoidance) in organisms subjected to thermal discharges.

A final adverse effects on aquatic organisms may arise from the use of biocides to control fouling organisms (Maes et al., 2004).

3.5. Aquaculture

Aquaculture is a fast-growing sector with worldwide production increasing by an average of 4% per year (FAO, 2020). This increased trend, especially of high valued carnivorous fish, requires increasing amounts of fish meal and fish oil to feed the farmed animals (Alder et al., 2008). This practice is currently dependent upon feeds formulated from high levels of marine fish meal and fish oil derived from industrial, feed-grade (reduction) fisheries of forage fish. Pressure on small pelagic fish (including previously unexploited species) has been reported elsewhere (Jackson et al., 2007). Globally, 90% of the small pelagic fish landings (or 27% of total landings) are processed into fishmeal and fish oil (FAO, 2020).

In Welsh waters, shellfish (mussel and oyster farming) is the dominant form of aquaculture (Callaway et al., 2012) and no offshore marine finfish production was recorded for Wales (Welsh National Marine Plan, 2019). However, aquaculture is one of the key food production sectors in Wales and with increasing drivers of food and nutritional security, a growing population and increasing demand for healthy products, the Welsh Government has intentions to increase aquaculture production to meet these needs and may be issuing licences for offshore finfish farming (Welsh National Marine Plan 2019).

Shellfish aquaculture may have a beneficial effect on surrounding fish communities. In contrast to finfish farms, shellfish feed on plankton particles naturally occurring in the water column (Shumway et al., 2003). In fact, the efficiency with which shellfish filter can help control populations of phytoplankton growth (top-down population control; (Cloern, 1982; Hulot et al., 2020), ensuring healthy oxygen levels for the ecosystem (Rice et al., 2008). Similarly, macro-algae farming is likely to have a positive impact, e.g. by providing shelter to juvenile fish. However, if offshore finfish farming activities were to go ahead, they would likely become a pressure to forage fish. It would increase the demand for protein-based feed which may introduce new fisheries targeting small pelagic fish. As mentioned previously (section 3.1 Fishing Industry), very few forage fish stocks are monitored and little is known about the population structure, both of which would be necessary to ensure any future fisheries operate sustainably. If offshore fish farming were to develop, additional indirect impacts may be the (localised) increases in nutrients around fish pens and cages as a result of faecal matter and surplus food protein.

4. Wider pressures

4.1. Contaminants

Nearshore and coastal waters include some of the most productive marine ecosystems in the world and are crucial to the life history and development of many aquatic organisms (Chapman and Wang, 2001; Dauvin, 2008). These habitats are strongly susceptible to pollution from anthropogenic input via rivers, marine traffic and coastal industry (Nicolaus et al., 2016). All forage fish species included in this study live and reproduce in or near these environments, and are therefore potentially exposed to a range of contaminants, including radioactive materials, polychlorinated biphenyls (PCBs), brominated diphenyl ethers (BDEs – flame retardant compounds) and metals that may affect species at both the individual and population level (Beyer et al., 2014; Jepson et al., 2016).

Radioactivity in the environment comes from several sources, including permitted radioactive discharges from both nuclear and non-nuclear sites, residues from the Chernobyl accident and atmospheric testing, plus natural radiation. In Welsh water radioactive influence (caesium-137 and tritium) from nuclear sites have been reported in the eastern Irish Sea (including Liverpool Bay) along the coast to the north and south of Sellafield, with levels decreasing with distance from the coast. In the Bristol Channel, the combined effect of tritium discharges from Cardiff, Berkeley, Oldbury and Hinkley Point nuclear sites remained evident in samples from nearby sampling sites. However, the general levels have been low. Overall caesium-137 concentrations in the Irish Sea show a decreasing trend (Environment Agency, Food Standards Agency, Northern Ireland Environment Agency and Scottish Protection Agency, 2008). The effect of reduced tritium discharges over the last decade, particularly from Cardiff, has resulted in much lower tritium concentrations in the Bristol Channel.

Little is published about the impacts of radioactivity on marine fish and specifically forage fish (Nakata K, Sugisaki, 2015). However, studies on the effects of prolonged exposure (197 days) of plaice found adverse impact on reproduction (Knowles, 1999), although the dose was much larger than that reported in the north-east Irish Sea off Sellafield. Due to their increased mobility, it is thought forage fish are less susceptible to contamination compared to demersal fish (Fiévet et al., 2017). However, their role as prey to top predators and evidence of bioaccumulation of radioactivity in higher trophic levels (Doi et al., 2012), confirms that a better understanding of radioactivity in forage fish is needed. As part of this, the mechanisms of radioactive substance migration in marine ecosystems need to be understood (Yoshida and Kanda 2012), which relies on an improved understanding of corresponding ecological mechanisms.

The same applies to the impacts of other contaminants, like polychlorinated biphenyls (PCBs), brominated diphenyl ethers (BDEs) and metals, which are released into the environment from both anthropogenic and natural inputs. In sites examined around the

UK, the highest concentrations of chlorobiphenyls (CBs) were found in the Bristol Channel/Celtic Sea area and of BDEs in the Tyne/Tees area (Law and Maes, 2012).

For vertebrate marine organisms, adverse effects of PCBs (Myers et al., 1998; Kannan et al., 2000; Hall et al., 2006) and metals (Besselink et al., 1997; Damiano et al., 2011; Beyer et al., 2014) have mainly been demonstrated for flatfish species and top predators. PCBs banned over 20 years ago are still found at concentrations in fish liver tissues which may pose a health risk to both the individual fish and their predators. Spatial monitoring of the concentrations and impacts of these contaminants on forage fish is required to understand the risk to top predators.

4.2. Marine plastic litter

The demand for manufactured goods and packaging increased throughout the twentieth century. The volume of particularly plastic material has increased with a growing population and an increasingly industrialized society. Unfortunately, society has been slow to anticipate the need for dealing adequately with end-of-life plastics, to prevent them entering the marine environment (GESAMP, 2015). Litter, including from packaging, enters the marine environment from a variety of sources, both directly (by beach visitors, discarded or lost fishing gear from fishing vessels, illegal dumping) and indirectly (riverine flow from land-based sources). As a result, substantial volumes of litter have been added to the ocean over the past 60 years, covering a very wide range of sizes (metres to nanometres in diameter).

There is sufficient scientific evidence that plastic marine litter can cause significant adverse environmental effects (Bakir et al., 2020). These are most clearly demonstrated for larger items (i.e. macro-plastics > 25 mm) and certain categories of litter (e.g. Abandoned Lost or otherwise Discarded Fishing Gear, ALDFG) and include ingestion by biota (macro, meso, and microplastics including microfibers) or entanglement/collision (e.g., ghost fishing caused: ALDFG). Ghost fishing by most ALDFG is not likely to have a significant effect on (small) forage fish although gillnets may have sufficiently small mesh to cause local mortality of individuals. Examples of these pressures specifically in Welsh waters are limited. An initial assessment of offshore seabed litter in UK waters, including a time series starting in 1992, indicated strong yearly fluctuations in litter concentrations but found consistently higher levels of litter off the west coast of England and Wales than in the North Sea: specifically Morecambe Bay, Cardigan Bay, Carmarthen Bay and the Celtic Deep (Law and Maes, 2012). While this macro-litter may not have a direct impact on forage fish, it poses potentially longer term issues as it breaks down into smaller particles and increases the chance of ingestion.

Microplastics are small pieces of plastic that may enter the ocean directly or may result from the fragmentation of larger items. Microplastics are widespread in the environment and are found in many coastal and shelf-sea biota. The routes through which organisms ingest microplastics may vary (Welden et al., 2018). Planktivorous forage fish are

particularly likely to be susceptible to ingesting microplastics: they feed either by filtering water and retaining small particles in their gill rakes or by actively feeding on specific particles.

The biological impact of microplastics on organisms in the marine environment is only just emerging (Gregory 1996; Barnes et al. 2009; Ryan et al. 2009; Cole et al. 2011, Roch et al., 2020) and include a broad and complex range of processes. Details are provided elsewhere (GESAMP, 2015, 2020) and a summary is provided here. At an organism level, adverse effects of microplastics can potentially arise from physical effects (physical obstruction or damage of feeding appendages or digestive tract or other physical harm). In addition, microplastics can act as vectors for chemical transport into marine organisms causing chemical toxicity (additives, monomers, sorbed chemicals). Translocation of microplastics from the gut to other tissues may result in 'internal' exposure of microplastics causing particle toxicity and particle dependent chemical toxicity of leached chemicals (GESAMP, 2015, 2020).

Despite a growing body of research, details about the effects of plastic ingestion on biota are less clear. While detrimental physical effects of microplastics have been reported (Wright et al., 2013), including mortality (Maes et al., 2020a), for forage fish, few studies have found adverse impacts. Studies in the North Sea found no significant differences in condition factors for herring, cod, whiting and horse mackerel between individuals that contained plastic and those without (Foekema et al., 2013). Neither were statistically significant adverse effects of ingested microplastics found in small pelagic fish species, including European anchovy, in South Africa (Bakir et al., 2020). However, despite a lack of negative correlation between microplastics and forage fish fitness, the prevalence of microplastics in these mid-trophic species is likely to impact top predators through bio-accumulation (Maes et al., 2020b).

In addition to impaired health, the ingestion of microplastics could potentially cause population and community level effects and affect ecosystem wide processes (Wright et al. 2013). Microplastics could also serve as carrier for the dispersal of chemicals and biota (invasive species, pathogens), thus greatly increasing dispersal opportunities in the marine environment, potentially endangering marine biodiversity. Negative effects on the photosynthesis of primary producers and on the growth of secondary producers, potentially result in a reduced productivity of the whole ecosystem and represent a primary concern.

4.3. Noise

Noise in the ocean has two sources: natural and anthropogenic. Natural sources include processes such as waves, rainfall, bio-acoustic sounds (e.g. marine mammals echolocation, fish calls), thermal agitation of the seawater, earthquakes. Anthropogenic noise is generated by numerous activities and its intensity and frequency can vary significantly. Sources of anthropogenic noise include shipping (e.g. propeller noise,

cavitation noise), oil and gas exploration (e.g. air gun arrays), fishing, construction and exploitation of offshore platforms (e.g. pile driving), offshore windfarms, dredging, aquaculture noise, military surveillance (e.g. sonar). The amount of anthropogenic noise has increased considerably during the last few decades in the open ocean and coastal areas, becoming more powerful and disruptive to the natural soundscape (Frisk, 2012; McKenna et al., 2012). For this reason, the World Health Organization has considered anthropogenic noise as a global pollutant (WHO 2011; Francis and Barber 2013; Shannon et al. 2016; Slabbekoorn et al. 2018).

The potential effects of anthropogenic noise on aquatic depends on several factors: the properties of the noise such as duration, intensity, frequency, predictability, amplitude (Neo et al., 2014; Kok et al., 2018, 2021); the number of different sources and the biological characteristics of the animals affected by the noise (anatomical, physiological, behavioural). Moreover, many marine organisms depend on sound for communication, predator/prey detection (Remage-Healey et al.,2006), larval settlement (Simpson et al. 2005) and coordinated behaviour (Boinski & Campbell 1995).

Given the important role of marine soundscapes in the ecosystem dynamics, anthropogenic sound can have a significant impact from individual level to the whole ecosystem.

The main effects of underwater noise include:

- Behavioural changes. Noise could force fish to move away from preferred habitats affecting feeding efficiency, growth, vulnerability to predation, survival and reproductive success (Carstensen et al., 2006; Kok et al., 2018, Popper and Hawkins, 2019). It may also affect the vertical use of the water column (Hawkins et al., 2014; Neo et al., 2014) which affects availability to predators. Pelagic fish have been found to exhibit changes in cohesion, and schooling patterns (Hawkins et al. 2014; Kok et al., 2021), which will change their availability to predators.
- Masking: anthropogenic noise could mask biological sounds, adversely affecting communications (Brumm and Slabbekoorn 2005). For example noise could mask sounds made by prey and predators reducing anti-predator defence and feeding efficiency, respectively, with potentially detrimental effects on growth and survival (Voellmy et al., 2014; Purser and Radford, 2011, Simpson et al., 2015). Spawning signals could be masked by noise affecting spawning success and recruitment (de Jong et al., 2020).
- Physical and physiology effects. Noise may produce damages to specific tissues (e.g. swimbladder; Kunc et al., 2016) or cause temporary or permanent hearing-loss depending on both the duration of noise exposure and the frequency (Smith & Monroe, 2016) with large negative effects on fitness and survival (Popper and Hawkins, 2019). The endocrine system could also be affected by noise leading to an increased production of stress hormones (cortisol) with potential negative effects on fitness, reproduction, growth and immunity (Nichols et al. 2015; Wysocki et al. 2006).

- Death. Immediate mortality or death induced by physical and/or physiological damage some time after the exposure could occur from exposure to brief high-level sounds (Hawkins and Popper, 2017).

Few studies on the effects of noise on forage fish have been carried out. One study found that sprat dispersed and mackerel exhibited vertical displacement, in response to pile driving noise. Both behavioural responses increased with increasing sound levels (Hawkins et al., 2014). Horizontal and vertical movements away from vessels have been observed for herring and Atlantic cod likely as a response to ship noise (Vabø et al., 2002; Handegard et al., 2003). Short term (vertical movement) and long-term (density decrease) behavioural effects were observed in herring and blue whiting (*Micromesistius potassou*) in response to seismic investigations (Slotte et al., 2003).

While no information is available for Welsh waters, several reviews have been published on this subject (e.g. Slabbekoorn et al. 2010; van der Sluijs et al. 2011; Popper et al. 2014; Radford et al. 2014; Williams et al. 2015; Kunc et al. 2016; Carroll et al. 2017; Hawkins and Popper 2017; Cox et al. 2018; Slabbekoorn et al. 2019). Many have highlighted the need for data on population level effects, in particular reproduction dynamics. Another consideration is the potential synergistic effects of noise with other stressors. Changes in fisheries catch rates during and after noisy human activities have been noted (e.g. Skalski et al., 1992; Parry and Gason, 2006; Løkkeborg et al., 2012) and climate change could exacerbate noise impact for the wider ecosystem (Kunc et al., 2016).

Considering the increasing numbers of marine renewable energy sites around Wales (section 3.2 Renewable Energy Industry) and other potential anthropogenic noise sources described in this report it is crucial to develop passive acoustic monitoring programs to identify baseline levels of noise including reliable threshold levels below which forage fish are not negatively impacted (Merchant et al., 2015).

4.4. Climate Change

The ocean is one of the ecosystems most impacted by climate change, caused by increasing carbon dioxide and other greenhouse gas emissions from human activities. This has resulted in a wide range of effects on the physical environment that can impact biological productivity directly. Apart from the temperature increase *per se*, a warmer climate could also: 1) alter wind patterns and intensities with effects on ocean currents, mixing and stratification (Bakun, 1990; Snyder et al., 2003; Vecchi et al., 2006; Bakun et al., 2015); 2) increase the intensity of the stratification with impacts on the fluxes of nutrients in the water column (McGowan et al., 2003; Behrenfeld et al., 2006); 3) decrease the level of micronutrients in the ocean due to a reduction of precipitation (Jickells et al., 2005; McTainsh and Strong, 2006).

Forage fish are very sensitive to environmental changes and exhibit highly variable population dynamics resulting in large scale fluctuations over the years, with potentially

large impacts on the ecosystem health and global economy (Alder *et al.*, 2008: Checkley et al., 2017). For these reasons climate change might have a big impact on forage fish in ways that are complex and still highly uncertain (Shannon *et al.*, 2009).

One of the most reported effects of climate change on forage fish is a shift in distribution, that could be driven by changes in temperature, food availability, species interactions and consequently by a reduction or expansion of the preferred habitats (Lima et al., 2022; Maynou et al., 2020; Last et al., 2011; Stramma et al., 2011; Booth et al., 2011). Moreover, many works have been published on the northward range expansion of different species with southern affinities in the North Atlantic (Quero, 1998, Stebbing et al., 2002, Brander et al., 2003, Genner et al., 2004, Genner et al., 2010, Perry et al., 2005, Simpson et al., 2011; Alheit et al., 2012). Climate change has been linked to an increase in species richness at temperate latitudes, explained from the fact that fish species richness in general decreases with latitude (Hiddink & Ter Hofstede).

Changes in distribution are best observed at the limits of the distributional range (Wooster and Bailey, 1989; Myers, 1998) and this applies to some of the forage fish populations that inhabit Welsh waters (Campanella & van der Kooij, 2021). This area can be considered a transition zone between colder boreal waters in the north and warmer Lusitanian waters in the south and for many fish species, constitutes either the upper (anchovy and sardine) or lower (herring and sprat) latitudinal range limits (Campanella & van der Kooij, 2021). An expansion of European anchovy in this area has been reported in recent years (Petitgas et al., 2012) and an increase of the occurrences of warm waters fish species has been observed during recent acoustic surveys conducted in the area (Campanella & van der Kooij, 2021). While this northward shift benefits warm water species in the area, colder water species may be pushed further north or into deeper waters (Dulvy et al., 2008). Pelagic fish are generally able to disperse as a response to changing conditions, as they undertake long-distance migrations annually or have pelagic larvae that are carried along by ocean currents. In addition, the continental shelves provide a continuous band of suitable habitat (Hiddink & Ter Hofsted, 2008) so species like sprat will be able to move northward as local conditions warm up. However, some forage fish, like herring and particularly sandeels, are limited in their dispersal ability as they are restricted by habitat characteristics such as the availability of specific seabed substrates (Rijnsdorp et al., 2010).

Temperature-induced latitudinal shifts could also occur in other organisms such as zooplankton. The potential changes in prey availability will indirectly affect zooplanktivorous forage fish. For example, a northward shift was observed in the copepod *Calanus finmarchicus*, a key prey species for many larval fish stages such as cod and sandeel (Beaugrand et al., 2002; Reygondeau and Beaugrand, 2010). Warming can also alter the timing of the spring bloom, zooplankton production and peak spawning periods of pelagic fish, such as sandeels, causing a mismatch between food availability and the larval growth period (MCCIP, 2018).

Considering the large scale at which climate change may impact forage fish and the complexity of the potential effects through which it operates, it is crucial to provide a baseline of their current dynamics in Welsh waters, in particular their distributions, diets and inter-specific interactions, (Campanella & van der Kooij, 2021). This information could then form the basis of modelling exercises to forecast likely future changes.

5. Evidence gaps and recommendations

The coastal and shelf seas off Wales support a range of anthropogenic activities many of which may act as pressures on forage fish. The main pressures, the processes through which they impact the marine environment and specifically forage fish, were evaluated based on available information in the literature. Despite a growing body of work, limited studies have focussed on the impacts of anthropogenic pressures on forage fish specifically, not just within the study area but also globally.

Most published case studies have focussed on the impacts of pressures on marine fish at organism level. Demersal fish, particularly flatfish such as dab and plaice, are most consistently used as indicator species. They tend to be less mobile and are typically restricted to specific seabed habitats. These features make them more vulnerable to particularly localised pressures such as aggregate extraction, noise from e.g. marine construction as well as contaminants which tend to accumulate in seabed substrates. Significant impacts have been recorded on the health of individual fish with possible adverse implications at population level.

Some of these impacts may also apply to forage fish and the high oil content of for example clupeiformes and sandeels make them vulnerable to accumulating hydrophobe contaminants. However, most forage fish species are more widely distributed, have limited site fidelity, and are mobile, allowing them to vacate the areas where localised pressures may act. Their generally short life span will also limit the adverse effects of contaminants. While this may reduce the impact to the individual forage fish, or indeed their population, migration away from an area will have an impact on the top-predators that rely on local forage fish for food, for example during the breeding season of birds. Equally, a change in behaviour (e.g. a change in vertical distribution) in response to a local pressure may reduce the availability of forage fish to predators. Therefore, an understanding of behavioural responses by forage fish to local pressures requires further examining. Pressures that operate at medium (>10s of kilometres) and large (regional and global) scales may provide a more significant challenge to forage fish, particularly during critical life-stages such as juveniles (nursery) or during spawning when individuals are more restricted in their movements. Future studies on the effect of all pressures on individual fish at different life stages, including physiological and behavioural responses, should therefore be expanded to include forage fish.

While impacts on individual forage fish are important, the effects of pressures on the wider population will determine its resilience and impacts on the wider ecosystem, including top -

predators. Healthy populations will be able to compensate for local pressure-related reductions in fitness or even mortality of individuals. A priority focus should therefore be to understand the population structures and dynamics of the forage fish community in Welsh waters (Campanella & van der Kooij 2021), starting with regular monitoring of the structure and inter-annual fluctuations in populations of forage fish communities.

Although discussed in individual sections, many of the pressures are linked and may even exacerbate each other. Construction of an offshore windfarm will introduce noise in the environment and is likely to involve disturbance of seabed substrates. Climate change may increase releases of contaminants into the environment from historic coastal landfills, caused by flooding, erosion and sea level rise (Brand et al., 2018). This has to be considered when future studies on pressures are conducted.

An integrated process for gathering and assessing chemical and biological effects data is therefore necessary and this is developed within ICES (International Council for the Exploration of the Sea) and the OSPAR Convention (Protection of the Marine Environment of the North-East Atlantic). Monitoring at coastal and offshore stations around England and Wales is conducted within the UK Clean Seas Environment Monitoring Programme (CSEMP), which seeks to integrate national and international monitoring programmes for all relevant UK government agencies. The CSEMP aims to ascertain the effectiveness of regulatory measures taken to reduce the inputs of hazardous substances to UK seas. In addition, it contributes to the UK's international monitoring obligations to demonstrate compliance with various Directives, including those defined under OSPAR (Law and Maes, 2012).

A range of potential impacts on forage fish have been discussed in this review. It has highlighted the general lack of specific knowledge on the impacts of anthropogenic pressures on forage fish at either individual or population level. This is of concern given that forage fish play a critical role in coastal and shelf-sea ecosystems. Their mid-trophic role makes them sensitive to bottom-up and top-down pressures which may manifest as strong interannual variations in population size that will impact other commercial finfish, top predators and society. A solid understanding of the population dynamics (stock structure and abundance) of the forage fish community is necessary. This would however have to be part of a wider ecosystem-based management of maritime sectors as well as an integrated spatial approach to planning and management of activities at sea.

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