



# MarLIN

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Information on the species and habitats around the coasts and sea of the British Isles

## *Mytilus edulis* beds on littoral mud

MarLIN – Marine Life Information Network  
Marine Evidence-based Sensitivity Assessment (MarESA) Review

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**Please note.** This MarESA report is a dated version of the online review. Please refer to the website for the most up-to-date version [<https://www.marlin.ac.uk/habitats/detail/1167>]. All terms and the MarESA methodology are outlined on the website (<https://www.marlin.ac.uk>)

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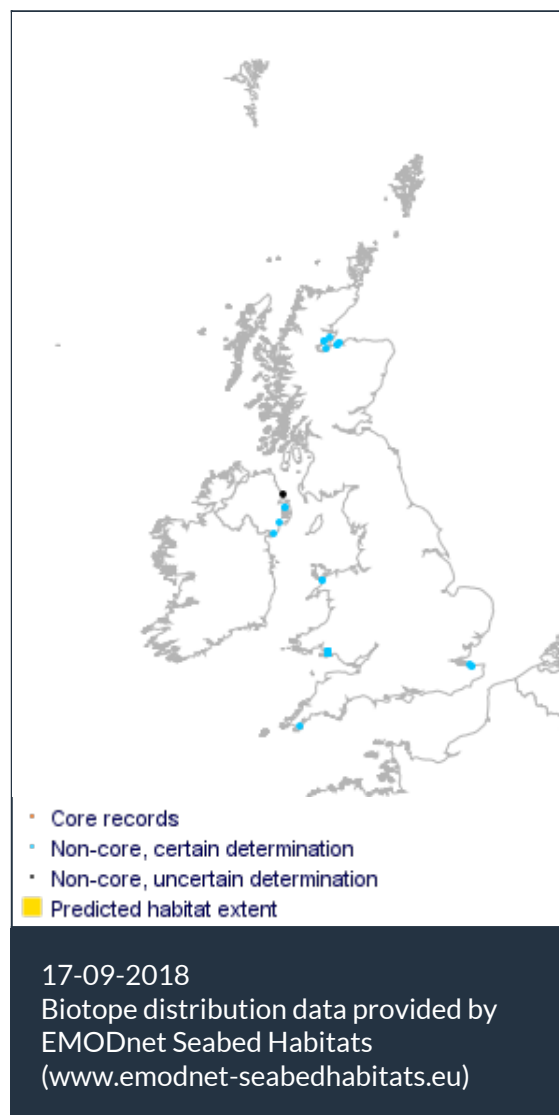
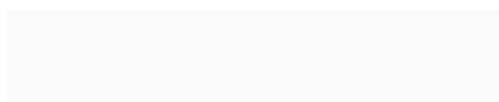
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Researched by Dr Heidi Tillin & Kathryn Mainwaring

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## Summary

### ☰ UK and Ireland classification

**EUNIS 2008** A2.7213 *Mytilus edulis* beds on littoral mud

**JNCC 2015** LS.LBR.LMus.Myt.Mu *Mytilus edulis* beds on littoral mud

**JNCC 2004** LS.LBR.LMus.Myt.Mu *Mytilus edulis* beds on littoral mud

**1997 Biotope**

### 🔍 Description

Dense mussel beds found in sheltered conditions on mud. There is a build up of pseudofaeces that results in a bed that is very soft to walk on, and sediment that is anoxic to the surface. Pools are often present in the mussel bed but they tend to contain few species. The sediment infauna is very poor as a result of anoxic conditions. The mussel valves are usually clean, without epifaunal growth. Where this biotope occurs naturally, all age classes are found within the mussel bed. This biotope also includes commercially laid mussel beds on soft sediments, which tend to be of uniform age structure. The species diversity of this sub-biotope is a lot lower than that of the other Myt

sub-biotopes. It occurs on sheltered mudflats, or areas that were previously rocky or cobble fields, but where pseudofaeces has accumulated, leading to the presence of a thick layer of mud. Mussels may settle on areas of cobble or mixed sediment (Myt.Mx), and lead to the build-up of a thick layer of pseudofaeces, changing the biotope to Myt.Mu over time. The layer of mud can prevent the attachment of mussels to the underlying stable substratum, thus making the mussel bed liable to be washed away during storms. This is known to occur in areas of Morecambe Bay. (Information from Connor *et al.*, 2004; JNCC, 2015).

### ↓ Depth range

Mid shore, Lower shore

### Additional information

-

### ✓ Listed By

- none -

### Further information sources

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## Sensitivity review

### Sensitivity characteristics of the habitat and relevant characteristic species

Although a wide range of species are associated with *Mytilus edulis* reef or bed biotopes, these characterizing species occur in a range of other biotopes and are therefore not considered to be obligate associates. *Mytilus edulis* beds are not dependent on associated species to create or modify habitat, provide food or other resources, although their loss would represent a loss of diversity. It should be noted that for attached organisms the sensitivity of the *Mytilus edulis* biotope would be of primary concern as removal of the reef would also lead to the removal of the attached species. The sensitivity assessments are, therefore, based on *Mytilus edulis* and only consider the sensitivity of associated species where they might augment any impact or cause secondary impacts.

### Resilience and recovery rates of habitat

Blue mussels, *Mytilus edulis*, are sessile, attached organisms that are unable to repair significant damage to individuals. Mussels do not reproduce asexually and, therefore, the only mechanism for recovery from significant impacts (where resistance is assessed as 'None', 'Low' or 'Medium') is larval recruitment to the bed or the area where previously a bed existed. Spawning occurs in spring and later summer allowing two periods of recruitment (Seed, 1969). *Mytilus edulis* has a high fecundity producing >1,000,000 eggs per spawning event. Larvae stay in the plankton for between 20 days to two months depending on water temperature (Bayne, 1976). In unfavourable conditions, they may delay metamorphosis for 6 months (Lane *et al.*, 1985). Larval dispersal depends on the currents and the length of time they spend in the plankton. Larvae subject to ocean currents for up to six months can have a high dispersal potential. Settlement occurs in two phases, an initial attachment using their foot (the pediveliger stage) and then a second attachment by the byssus thread before which they may alter their location to a more favourable one (Bayne, 1964). The final settlement often occurs around or between individual mussels of an established population. In areas of high water flow the mussel bed will rely on recruitment from other populations as larvae will be swept away and therefore recovery will depend on recruitment from elsewhere.

Larval mortality can be as high as 99% due to adverse environmental conditions, especially temperature, inadequate food supply (fluctuations in phytoplankton populations), inhalation by suspension feeding adult mytilids, difficulty in finding suitable substrata and predation (Lutz & Kennish 1992). After settlement, the larvae and juveniles are subject to high levels of predation as well as dislodgement from waves and sand abrasion, depending on the area of settlement. Height on the shore generally determines lifespan, with mussels in the low shore only surviving between 2-3 years due to high predation levels whereas higher up on the shore a wider variety of age classes are found (Seed, 1969). Theisen (1973) reported that specimens of *Mytilus edulis* could reach 18-24 years of age.

Mainwaring *et al.* (2014) reviewed the evidence for recovery of *Mytilus.edulis* beds from disturbance and an earlier study by Seed & Suchanek (1992) reviewed studies on the recovery of 'gaps' in *Mytilus* spp. beds. It was concluded that beds occurring high on the shore and on less exposed sites took longer to recover after a disturbance event than beds found low on the shore or at more exposed sites. However, the slowest recovering sites (high shore and sheltered shores) are at the least risk of natural disturbance and often considered more 'stable' (Lewis, 1964) as they are less vulnerable to removal by wave action or wave driven logs. Continued disturbance will lead

to a patchy distribution of mussels.

Recruitment of *Mytilus edulis* is often sporadic, occurring in unpredictable pulses (Seed & Suchanek, 1992), although persistent mussel beds can be maintained by relatively low levels or episodic recruitment (McGrorty *et al.*, 1990). A good annual recruitment could result in rapid recovery (Holt *et al.*, 1998). However, the unpredictable pattern of recruitment based on environmental conditions could result in recruitment taking much longer. In the northern Wadden Sea, strong year classes (resulting from a good recruitment episode) that lead to the rejuvenation of blue mussel beds are rare and usually follow severe winters, even though mussel spawning and settlement are extended and occur throughout the year (Diederich, 2005). In the List tidal basin (northern Wadden Sea) a mass recruitment of mussels occurred in 1996 but had not been repeated by 2003 (the date of the study), i.e. for seven years (Diederich, 2005).

In some long-term studies of *Mytilus californianus* it was observed that gaps could continue to increase in size post-disturbance due to wave action and predation (Paine & Levin, 1981; Brosnan & Crumrine, 1994; Smith & Murray, 2005) potentially due to the weakening of the byssus threads leaving them more vulnerable to environmental conditions (Denny 1987). On rocky shores, barnacles and fucoids are often quick to colonize the 'gaps' created. The presence of macroalgae appears to inhibit recovery whilst the presence of barnacles enhances subsequent mussel recruitment (Seed & Suchanek 1992). Brosnan & Crumrine (1994) observed little recovery of the congener *Mytilus californianus* in two years after trampling disturbance. Paine & Levin (1981) estimated that recovery times of beds could be between 8-24 years while Seed & Suchanek (1992) suggested it could take longer-time scales, suggesting that meaningful recovery is unlikely in some areas. It has, however, been suggested that *Mytilus edulis* recovers quicker than other *Mytilus* species (Seed & Suchanek 1992), which may mean that these predicted recovery rates are too low for *Mytilus edulis*.

**Resilience assessment.** The evidence for recovery rates of *Mytilus edulis* beds from different levels of impact is very limited and whether these rates are similar, or not, between biotopes is largely unclear. Recovery rates are clearly determined by a range of factors such as the degree of impact, the season of impact, larval supply and local environmental factors including hydrodynamics so that confidence in the applicability of generic assessments is 'Low'. Overall, *Mytilus* spp. populations are considered to have a strong ability to recover from environmental disturbance (Holt *et al.*, 1998; Seed & Suchanek, 1992). A good annual recruitment may allow a bed to recovery rapidly, though this cannot always be guaranteed within a certain time-scale due to the episodic nature of *Mytilus edulis* recruitment (Lutz & Kennish, 1992; Seed & Suchanek, 1992) and the influence of site-specific variables. Resilience will vary depending on larval supply and wave exposure with areas with low larval supply and high wave exposure on sandy substrata experiencing the longest recovery rates. The resilience assessments have adopted the rates used by Mainwaring *et al.* (2014) who suggested that where resistance is 'High' then there is no effect to recover from and resilience should be assessed as 'High'. Littoral and sublittoral beds are considered to have '**Medium**' resilience (2 -10 years) to represent the potential for recovery within a few years where a proportion of the bed remains ('Medium' or 'Low' resistance). Resilience is assessed as '**Low**' (over 10 years) for all biotopes where resistance is assessed as 'None', as recovery is dependent on recruitment from other areas and recruitment can be sporadic. Due to the variation in recovery rates reported in the literature, while the evidence for resilience is of 'High' quality and 'High' applicability (for recovery from the same pressures or otherwise assessed as 'Low'), the degree of concordance is 'Medium'.

**NB:** The resilience and the ability to recover from human-induced pressures is a combination of

the environmental conditions of the site, the frequency (repeated disturbances versus a one-off event) and the intensity of the disturbance. Recovery of impacted populations will always be mediated by stochastic events and processes acting over different scales including, but not limited to, local habitat conditions, further impacts and processes such as larval-supply and recruitment between populations. Full recovery is defined as the return to the state of the habitat that existed prior to impact. This does not necessarily mean that every component species has returned to its prior condition, abundance or extent but that the relevant functional components are present and the habitat is structurally and functionally recognizable as the initial habitat of interest. It should be noted that the recovery rates are only indicative of the recovery potential.

## Hydrological Pressures

	Resistance	Resilience	Sensitivity
Temperature increase (local)	High Q: High A: High C: Medium	High Q: High A: High C: High	Not sensitive Q: High A: High C: Medium

Local populations may be acclimated to the prevailing temperature regime and may, therefore, exhibit different tolerances to other populations subject to different salinity conditions and therefore caution should be used when inferring tolerances from populations in different regions. *Mytilus edulis* is a eurytopic species found in a wide temperature range from mild, subtropical regions to areas which frequently experience freezing conditions and are vulnerable to ice scour (Seed & Suchanek, 1992). In recent years, *Mytilus edulis* has been observed to be expanding its range pole-wards and has reappeared in Svalbard, due to an increase in sea temperature in that region (Berge *et al.*, 2005), whilst its equatorial limits are contracting due to increases in water temperature beyond the lethal limit (Jones *et al.*, 2010). In British waters, 29°C was recorded as the upper sustained thermal tolerance limit for *Mytilus edulis* (Read & Cumming, 1967; Almada-Villela, *et al.*, 1982), although it is thought that European mussels will rarely experience temperatures above 25°C (Seed & Suchanek, 1992).

Tsuchiya (1983) documented the mass mortality of *Mytilus edulis* in in Mutsu Bay, northern Japan in August 1981 due to air temperatures of 34°C that resulted in mussel tissue temperatures in excess of 40°C. In one hour, 50% of the *Mytilus edulis* from the upper 75% of the shore had died. It could not be concluded from this study whether the mortality was due to high temperatures, desiccation or a combination of the two. Lethal water temperatures appear to vary between areas (Tsuchiya, 1983) although it appears that their tolerance at certain temperatures vary, depending on the temperature range to which the individuals are acclimated (Kittner & Riisgaard, 2005). After acclimation of individuals of *M. edulis* to 18°C, Kittner & Riisgaard (2005) observed that the filtrations rates were at their maximum between 8.3 and 20°C and below this at 6°C the mussels closed their valves. However, after being acclimated at 11°C for five days, the mussels maintained the high filtration rates down to 4°C. Hence, given time, mussels can acclimatise and shift their temperature tolerance. Filtration in *Mytilus edulis* was observed to continue down to -1°C, with high absorption efficiencies (53-81%) (Loo, 1992).

At the upper range of a mussels tolerance limit, heat shock proteins are produced, indicating high stress levels (Jones *et al.*, 2010). After a single day at 30°C, the heat shock proteins were still present over 14 days later, although at a reduced level. Increased temperatures can affect reproduction in *Mytilus edulis* (Myrand *et al.*, 2000). In shallow lagoons, mortality began in late July at the end of a major spawning event when temperatures peaked at >20°C. These mussels had a low energetic content post-spawning and had stopped shell growth. It is likely that the high

temperatures caused mortality due to the reduced condition of the mussels post-spawning (Myrand *et al.*, 2000). Gamete production does not appear to be affected by temperature (Suchanek, 1985).

Temperature changes may also lead to indirect effects. For example, an increase in temperature increases the mussels' susceptibility to pathogens (*Vibrio tubiashii*) in the presence of relatively low concentrations of copper (Parry & Pipe, 2004). Increased temperatures may also allow for range expansion of parasites or pathogens which will have a negative impact on the health of the mussels if they become infected.

Power stations have the potential to cause an increase in sea temperature of up to 15°C (Cole *et al.*, 1999), although this impact will be localised. However, as mussels are of the most damaging biofouling organisms on water outlets of power stations, they are clearly not adversely affected (Whitehouse *et al.*, 1985; Thompson *et al.*, 2000).

**Sensitivity assessment.** Based on the wide range of temperature tolerance of *Mytilus edulis* and its limited effect on its physiology, it is concluded that the acute and chronic changes described by the benchmarks of 2-5°C would have limited effect. Therefore, the biotope is considered to have a 'High' resistance to temperature change, a 'High' resilience, and is considered to be 'Not Sensitive' at the benchmark level.

Temperature decrease  
(local)

High

Q: High A: High C: Medium

High

Q: High A: High C: High

Not sensitive

Q: High A: High C: Medium

Local populations may be acclimated to the prevailing temperature regime and may, therefore, exhibit different tolerances to other populations subject to different salinity conditions and therefore caution should be used when inferring tolerances from populations in different regions. *Mytilus edulis* is a eurytopic species found in a wide temperature range from mild, subtropical regions to areas which frequently experience freezing conditions and are vulnerable to ice scour (Seed & Suchanek 1992).

The lower lethal limit of *Mytilus edulis* depends on the length of time exposed to a low temperature and the frequency of exposure (Bourget, 1983). Williams (1970) observed that *Mytilus edulis* tolerated a tissue temperature as low as -10°C. In a laboratory experiment, Bourget (1983) showed that the median lethal temperature for 24 hours of exposure in *Mytilus edulis* was -16 °C for large mussels (>3 cm) and -12.5°C for juveniles (<1.5 cm). However, when exposed to reduced temperatures for only 16 hours, the median lethal temperature of large mussels decreased to -20°C. It was also reported that mussels exposed to sub lethal temperatures cyclically, e.g. -8°C every 12.4 hours for 3-4 days, suffered significant damage likely to lead to death (Bourget, 1983), which suggested that while *Mytilus edulis* could tolerate occasional sharp frost events it was not likely to survive prolonged periods of very low temperatures. During the cold winter of 1962/63, *Mytilus edulis* was reported to have experienced relatively few effects with only 30% mortality being recorded from the south-east coast of England (Whitstable area) and only about 2% mortality was reported from Rhosilli in South Wales (Crisp, 1964). Crisp (1964) also noted that the mortality was mainly from predation on the individuals that were weakened by the low temperatures rather than the temperature itself. It is thought that the use of nucleating agents in the haemolymph and the maintenance of a high osmotic concentration in the mantle fluid during periods of winter isolation allows *Mytilus edulis* to tolerate such low temperatures (Aunaas *et al.*, 1988).



Shell growth is not expected to be majorly influenced by low temperatures. Bayne (1976) demonstrated that between 10-20°C water temperature had little effect on the scope for growth, similar to the findings of (Page & Hubbard, 1987) who found that a temperature range of 10-18°C did not influence growth rate. In addition, Loo (1992) recorded growth rates of up to 0.7% at temperatures as low as -1°C, with an excess of seston, a rate higher than the same author recorded in mussel culture in Sweden (Loo & Rosenberg, 1983). They concluded that food availability was more of a limiting factor to growth than temperature (Loo, 1992).

**Sensitivity assessment.** Based on the wide range of temperature tolerance of *Mytilus edulis* and its limited effect on its physiology, it is concluded that the acute and chronic changes described by the benchmarks of 2-5°C would have limited effect. Therefore, the biotope is considered to have a 'High' resistance to temperature change, a 'High' resilience, and is considered to be 'Not Sensitive' at the benchmark level.

<b>Salinity increase (local)</b>	<b>High</b>	<b>High</b>	<b>Not sensitive</b>
	Q: High A: High C: Medium	Q: High A: High C: High	Q: High A: High C: Medium

Local populations may be acclimated to the prevailing salinity regime and, therefore, exhibit different tolerances to other populations subject to different salinity conditions. Therefore caution should be used when inferring tolerances from populations in different regions. *Mytilus edulis* is found in a wide range of salinities from variable salinity areas (18-35 ppt) such as estuaries and intertidal areas to areas of more constant salinity (30-35 ppt) in the sublittoral (Connor *et al.*, 2004). Furthermore, mussels in rock pools are likely to experience hypersaline conditions on hot days. Newell (1979) recorded salinities as high as 42 psu in intertidal rock pools, suggesting that *Mytilus edulis* can tolerate hypersaline conditions.

**Sensitivity assessment.** Increased salinity is likely to change a reduced salinity area to a fully marine area where it is known that mussels can survive in abundance. Also, an increase in salinity from full to raised salinity (> 40 units), is less than that encountered in rock pools, where *Mytilus edulis* survives. Therefore, *Mytilus edulis* is recorded as having a 'High' resistance to an increase in salinity at the pressure benchmark and a 'High' resilience and this biotope is, therefore, assessed as 'Not sensitive' at the benchmark level.

<b>Salinity decrease (local)</b>	<b>High</b>	<b>High</b>	<b>Not sensitive</b>
	Q: High A: High C: Medium	Q: High A: High C: High	Q: High A: High C: Medium

Local populations may be acclimated to the prevailing salinity regime and may, therefore, exhibit different tolerances to other populations subject to different salinity conditions. Hence, caution should be used when inferring tolerances from populations in different regions. *Mytilus edulis* is found in a wide range of salinities from variable salinity areas (18-35ppt) such as estuaries and intertidal areas to areas of more constant salinity (30-35 ppt) in the sublittoral (Connor *et al.*, 2004). In addition, *Mytilus edulis* thrives in brackish lagoons and estuaries, although, this is probably due to the abundance of food in these environments rather than the salinity (Seed & Suchanek, 1992). Furthermore, mussels in rock pools are likely to experience hypersaline conditions on hot days. Newell (1979) recorded salinities as high as 42psu in intertidal rock pools, suggesting that *Mytilus edulis* can tolerate high salinities. Also, *Mytilus edulis* was recorded to grow in a dwarf form in the Baltic sea where the average salinity was 6.5psu (Riisgård *et al.*, 2013).

*Mytilus edulis* is an osmoconformer and maintains its tissue fluids iso-osmotic (equal ionic strength)

with the surrounding medium by mobilisation and adjustment of the tissue fluid concentration of free amino acids (e.g. taurine, glycine and alanine) (Bayne, 1976; Newell, 1989). But mobilizing amino acids may result in loss of protein, increased nitrogen excretion and reduced growth. However, Koehn (1983) and Koehn & Hilbish (1987) reported a genetic basis to adaptation to salinity. *Mytilus edulis* exhibits a defined behavioural response to reducing salinity, initially only closing its siphons to maintain the salinity of the water in its mantle cavity, which allows some gaseous exchange and therefore maintains aerobic metabolism for longer. If the salinity continues to fall the valves close tightly (Davenport, 1979; Rankin & Davenport, 1981). In the long-term (weeks) *Mytilus edulis* can acclimate to lower salinities (Almada-Villela, 1984; Seed & Suchanek 1992; Holt *et al.*, 1998). Almada-Villela (1984) reported that the growth rate of individuals exposed to only 13 psu reduced to almost zero but had recovered to over 80% of control animals within one month. Observed differences in growth are due to physiological and/or genetic adaptation to salinity.

Decreased salinity has physiological effects on *Mytilus edulis*; decreasing the heart rate (Bahmet *et al.*, 2005), reducing filtration rates (Riisgård *et al.*, 2013), reducing growth rate (Gruffydd *et al.*, 1984) and reducing the immune function (Bussell *et al.*, 2008). Both Bahmet *et al.* (2005) and Riisgård *et al.* (2013) noted that filtration and heart rates return to normal within a number of days acclimation or a return to the original salinity. However, Riisgård *et al.* (2013) observed that mussels from an average of 17 psu found it harder to acclimate between the salinity extremes than those from an average of 6.5 psu. This observation may mean that mussels in a variable/ lower salinity environment are more able to tolerate change than those found at fully marine salinities. A sharp salinity change also induces a behavioural response to close the shell (Riisgård *et al.*, 2012) to maintain the salinity within the mantle cavity. In extreme low salinities, e.g. resulting from storm runoff, large numbers of mussels may be killed (Keith Hiscock pers comm.). However, Bailey *et al.* (1996) observed very few mortalities when exposing *Mytilus edulis* to a range of salinities as low as 0 ppt for two weeks at a range of temperatures. It was also noted that there was a fast recovery rate.

**Sensitivity assessment**, Most of the literature found on this topic considered short-term (days to weeks) impacts of changes in salinity whilst the benchmark refers to a change for one year. However, *Mytilus edulis* was shown to be capable of acclimation to changes in salinity. As *Mytilus edulis* is found in salinities to as low as 4-5 psu (Riisgård *et al.*, 2013), it is likely to be able to acclimate to a decrease in salinity from full (30-35 units) to variable (18-40 units) or reduced (18-30 units). Therefore, *Mytilus edulis* is recorded as having a '**High**' resistance to a decrease in salinity and a '**High**' resilience (no impact to recover from). The blue mussel bed biotopes are, therefore, considered to be '**Not Sensitive**' at the benchmark level.

#### Water flow (tidal current) changes (local)

**Medium**

Q: High A: High C: Medium

**Medium**

Q: High A: Low C: Medium

**Medium**

Q: High A: Low C: Medium

Blue mussels are active suspension feeders generating currents by beating cilia and are therefore not entirely dependent on water flow to supply food (organic particulates and phytoplankton). Therefore, they can survive in very sheltered areas, but water flow (due to tides, currents or wave action) can enhance the supply of food, carried from outside the area or resuspended into the water column.

The growth rate of *Mytilus edulis* in relation to water flow was investigated by Langan & Howell (1994) who found that the growth rate over 24 days was 0.1, 1.8, 2.0, 1.9 and 1.5 mm at flow rates

of 0, 0.01, 0.02, 0.04 and 0.08 m/s respectively. The only growth rate found to be significantly different was at zero flow. However, the pattern did follow that predicted by the “inhalant pumping speed” hypothesis that suggested maximal growth at water speeds of about 0.02 m/s and decreased growth rates at higher and lower speeds (Langan & Howell 1994). Higher current speed brings food to the bottom layers of the water column, and hence near to the mussels, at a higher rate (Frechette *et al.*, 1989). Frechette *et al.* (1989) developed a model based on measurements in the St. Lawrence River estuary (Québec). The model suggested that *Mytilus edulis* consumption rate depends on the flow of water.

Widdows *et al.* (2002) found that there was no change in filtration rate of *Mytilus edulis* between 0.05 and 0.8 m/s. They noted that their finding contradicted earlier work that found a marked decline in filtration rates from 0.05 to 0.25 m/s (Newell, 1999; cited in Widdows *et al.*, 2002) but suggested that the difference might be caused in differences in population studied, as the earlier work was based in the USA and their study used mussels from the Exe estuary in the UK. Widdows *et al.* (2002) also noted that above 0.8 m/s the filtration rate declined mainly because the mussels became detached from the substratum in the experimental flume tank. Widdows *et al.* (2002) noted that their results were consistent with field observations, as mussels show preferential settlement and growth in areas of high flow, such as the mouth of estuaries and at the base of power station cooling systems (Jenner *et al.*, 1998). They also reported that Jenner *et al.* (1998; cited in Widdows *et al.*, 2002) observed that biofouling of cooling water systems by mussels was only reduced significantly when mean current speeds reached 1.8-2.2 m/s and mussel biofouling was absent at >2.9 m/s.

Increased flow rate increases the risk of mussels being detached from the bed and transported elsewhere where their chance of survival will be significantly reduced due to the risk of predation and siltation (Dare, 1976). It is the strength of the byssal attachment that determines the mussel's ability to withstand increases in flow rate. Flow rate itself has been shown to influence the strength and number of byssus threads that are produced by *Mytilus edulis* and other *Mytilus* spp., with mussels in areas of higher flow rate demonstrating stronger attachment (Dolmer & Svane, 1994; Alfaro, 2006). Dolmer & Svane (1994) estimated the potential strength of attachment for *Mytilus edulis* in both still water and flows of 1.94 m/sec, by counting the number of established byssus threads and measuring the strength of attachment of individual detached byssus threads. It was found that in still water the strength of the attachment was 21% of the potential strength whilst at 19.4 cm/sec it was 81% of the potential strength, suggesting that *Mytilus edulis* has the ability to adapt the strength of its attachment based on flow rate. Young (1985) demonstrated that byssus thread production and attachment increased with increasing water agitation. She observed the strengthening of byssal attachments by 25% within eight hours of a storm commencing and an ability to withstand surges up to 16 m/s. However, it was concluded that sudden surges may leave the mussels susceptible to being swept away (Young, 1985) as they need time to react to the increased velocity to increase the attachment strength. *Mytilus edulis* beds could, therefore, adapt to changes in water flow at the pressure benchmark.

Alfaro (2006) found that when a sudden increase in flow (to 0.13 m/s) was experienced by *Perna canaliculus* (another mussel species) in areas of low flow rate they were more susceptible to detachment than those that had been exposed to a higher flow rate. It was also noted that the individuals kept at higher water flows (e.g. 10 cm/sec) produced more byssus threads. The increased energy used for byssus production in the high flow environments may reduce the energy that is available for other biological activities (Alfaro, 2006).

Individuals attached to solid substrata (rock) are likely to display more resistance than individuals

attached to boulders, cobbles or sediment. For example, mussel reefs in the Wash, Morecambe Bay and the Wadden Sea are vulnerable to destruction by storms and tidal surges (Holt *et al.*, 1998). Widdows *et al.* (2002) examined mussel beds in the mouth of the Exe estuary and along the coast at Exmouth. In flume tank studies between 0.1 and 0.35 m/s, the resuspension rate of sediment in mussel beds on sandy substrata was four and five times higher for areas with 25% and 50% mussel cover compared to bare sediment due to the increased turbulence and scouring around the mussels. However, at high densities (100% cover) the beds remained stable (up to 0.35 m/s), with resuspension being about three times lower than areas with 0% cover, due to the high number of byssal attachments between individuals (Widdows *et al.*, 2002). Where mussel beds occurred on pebble and sand substrata (mixed substrata) sediment erosion was lower than that of the 100% cover on the sandy substrata regardless of mussel density. Low density mussel beds formed small clumps with a lower mass ratio of mussels attached to the substratum to increase anchorage. In low density beds, increased scour resulted in some mussel detaching from the bed and in areas with 50% cover the erosion of the bed resulted in the burial of a large proportion of the mussels. The mussels returned to the surface afterwards and recovered in 1-2 days. Widdows *et al.* (2002) also noted a linear relationship between mussel beds density and sediment stability on cohesive mud substratum, taken from Cleethorpes, and exposed to currents of 0.15 to 0.45 m/s. Again increased mussel cover increased sediment stability. Widdows *et al.* (2002) found that the mussel bed at Exmouth experienced a peak flow of 0.9m/s before and after high water, which only reduced to 0.2 m/s at slack water.

Water flow also affects the settlement behaviour of larvae. Alfaro (2005) observed that larvae settling in a low water flow environment are able to first settle and then detach and reattach displaying exploratory behaviour before finally settling and strengthening their byssus threads. However, larvae settling in high flow environments did not display this exploratory behaviour. Pernet *et al.* (2003) found that at high velocities, larvae of *Mytilus* spp. were not able to exercise much settlement preference. It was thought that when contact with suitable substratum is made the larvae probably secure a firm attachment. Movement of larvae from low shear velocities, where they use their foot to settle, to high shear velocities where they use their byssal thread to settle was observed by Dobretsov & Wahl (2008).

**Sensitivity assessment.** The blue mussel bed biotopes assessed are recorded from weak (<0.5 m/s) to strong (up to 3 m/s) tidal streams. The sensitivity of sedimentary biotopes to increased flow is dependent on the substratum and the degree of cover, with dense beds of ca 100% cover being more stable than patchy beds, and more stable on mixed substrata with cobble and boulders than sand and mud. Connor *et al.* (2004) noted that the build-up of mussel mud beneath beds could result in a change from sandy to muddy substrata underneath the bed and reduce attachment resulting in increased risk of removal by storms.

A decrease in water flow is unlikely to affect adversely blue mussel beds directly. The evidence above suggests that they can grow at water flow as low as 0.01 – 0.02 m/s and filter at 0.05 m/s; significantly less than weak tidal streams (<0.5 m/s). At very low or negligible water flow, the effects of siltation may have adverse effects (see relevant pressure). Dense beds are probably stable on mixed substrata, so resistance to change in water flow is probably **'High'**, resilience is assessed as **'High'** (no effect to recover from) and the biotope is assessed as **'Not sensitive'**. However, on sandy substrata and possibly to a greater extent on muddy substrata (Myt.Mu), especially where mussel mud has accumulated and/or the beds are patchy; an increase of water flow at the benchmark level is likely to remove parts of the bed. Therefore, resistance to change in water flow is probably **'Medium'**, resilience is assessed as **'Medium'** and the biotope is assessed as having **'Medium'** sensitivity.

**Emergence regime changes****Medium**

Q: High A: High C: Medium

**Medium**

Q: High A: Low C: Medium

**Medium**

Q: High A: Low C: Medium

*Mytilus edulis* beds are found at a wide range of shore heights from in the strandline down to the shallow sublittoral (Connor *et al.*, 2004). Their upper limits are controlled by temperature and desiccation (Suchanek, 1978; Seed & Suchanek 1992; Holt *et al.*, 1998) while the lower limits are set by predation, competition (Suchanek, 1978) and sand burial (Daly & Mathieson, 1977).

Mussels found higher up the shore display slower growth rates (Buschbaum & Saier, 2001) due to the decrease in time during which they can feed and also a decrease in food availability. It has been estimated that the point of zero growth occurs at 55% emergence (Baird, 1966) although this figure will vary slightly depending on the conditions of the exposure of the shore (Baird, 1966; Holt *et al.*, 1998). Increasing shore height does, however, increase the longevity of the mussels due to reduced predation pressure (Seed & Suchanek 1992; Holt *et al.*, 1998), resulting in a wider age class of mussels found on the upper shore. The lower limit of *Mytilus* beds is mainly set by predation from *Asterias rubens* and *Carcinus maenas* which may increase with a decrease in emergence potentially reducing the lower limit or reducing the number of size classes and age of the mussels at the lower range of the bed (Saier, 2002).

**Sensitivity assessment.** An increase in emergence is likely to reduce the abundance of the biotope at the upper limit due to desiccation and the mussels are likely to be replaced by barnacles on rocky shores, particularly on sheltered shores where there is little spray. Increased emergence is likely to have more of an impact on sandy substrata where burial by sand could limit the mussels' ability to extend its lower range resulting in a reduced mussel bed. A decrease in emergence would probably reduce the abundance of mussels at the lower limit due to increased predation but allow the bed to extend further up the shore.

Intertidal *Mytilus edulis* beds are considered to express '**Medium**' resistance to changes in emergence with mussels at the upper and lower limits exhibiting the greatest effects. Resilience is assessed as '**Medium**' and sensitivity is, therefore, assessed as '**Medium**'.

**Wave exposure changes (local)****Low**

Q: High A: Medium C: Medium

**Medium**

Q: High A: Low C: Medium

**Medium**

Q: High A: Low C: Medium

Blue mussel beds are found in a wide range of wave exposures, from extremely exposed areas to extremely sheltered (Seed 1976; Connor *et al.*, 2004). The littoral mixed sediment biotope LS.LBR.LMus.Myt.Mu occurs in moderate wave exposure to sheltered conditions.

*Mytilus edulis* is able to increase the strength of their attachment to the substratum in more turbulent conditions (Price, 1982; Young, 1985). Young (1985) demonstrated an increase in strength of the byssal attachment by 25% within 8 hours of a storm commencing. When comparing mussels in areas of high flow rate and low flow rate those at a higher flow rate exhibit stronger attachments than those in the areas of lower flow (Dolmer & Svane, 1994; Alfaro, 2006). Dolmer & Svane (1994) found that in still water the strength of the attachment was 21% of the potential strength whilst at 1.94 m/sec it was 81% of the potential strength. Alfaro (2006) also noted that the individuals kept at higher water flows produce more byssal threads. The increased energy used for byssus production in the high flow environments may reduce the energy that is available for other biological activities (Alfaro 2006). Whilst this clearly demonstrates the ability of mussels to adapt to the various conditions to avoid dislodgement, the mussels are unlikely to adapt instantly and a sudden increase in flow is likely to result in dislodgement (Young, 1985).

Widdows *et al.* (2002) examined mussel beds in the mouth of the Exe estuary and along the coast at Exmouth. Where the mussel beds occurred on sandy substratum the re-suspension rate was four and five times higher for areas with 25% and 50% mussel cover compared to bare sediment due to the increased turbulence and scouring around the mussels. In low density beds, this increased scour resulted in some mussel detaching from the bed and in areas with 50% cover the erosion of the bed resulted in the burial of a large proportion of the mussels. The mussels returned to the surface after 1-2 days and recovered. However, at high densities (100% cover) the beds remained stable, with re-suspension being about 3 times lower than areas with 0% cover, due to the high number of byssal attachments between individuals (Widdows *et al.*, 2002). Where mussel beds occurred on pebble and sand substratum (mixed substratum) sediment erosion was lower than that of the 100% cover on the sandy substratum regardless of density despite experiencing flows of 0.9 m/s. The low density mussels were observed to form small clumps with a lower mass ratio of mussels attached to the substratum to increase anchorage.

Widdows *et al.* (2002) suggest that 100% mussel cover on sandy substrata reduces the risk of dislodgement. However, Harger & Landenberger (1971) suggest that growth in mussel beds results in fewer mussels being attached to the substratum and therefore strong seas can “roll up the whole mass of mud and mussels like a carpet and break it to pieces on the foreshore”. It was also noted that on gravelly substratum, single layer mussel beds incurred less damage in storm conditions than heavier multi-layered beds (Harger & Landenberger, 1971).

Large-scale destruction of mussel beds has been reported in many areas such as the Wash, Morecambe Bay and the Wadden Sea (Holt *et al.*, 1998). It appears that because of high wave exposure and destruction, reefs found in wave exposed areas are likely to be more dynamic (Nehls & Thiel, 1993). Furthermore, increased wave exposure leads to a higher risk of damage from drift logs (or other flotsam), which once they have destroyed a patch of mussels, leave the mussels around that patch at a higher risk of erosion (Seed & Suchanek, 1992). Mussels with high abundance of epizoic and epiphytic (e.g. barnacles and macroalgae) growing on mussels are also more susceptible to removal in areas of high wave exposure due to increased drag caused by these fouling organisms (Suchanek, 1985; Seed & Suchanek, 1992). However, mussel beds are prevalent in areas of high wave exposure suggesting a high resilience despite the destruction.

Blue mussels display a high resistance to increases in water flow, but the oscillatory water movement that occurs on shores of higher wave exposure is likely to have a higher impact due to the ‘to and fro’ motion which is more likely to weaken the attachments. Westerbom & Jattu (2006) found that in subtidal mussel beds, mussel densities increased with increasing wave exposure. The highest biomass was found in areas of intermediate exposure, potentially due to the larger mussels being removed at high wave exposure levels. It was suggested that the lower densities found in more sheltered areas were due to low recruitment, early post-recruitment mortality, increased predation or stagnant settlement on rocks. Furthermore, it was also noted that high sedimentation which is more prevalent in sheltered areas, as there is less energy for re-suspension, prevents colonization and result in the death of small mussels that are living close to the sediment surface by smothering and the clogging up of their feeding apparatus (Westerbom & Jattu, 2006). Therefore, colonization of new space in sheltered areas could be slow, particularly in areas where there is a low availability of adult mussels.

An increase in wave exposure may increase density in subtidal beds (Westerbom & Jattu, 2006) unless there is a very sudden storm surge. Mussels on sedimentary substrata are exposed to a higher risk of dislodgement (Widdows *et al.*, 2002). A decrease in wave exposure is likely to result in increased sedimentation and reduced densities (Westerbom & Jattu, 2006) although the risk of



dislodgement will be greatly reduced creating more stable beds (Nehls & Thiel, 1993).

The above evidence is variable as different studies have examined beds that differ in habitat, wave exposure, substratum and mussel density. However general trends can be seen. In rocky habitats, increased wave exposure allows mussel to dominate and form beds, especially where the rock surface has a low slope. Where the beds are patchy or damaged (from natural or human activities) they are more susceptible to further damage as a result of wave action or storms (Seed & Suchanek, 1992; Brosnan & Crumrine, 1994). Multi-layered mussel beds are less susceptible to damage, especially where only the surface layer is removed. It has been noted that the build-up of mussel mud (pseudofaeces) under the bed can reduce the attachment of the bed to the underlying substratum. But in areas of wave exposure, the flow of water through the bed will probably prevent the 'mussel mud' accumulating.

On sedimentary habitats, which themselves occur in wave sheltered environments, the mussel beds stabilise the sediment surface (Widdows *et al.*, 2002), especially at high percentage cover, although at low cover (e.g. in patchy beds) turbulent flow caused by the mussels may increase erosion of the sediment. Coarse and mixed sediments were more stable, although Widdows *et al.* (2002) also noted that cohesive muds were also stabilised by mussel beds. Nevertheless, strong wave action or storms can roll up an entire bed or section of a bed (Harger & Landenberger, 1971), and presumably remove patches of mussels, and that multi-layered bed suffer more damage. In sedimentary wave sheltered habitats, the build-up of mussel muds may reduce attachment to the substratum and increase the susceptibility of the bed to wave action (Seed & Suchanek, 1992). The growth of other organisms on the mussels themselves, will increase drag and hence increase the possibility of damage due to wave action. In sheltered conditions, large macroalgae (e.g. kelps, fucoids) growing on mussels may result in removal of clumps of mussels.

**Sensitivity assessment.** A decrease in wave exposure is unlikely to adversely affect beds in sheltered, sedimentary habitats, except that muddy sediment will probably increase. Blue mussel beds on sediment may be more susceptible to damage, as increased wave height increases the possibility of a piece of the bed being removed, or even 'rolled up, especially in stormy weather. Therefore, a resistance of 'Low' is suggested, with a resilience of 'Medium', resulting in a sensitivity of 'Medium'.

## Chemical Pressures

	Resistance	Resilience	Sensitivity
<b>Transition elements &amp; organo-metal contamination</b>	Not Assessed (NA) Q: NR A: NR C: NR	Not assessed (NA) Q: NR A: NR C: NR	Not assessed (NA) Q: NR A: NR C: NR

Contamination at levels greater than the benchmark may impact this biotope. The effects of contaminants on *Mytilus* sp. were extensively reviewed by Widdows & Donkin (1992) and Livingstone & Pipe (1992). Widdows & Donkin (1992) list tolerances of *Mytilus edulis* adults and larvae but note that lethal responses give a false impression of high tolerance since the adults can close their valves and isolate themselves from the environment for days. They suggested that sublethal effects e.g. shell growth and 'scope for growth' (SFG), are more sensitive indicators of the effects of contaminants. Reported effects of heavy metals follow.

- Adult 15 day LC<sub>50</sub> to 50µg/l Cu (Widdows & Donkin, 1992).

- Crompton (1997) reported that adult bivalve mortalities occurred after 4-14 day exposure to 0.1-1 µg/l Hg, 1-10 µg/l Cu and Cd, 10-100 µg/l Zn but 1-10 mg/l for Pb and Ni.
- Widdows *et al.* (1995) reported 'no observed effect thresholds' on feeding or SFG in *Mytilus edulis* tissues of 150 µg Cd/g dry wt, 25 µg Cu/g dry wt, (lethal at 60 µg Cu/g dry wt), 12 µg Hg/g dry wt, 10 mg Pb/g dry wt, and 300 µg Zn/g dry wt. However, the tissue concentration of heavy metals at the sites studied was not high enough to reduce SFG significantly.
- Mussels were reported to be missing from a wider area than other shore organisms on a Cumbrian shore in the vicinity of a phosphate rich effluent outfall contaminated by a number of heavy metals (Holt *et al.*, 1998).
- Adults are ca >10 fold more intolerant than larvae to Cu, petroleum hydrocarbons and sewage sludge (Widdows & Donkin, 1992).

Overall, *Mytilus edulis* is probably relatively tolerant of heavy metal contamination. However, this pressure is **Not assessed** but evidence is presented where available.

#### Hydrocarbon & PAH contamination

Not Assessed (NA)

Q: NR A: NR C: NR

Not assessed (NA)

Q: NR A: NR C: NR

Not assessed (NA)

Q: NR A: NR C: NR

This pressure is **Not assessed** but evidence is presented where available.

Widdows & Donkin (1992) list tolerances of *Mytilus edulis* adults and larvae but note that lethal responses give a false impression of high tolerance since the adults can close their valves and isolate themselves from the environment for days. They suggested that sublethal effects e.g. shell growth and 'scope for growth' (SFG), are more sensitive indicators of the effects of contaminants.

- Widdows *et al.* (1995) demonstrated that toxic hydrocarbons, primarily poly-aromatic hydrocarbons, made a large contribution to the decline in SFG observed along the North Sea coast. Hydrocarbons reduce clearance rate through 'non-specific narcosis'.
- Mussel populations in Sullom Voe experienced moderate hydrocarbon pollution and a reduced SFG but had sufficient capacity to grow, reproduce and maintain a viable population (Widdows *et al.*, 1987).
- Widdows *et al.* (1987) examined the response of *Mytilus edulis* to high oil (water accommodated fraction of diesel oil) ( $125 \pm 28$  µg/l) and low oil ( $28 \pm 7$  µg/l) over an 8 month period and subsequent recovery. They observed a marked reduction in SFG (due to reduced feeding rate and food absorption efficiency), and a correlation between the reduction in SFG and the hydrocarbon tissue burden (Widdows *et al.*, 1987; Widdows & Donkin, 1992; Widdows *et al.*, 1995). Mussels exposed to high oil conditions showed a negative SFG and weight loss. During recovery, 22 days after removal to 'clean' seawater the high oil mussels depurated (removed) hydrocarbons more rapidly than low oil mussels and showed an increased clearance rate and growth rate associated with 'catch-up' growth. Both high and low oil mussels recovered completely within 55 days.
- Widdows *et al.* (1987) also reported that high and low oil contamination of the experimental basins resulted in 100% mortality amongst mussels kept in the basins from autumn 1982 to summer 1983 and from spring 1983 to summer 1984 respectively.
- Widdows *et al.* (1992) reported the following tolerances of adult *Mytilus edulis* to hydrocarbons; a 4 day LC<sub>50</sub> of 1-10 mg/l of crude oil, and a 4 month LC<sub>50</sub> to 125 µg/l of diesel.
- A sunflower oil tanker spill off the Anglesey coast resulted in ingestion of oil droplets and



subsequent mortalities after spawning (Mudge *et al.*, 1993; Holt *et al.*, 1998).

- Bokn *et al.*, (1993) demonstrated that *Mytilus edulis* was lost from mesocosm experiments continuously dosed with 30.1 to 129.4 µg/l of the water accommodated fraction of diesel, and was the most intolerant of the intertidal species studied.
- *Mytilus edulis* dominated jetty piles immediately adjacent to an oil refinery effluent in Milford Haven, suggesting a high tolerance of hydrocarbon contamination (K. Hiscock, pers. comm.).

Overall, hydrocarbon tissue burden results in decreased SFG and in some circumstances may result in mortalities, reduced abundance or extent of *Mytilus edulis*.

#### Synthetic compound contamination

Not Assessed (NA)

Q: NR A: NR C: NR

Not assessed (NA)

Q: NR A: NR C: NR

Not assessed (NA)

Q: NR A: NR C: NR

This pressure is **Not assessed** but evidence is presented where available.

The effects of contaminants on *Mytilus* sp. were extensively reviewed by Widdows & Donkin, (1992) and Livingstone & Pipe (1992). Mussels are suspension feeders and, therefore, process large volumes of water together with suspended particulates and phytoplankton. Mussels absorb contaminants directly from the water, through their diet and via suspended particulate matter (Widdows & Donkin, 1992), the exact pathway being dependant on the nature of the contaminant.

- Widdows and Donkin (1992) reported 50% mortality from a tissue burden of 20 µg/g TBT.
- Exposure of *Mytilus edulis* to detergent (BP1002) in seawater resulted in 100% mortality at 10 ppm detergent, although all survived at 5 ppm detergent (Smith, 1968).
- Liu & Lee (1975) reported a LC<sub>50</sub> of 250 µg/l of the herbicide trifluralin in *Mytilus galloprovincialis*
- *Mytilus edulis* has been reported to bioaccumulate the insecticide ivermectin, although no adverse effects were observed (Cole *et al.*, 1999).
- Biphenyl (a dye carrier) reduced the feeding rate of *Mytilus edulis* by 50% at 0.3 mg/l (Donkin *et al.*, 1989).
- PCBs accumulate in gonads, although tissue concentrations are significantly reduced after spawning, although this may affect the next generation (Hummel *et al.*, 1989; Holt *et al.*, 1995).
- Significant increases in the incidence of tumours (neoplasia) were reported in the US Mussel Watch programme in the presence of higher concentrations of combustion related poly-aromatic hydrocarbons, *cis*-chlordane pesticides and cadmium (Hillman, 1993; Holt *et al.*, 1998).
- *Mytilus edulis* survived in a power station cooling water culvert, exposed to 0.1-0.2 mg/l hypochlorite, although their growth rates were reduced by about a third. Mussels were able to recover in hypochlorite free periods between chlorination dosing (Thompson *et al.*, 1997). *Mytilus edulis* and *Mytilus galloprovincialis* were reported to suffer 100% mortality after 15-135 days continuous exposure to 0.2-1.0 mg/l hypochlorite (Khalanski & Borget, 1980; cited in Thompson *et al.*, 1997).
- Holt *et al.* (1995) also report that mussels may be absent from areas of high boating activity, presumably due to TBT.

Widdows *et al.* (1995) compared 'scope for growth' (SFG) and chemical contaminants in tissues of mussels from 26 coastal and 9 offshore sites around the United Kingdom. They noted that polar

organics (probably derived from phytoplankton) accounted for some reduction in SFG, while organo-chlorides showed a significant correlation with an unexplained component of the decline in SFG. However, TBT levels were only high enough to cause an effect (<10% reduction in SFG) at 8 study sites (Widdows *et al.*, 1995). *Mytilus edulis* is probably relatively tolerant of contaminants. Widdows & Donkin (1992) list tolerances of *Mytilus edulis* adults and larvae, but note that lethal responses give a false impression of high tolerance since the adults can close their valves and isolate themselves from the environment for days. They suggest that sublethal effects (shell growth and 'scope for growth') are more sensitive indicators of the effects of contaminants. Also, adults are ca. 4 times more sensitive than larvae to TBT (Widdows & Donkin, 1992).

### Radionuclide contamination

No evidence (NEv)

Q: NR A: NR C: NR

No evidence (NEv)

Q: NR A: NR C: NR

No evidence (NEv)

Q: NR A: NR C: NR

The periostracum of *Mytilus edulis* was reported to concentrate uranium (Widdows & Donkin, 1992). Mussels have also been reported to bioaccumulate  $^{106}\text{Ru}$ ,  $^{95}\text{Zr}$ ,  $^{95}\text{Nb}$ ,  $^{137}\text{Cs}$  and  $^{90}\text{Sr}$  (Cole *et al.*, 1999). While the above data demonstrates that *Mytilus edulis* can accumulate radionuclides, little information concerning the effects of radionuclides on marine organisms was found. Sensitivity to this pressure is therefore not assessed based on lack of evidence.

### Introduction of other substances

Not Assessed (NA)

Q: NR A: NR C: NR

Not assessed (NA)

Q: NR A: NR C: NR

Not assessed (NA)

Q: NR A: NR C: NR

This pressure is **Not assessed**.

### De-oxygenation

High

Q: High A: High C: High

High

Q: High A: High C: High

Not sensitive

Q: High A: High C: High

*Mytilus edulis* is capable of anaerobic metabolism. In aerial exposure (emersion) the mussel closes its valves, resulting in a low rate of oxygen exchange and consumption, and conservation of energy (Widdows *et al.*, 1979a; Zwaan de & Mathieu 1992).

*Mytilus edulis* is regarded as euryoxic, tolerant of a wide range of oxygen concentrations including zero (Zandee *et al.*, 1986; Wang & Widdows 1991; Gosling, 1992; Zwaan de & Mathieu 1992; Diaz & Rosenberg 1995; Gray *et al.*, 2002). Diaz & Rosenberg (1995) suggest it is resistant to severe hypoxia. Adult mytilids exhibited high tolerance of anoxia in laboratory tests, e.g. Theede *et al.*, (1969) reported LD<sub>50</sub> of 35 days for *Mytilus edulis* exposed to 0.21 mg/l O<sub>2</sub> at 10°C, which was reduced to 25 days with the addition of sulphide (50 mg/l Na<sub>2</sub>S.9H<sub>2</sub>O). Jorgensen (1980) observed, by diving, the effects of hypoxia (0.2 - 1 mg/l) on benthic macrofauna in marine areas in Sweden over a 3-4 week period. Mussels were observed to close their shell valves in response to hypoxia and survived for 1-2 weeks before dying (Cole *et al.*, 1999; Jorgensen, 1980).

All life stages show high levels of tolerance to low oxygen levels. *Mytilus edulis* larvae, for example, are tolerant down to 1.0 ml/l, and although the growth of late-stage larvae is depressed in hypoxic condition, the settlement behaviour does not seem to be affected (Diaz & Rosenberg, 1995). Based on the available evidence *Mytilus edulis* are considered to be resistant to periods of hypoxia and anoxia although sub-lethal effects on feeding and growth may be expected.

**Sensitivity assessment** *Mytilus edulis* is considered to be not sensitive to de-oxygenation at the

pressure benchmark. Resistance is, therefore, assessed as 'High', resilience as 'High' (no effect to recover from), and sensitivity assessed as 'Not sensitive' at the benchmark level.

<b>Nutrient enrichment</b>	Not relevant (NR)	Not relevant (NR)	Not sensitive
	Q: NR A: NR C: NR	Q: NR A: NR C: NR	Q: NR A: NR C: NR

This pressure relates to increased levels of nitrogen, phosphorus and silicon in the marine environment compared to background concentrations. Nutrient enrichment may impact mussel beds by altering the biomass of phytoplankton and macroalgae. At low levels, nutrient enrichment may stimulate the growth of phytoplankton used as food - a potentially beneficial effect. In the Wadden Sea, where fishing had caused the destruction of the local population of *Sabellaria spinulosa*, *Mytilus edulis* was able to colonize, partly because of the increase in coastal eutrophication (Maddock, 2008). Conversely, Dinesen *et al.* (2011) observed that a reduction in nutrient loading to comply with the WFD resulted in a decrease of mussel biomass in estuaries.

High levels of enrichment may stimulate algal blooms and macroalgal growth. The growth of macrophytes on the mussel beds may result in increased drag on the mussel bed and hence increase susceptibility to damage from wave action and/or storms (see changes in wave exposure pressure). Algal blooms may die off suddenly, causing de-oxygenation (see de-oxygenation pressure) where the algae decompose on the seabed. The thresholds at which these blooms occur depend on site-specific conditions and be mitigated by the degree of mixing and tidal exchange. Some algae have been shown to negatively affect *Mytilus edulis* when present in high concentrations. For example, blooms of the algae *Phaeocystis* sp., have been observed to block the mussel's gills when present in high concentrations reducing clearing rates, and at high levels, they caused a complete cessation of clearance (Smaal & Twisk, 1997). Blockage of the gills is also likely to reduce ingestion rates, prevent growth and cause reproductive failure (Holt *et al.*, 1998). Other species known to negatively impact *Mytilus edulis* are *Gyrodinium aureolum* (Tangen, 1977; Widdows *et al.*, 1979b) and a non-flagellated chrysophycean alga (Tracey, 1988). The accumulation of toxins from algal blooms has also been linked to outbreaks of paralytic shellfish poisoning resulting in the closure of shellfish beds (Shumway, 1990).

**Sensitivity assessment.** *Mytilus edulis* beds are considered to be 'Not sensitive' to nutrient enrichment at levels that comply with the requirements for good status for transitional and coastal water bodies (UKTAG, 2014).

<b>Organic enrichment</b>	High	High	Not sensitive
	Q: High A: High C: High	Q: High A: High C: High	Q: High A: High C: High

Organic enrichment can result from inputs of additional organic matter. Organic enrichment may lead to eutrophication with adverse environmental effects including deoxygenation, algal blooms and changes in community structure (see nutrient enrichment and de-oxygenation).

It has been shown that regardless of the concentration of organic matter, *Mytilus edulis* will maintain its feeding rate by compensating with changes to filtration rate, clearance rates, production of pseudofaeces and absorption efficiencies (Tracey, 1988; Bayne *et al.*, 1993; Hawkins *et al.*, 1996). A number of studies have highlighted the ability of *Mytilus edulis* to utilise the increased volume of organic material available at locations around salmon farms. Reid *et al.* (2010) noted that *Mytilus edulis* could absorb organic waste products from a salmon farm with great efficiency. Increased shell length, wet meat weight, and condition index were shown at locations

within 200 m from a farm in the Bay of Fundy allowing a reduced time to market (Lander *et al.*, 2012). *Mytilus edulis* have also been recorded in areas around sewage outflows (Akaishi *et al.*, 2007; Lindahl & Kollberg, 2008; Nenonen *et al.*, 2008; Giltrap *et al.*, 2013) suggesting that they are highly tolerant of the increase in organic material that would occur in these areas. It should be noted that biotopes occurring in tide-swept or wave exposed areas are less likely to experience the effects of organic enrichment as the organic matter will be rapidly removed.

**Sensitivity assessment.** Based on the observation of *Mytilus edulis* thriving in areas of increased organic matter (Lander *et al.*, 2012, Reid *et al.*, 2010), it was assumed that *Mytilus edulis* beds had a 'High' resistance to increased organic matter at the pressure benchmark. Resilience is, therefore, assessed as 'High' (no effect to recover from) and sensitivity assessed as 'Not sensitive'.

## A Physical Pressures

	Resistance	Resilience	Sensitivity
Physical loss (to land or freshwater habitat)	<b>None</b> Q: High A: High C: High	<b>Very Low</b> Q: High A: High C: High	<b>High</b> Q: High A: High C: High

All marine habitats and benthic species are considered to have a resistance of 'None' to this pressure and to be unable to recover from a permanent loss of habitat (resilience is 'Very Low'). Sensitivity within the direct spatial footprint of this pressure is, therefore 'High'. Although no specific evidence is described confidence in this assessment is 'High', due to the incontrovertible nature of this pressure. Adjacent habitats and species populations may be indirectly affected where meta-population dynamics and trophic networks are disrupted and where the flow of resources e.g. sediments, prey items, loss of nursery habitat etc. is altered.

Physical change (to another seabed type)	<b>None</b> Q: Medium A: NR C: NR	<b>Very Low</b> Q: High A: High C: High	<b>High</b> Q: Medium A: Low C: Low
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*Mytilus edulis* can be found on a wide range of substrata including artificial substratum (e.g. metal, wood, concrete), bedrock, biogenic reef, caves, crevices / fissures, large to very large boulders, mixed, muddy gravel, muddy sand, rock pools, sandy mud, small boulders, under boulders (Connor *et al.*, 2004). An increase in the availability of hard substratum may be beneficial in areas where sedimentary habitats were previously unsuitable for colonization e.g. coarse, mobile sediments. It should be noted that differences in diversity and other structural characteristics of assemblages between natural and artificial substratum have been observed suggesting that there is not a direct, compensatory effect.

Mussels themselves will often cause a change in substrata by the deposition of large quantities of 'mussel-mud' composed of faecal matter and pseudofaeces (Dare, 1976) particularly in areas of low water movement. A change from rock to sand in an area of high water flow would increase the mussels' vulnerability to dislodgement and scour (Widdows *et al.*, 2002) and, potentially, smothering as sand smothering has been shown to set the lower limit of *Mytilus* beds in some areas (Daly & Mathieson 1977).

**Sensitivity assessment.** A change in substratum type would not necessarily reduce habitat quality for individual *Mytilus edulis* which can colonize a wide range of hard and sedimentary habitats. However, a change in substratum type would alter biotope classification. Hence, the resistance of

the biotope is assessed as '**None**' (loss of >75% of extent), resilience (following habitat recovery) is assessed as '**Very low**' (the pressure is a permanent change). Sensitivity, based on combined resistance and resilience is assessed as '**High**'. The more precautionary assessment for the biotope, rather than the species, is presented in the table as it is considered that any change to a reef habitat from a sedimentary habitat would alter the biotope classification and hence the more sensitive assessment is appropriate.

#### Physical change (to another sediment type)

**None**

Q: Medium A: NR C: NR

**Very Low**

Q: High A: High C: High

**High**

Q: Medium A: Low C: Low

*Mytilus edulis* can be found on a wide range of sediment substrata including, mixed, muddy gravel, muddy sand, rock pools, sandy mud, small boulders, under boulders (Connor et al., 2004). It should be noted that the mussels themselves will often cause a change in substrata by the deposition of large quantities of 'mussel-mud' composed of faecal matter and pseudofaeces (Dare, 1976) particularly in areas of low water movement. A change from rock to sand in an area of high water flow would increase the mussels' vulnerability to dislodgement and scour (Widdows et al., 2002) and, potentially, smothering as sand smothering has been shown to set the lower limit of *Mytilus* beds in some areas (Daly & Mathieson, 1977).

**Sensitivity assessment.** The pressure benchmark refers to the simplified Folk classification developed by Long (2006) and the UK Marine Habitat Classification Littoral and Sublittoral Sediment Matrices (Connor et al., 2004). In most instances, the pathway (human activity) by which the substratum is changed would remove or smother mussels. However, these effects are addressed under the 'hydrological change', 'abrasion'; 'penetration and disturbance' and 'smothering' pressures above.

The natural modification of the sediment due to the build-up of mussel-mud could result in a change of sediment type from mixed and sand dominated, to anoxic mud, depending on location and hydrography. In addition, a change in sediment type would also change the biotope definition. That is, a change from mud to sand would change the biotope from LS.LBR.LMus.Myt.Mu to LS.LBR.LMus.Myt.Sa. The blue mussel bed would survive, as the build up of 'mussel-mud' can transform Myt.Mx to Myt.Mu and the blue mussel bed itself is probably 'Not sensitive' to a change in sediment type of 1 Folk class. However, **technically the biotope Myt.Mu would be lost and the biotope replaced by Myt.Sa or Myt.Mx** (depending on the nature of the change). Therefore, resistance is assessed a '**None**', resilience as '**Very low**' (as the pressure represents a permanent change) and sensitivity is assessed as '**High**'.

#### Habitat structure changes - removal of substratum (extraction)

**None**

Q: High A: High C: High

**Low**

Q: High A: Low C: Medium

**High**

Q: High A: Low C: Medium

The process of extraction will remove the entire mussel bed and the associated community; therefore a resistance of '**None**' is recorded. Hence, resilience is assessed as '**Low**', and sensitivity as '**High**'.

#### Abrasion/disturbance of the surface of the substratum or seabed

**Low**

Q: High A: Medium C: Medium

**Medium**

Q: High A: Low C: Medium

**Medium**

Q: High A: Low C: Medium

*Mytilus edulis* lives on the surface of the seabed held by byssus threads attached to either the substratum or to other mussels in the bed. Activities resulting in abrasion and disturbance can either directly affect the mussel by crushing them, or indirectly affect them by the weakening or breaking of their byssus threads making them vulnerable to displacement (Denny, 1987) where they are unlikely to survive (Dare, 1976). In addition, abrasion and sub-surface damage may attract mobile scavengers and predators including fish, crabs, and starfish to feed on exposed, dead and damaged individuals and discards (Kaiser & Spencer, 1994; Ramsay *et al.*, 1998; Groenewold & Fonds, 2000; Bergmann *et al.*, 2002). This effect will increase predation pressure on surviving damaged and intact *Mytilus edulis*. A number of activities or events that result in abrasion and disturbance and their impacts on mussel beds are described below, based on the review by Mainwaring *et al.* (2014).

The effects of trampling have been more widely studied in the terrestrial community showing that when areas are intensively trampled bare patches are likely to result as a result of erosion or equally soil compaction may result (Liddle, 1997). There are a number of studies which have focused on the impact of trampling on the intertidal rocky shore whereas the impact on sedimentary shores is relatively poorly studied (Tyler-Walters & Arnold, 2008). In general, studies have found that trampling is an additional disturbance to the natural disturbances that the intertidal organisms are adapted to tolerate. Large declines of the *Mytilus californianus* from mussel beds due to trampling have been reported (Brosnan, 1993; Brosnan & Crumrine, 1994; Smith & Murray, 2005). Brosnan & Crumrine (1994) recorded the loss of 54% of mussels from a single experimental plot on one day. Mussels continued to be lost throughout the experimental period, forming empty patches larger than the experimental plots. The empty patches continued to expand after trampling had ceased, due to wave action. At another site, the mussel bed was composed of two layers, so that while mussels were lost, cover remained. Brosnan (1993) also reported a 40% loss of mussels from mussel beds after three months of trampling and a 50% loss within a year. Van de Werfhorst & Pearse (2007) examined *M. californianus* abundance at sites with differing levels of trampling disturbance. The highest percentage of mussel cover was found at the undisturbed site while the severely disturbed site showed low mussel cover.

Smith & Murray (2005) examined the effects of low-level disturbance on an extensive bed of *Mytilus californianus* (composed of a single layer of mussels) in southern California. Smith & Murray (2005) reported that in experimental plots exposed to trampling, mussel loss was 20-40% greater than in untreated plots. A decrease in mussel mass, density, cover and maximum shell length were recorded even in low intensity trampling events (429 steps/m<sup>2</sup>). However, only 15% of mussel loss was as a direct result of trampling, with the remaining loss occurring during intervals between treatment applications. Brosnan & Crumrine (1994) suggested that trampling destabilizes the mussel bed, making it more susceptible to wave action, especially in winter. Smith & Murray (2005) suggested that an indirect effect of trampling was weakening of byssal threads, which increases mussel susceptibility to wave disturbance (Denny, 1987). Brosnan & Crumrine (1994) observed recruitment within experimental plots did not occur until after trampling had ceased, and no recovery had occurred within 2 years

Brosnan and Crumrine (1994) noted that mussels that occupied hard substrata but did not form beds were also adversely affected. Although only at low abundance (2.5% cover), all mussels were removed by trampling within 4 months. Brosnan & Crumrine (1994) noted that mussels were not common and confined to crevices in heavily trampled sites. Similarly, the mussel bed infauna (e.g. barnacles) was adversely affected and were crushed or lost with the mussels to which they were attached. However, Beauchamp & Gowing (1982) did not observe any differences in mussel density between sites that differed in visitor use.

Paine & Levine (1981) examined natural patch dynamics in a *Mytilus californianus* bed in the USA. They suggested that it may take up to seven years for large barren patches to recover. However, chronic trampling may prevent recovery altogether. This would result in a shift from a mussel dominated habitat to one dominated by an algal turf or crust (Brosnan & Cumrine, 1994), completely changing the biotope. However, a small period of trampling could allow communities to recover at a similar rate to that of natural disturbance as the effects are similar. The associated epifauna and epiflora suffer the greatest amount of damage as they are the first organisms that a foot makes contact with (Brosnan & Crumrine, 1994). The loss of epifauna and epiflora could initially be of benefit to the mussel bed, despite the obvious decrease in species diversity, as there will be a decrease in drag for the mussels reducing the risk of dislodgement (Witman & Suchanek 1984) and freeing up more energy for growth and reproduction. However, it is likely that after continued trampling this effect will be minimal compared with the increased risk of dislodgement caused by trampling. No studies assessing the effect of trampling on mussels on intertidal muddy sand or sediments were found. Losses to the adult mussels by crushing or by suffocation where these are forced into the sediment are expected. There is the potential that this will open up areas for new recruitment or it may just create a similar situation to that seen on the rocky shore where wave damage and continual trampling prevent settlement and recovery.

The collision of objects with the bed, such as wave driven logs (or similar flotsam), is known to cause the removal of patches of mussels from mussel beds (Seed & Suchanek, 1992; Holt *et al.*, 1998). When patches occur in mussel beds a good recruitment could result in a rapid recovery or the patch may increase in size through the weakening of the byssus threads of the remaining mussels leaving them vulnerable to erosion from storm damage (Denny, 1987). Damage in areas of high wave exposure is likely to result in increased erosion and a patchy distribution although recruitment may be high. In sheltered areas, damage may take a lot longer due to limited larval supply, although the frequency of destruction through wave driven logs would be less than in high wave exposure. Similar effects could be observed through the grounding of a vessel, the dropping of an anchor or the laying of a cable, although the scale of damage clearly differs. Shifting sand is known to limit the range of *Mytilus edulis* through burial and abrasion (Daly & Mathieson, 1977).

Various fishing methods also result in abrasion of the mussel beds. Bait collection through raking will cause surface abrasion and the removal of patches of mussel resulting in the damage and recovery times described above. Holt *et al.*, (1998) reported that hand collection, or using simple hand tools occurs in small artisanal fisheries. They suggested that moderate levels of collection by experienced fishermen may not adversely affect the biodiversity of the bed. But they also noted that even artisanal hand fisheries can deplete the mussel biomass on accessible beds in the absence of adequate recruitment of mussels. Smith & Murray (2005) observed a significant decrease in mussel mass ( $\text{g}/\text{m}^2$ ), density ( $\text{no.}/\text{m}^2$ ), percentage cover and mean shell length due to low-intensity simulated bait-removal treatments (2 mussels/month) for 12 months (Smith & Murray, 2005). They also stated that the initial effects of removal were 'overshadowed' by the loss of additional mussels during time periods between treatments, probably due to the indirect effect of the weakening of byssal threads attachments between the mussel leaving them more susceptible to wave action (Smith & Murray, 2005). The low-intensity simulated bait-removal treatments had reduced percentage cover by 57.5% at the end of the 12 month experimental period. Smith & Murray (2005) suggested that the losses incurred from collection and trampling are far greater than those that occur by natural causes. This conclusion was reached due to significant results being displayed for human impact despite the experiment taking place during a time of high natural disturbance from El Niño–Southern Oscillation (ENSO).

**Sensitivity assessment.** Based on the available evidence it is concluded that all mussel biotopes



are sensitive to abrasion and that resistance is '**Low**' (loss of 25-75% of bed within direct impact footprint), resilience is assessed as '**Medium**', resulting in a sensitivity of '**Medium**'.

**Penetration or disturbance of the substratum subsurface**

**Low**

Q: High A: High C: Medium

**Medium**

Q: High A: Low C: Medium

**Medium**

Q: High A: Low C: Medium

*Mytilus edulis* lives on the surface of the seabed held in one place by byssus threads that either attach to the substratum or to other mussels in the bed. Activities resulting in penetration and disturbance can either directly affect the mussel by crushing or removal, or indirectly affect them by the weakening or breaking of their byssus threads making them vulnerable to displacement (Denny, 1987) where they are unlikely to survive (Dare, 1976). Where mussels are removed the associated fauna and flora will also be removed. In addition, abrasion and sub-surface damage attract mobile scavengers and predators including fish, crabs, and starfish to feed on exposed, dead and damaged individuals and discards (Kaiser & Spencer, 1994; Ramsay *et al.*, 1998; Groenewold & Fonds, 2000; Bergmann *et al.*, 2002). This effect could increase predation pressure on surviving damaged and intact *Mytilus edulis*.

Mussel dredging is the main form of activity that results in penetration around mussel beds. Holt *et al.* (1998) noted that several thousand tonnes of mussels were fished in the Wash by dredgers in good years. Dredging will remove the substratum along with the mussels and their associated flora and fauna. Temporary re-suspension of sediment also occurs with mussel dredging (Holt *et al.*, 1998) in volumes of 1470 g/m<sup>2</sup> (Riemann & Hoffmann, 1991), which could potentially result in localised smothering. Dredging is also likely to increase the vulnerability of the remaining mussels to storm damage through the weakening of byssal attachment and creating patches in the bed (Denny, 1987).

The Scottish MPA Project Fisheries Management Guidance (JNCC, 2013a) suggests that scallop dredges and other demersal towed gear are also likely to result in the removal of a proportion of the bed along with its associated fauna and flora. The same report suggested that potting and other demersal static gear would have a lower impact than mobile gear. There is no evidence for the impacts of hydraulic dredging on mussels but Hall *et al.* (1990) observed that when using hydraulic dredging for *Ensis* sp. the immediate effects were a reduction in the number of target species and many macrofaunal species. However, after 40 days the effect of the fishing gear could no longer be seen.

Holt *et al.* (1998) noted that natural 'wild' beds are susceptible over-exploitation, especially in some embayments and that over-exploitation can reduce recruitment. Holt *et al.* (1998) also point out that the source areas for recruitment to beds is unknown and the relationship between stock and recruitment poorly understood. This statement is consistent with the sporadic and unpredictable nature of recruitment and recovery in mussels beds (Seed & Suchanek, 1992).

**Sensitivity assessment.** The activities that penetrate the seabed could result in removal of part of a bed and its associated fauna and flora. Based on the available evidence it is concluded that all sedimentary mussel biotopes are sensitive to 'penetration and/or disturbance of the seabed'. Therefore, resistance is assessed as '**Low**' (loss of 25-75% of bed within direct footprint), resilience is assessed as '**Medium**', and sensitivity as '**Medium**'.



## Changes in suspended solids (water clarity)

**High**

Q: High A: High C: Medium

**High**

Q: High A: High C: High

**Not sensitive**

Q: High A: High C: Medium

*Mytilus edulis* does not rely on light penetration for photosynthesis. In addition, visual perception is limited and the species does not rely on sight to locate food or other resources. An indirect effect of increased turbidity and reduced light penetration may be reduced phytoplankton productivity which could reduce the food availability for *Mytilus edulis*. However, as *Mytilus edulis* uses a variety of food sources and food is brought in from other areas with currents and tides, the effect is likely to be minimal. This species and the biotopes it forms are therefore not sensitive to changes in water clarity that alter light penetration.

*Mytilus edulis* is often found in areas with high levels of turbidity. For example, the average suspended particulate matter (SPM) concentration at Hastings Shingle Bank was 15 -20 mg/l in June 2005, reaching 50 mg/l in windier (force 4) conditions, although a concentration of 200 mg/l was recorded at this site during gales (Last *et al.*, 2011). Winter (1972, cited by Moore, 1977) recorded 75% mortality of *Mytilus edulis* in concentrations of 1.84-7.36 mg/l when food was also available. However, a relatively small increase in SPM concentration e.g. from 10 mg/l to 90 mg/l was found to increase growth rates (Hawkins *et al.*, 1996). Concentrations above 250 mg/l have been shown to impair the growth of filter-feeding organisms (Essink, 1999). But Purchon (1937) found that concentrations of particulates as high as 440 mg/l did not affect *Mytilus edulis* and that mortality only occurred when mud was added to the experiment bringing the concentrations up to 1220 mg/l. The reason for some of the discrepancy between studies may be due to the volume of water used in the experiment. Loosanoff (1962) found that in small quantities of turbid water (due to particulates) the mussel can filter out all of the particulates within a few minutes whereas in volumes >50 gallons per individual the mussel becomes exhausted before the turbidity has been significantly lowered, causing it to close its shell and die.

It may be possible for *Mytilus edulis* to adapt to a permanent increase in SPM by decreasing their gill size and increasing their palp size in areas of high turbidity (Theisen, 1982; Essink, 1999). In areas of variable SPM, it is likely that the gill size would remain the same but the palp would adapt (Essink, 1999). Whilst the ability to adapt may prevent immediate declines in health, the energetic costs of these adaptations may result in reduced fitness; the extent of which is still to be established.

*Mytilus edulis* uses the circadian clock to determine the opening of the shell gape in nocturnal gape cycles (Ameyaw-Akumfi & Naylor, 1987). Last *et al.* (2011) investigated the effects on increased SPM concentrations on both the gape pattern and mortality in order to establish the effect that aggregate dredging will have on *Mytilus edulis* and other benthic invertebrates. Therefore they tested concentrations similar to those expected within a few hundred meters of an aggregate extraction site. The highest concentration tested using a pVORT (paddle VOrtex Resuspension Tanks) was ~71 mg/l. They showed that there is a significant reduction of the strength of the nocturnal gape cycle at high suspended sediment loads as well as a change in the gape period. The effects of these changes are not fully known but as it is likely that the gape pattern is a strategy to avoid diurnal predators the change may result in an increased risk of predation. On the other hand, the increased turbidity may reduce predation by visual predators such as fish and birds (Essink, 1999). After continued measurements of the gape cycle for 4 days post-treatment, Last *et al.* (2011) observed that the cycle took longer than this to recover from the cycle disruption. Further study is required to determine the length of time required for recovery of this behavioural response (Last *et al.*, 2011).

Based on a comprehensive literature review, Moore (1977) concluded that *Mytilus edulis* displayed a higher tolerance to high SPM concentrations than many other bivalves although the upper limit of this tolerance was not certain. He also hypothesised that the ability of the mussel to clean its shell in such conditions played a vital role in its success along with its pseudofaecal expulsion. A reduction in SPM concentrations may be caused by the erecting of dams and hydroelectric power stations (Moore, 1977), which could leave subtidal mussel beds more vulnerable to visual predators such as birds and fish. The recovery time from increased predation pressures would depend on the duration of the reduced turbidity. If reduced SPM concentration is also linked with a reduction of suspended organic matter then it could be assumed that the mussel fitness would be negatively affected by a reduction in food supply. However, as active filter feeders, they are not dependent on water flow to supply food.

**Sensitivity assessment.** Evidence indicates that *Mytilus edulis* and hence blue mussel beds can tolerate a broad range of suspended solids. The benchmark for this pressure refers to a change in turbidity of one rank on the Water Framework Directive (WFD) scale. Mussel beds form in relatively clear waters of open coasts and wave exposed shores, and on sediments in the sheltered coast (where turbulent water flow over the mussel beds could resuspend sediments locally) and in turbid bays and estuaries. Therefore, is unlikely that a change in turbidity by of one rank (e.g. from 300 to 100 mg/l or <10 to 100 mg/l) will significantly affect the mussel bed. Hence, resistance to this pressure is assessed as '**High**', recovery is assessed as '**High**' (no impact to recover from), and sensitivity is assessed as '**Not sensitive**' at the benchmark level.

#### Smothering and siltation rate changes (light)

**Medium**

Q: High A: High C: Medium

**Medium**

Q: High A: Low C: Medium

**Medium**

Q: High A: Low C: Medium

The main human activity that increases sedimentation is dredging and the dumping of dredged sediments in estuarine and coastal waters. Aggregate dredging and fishing gear can cause localised sedimentation and smothering. However, changes in water flow can cause localised smothering within mussel beds (Widdows *et al.*, 2002), and storms may move large volumes of sediment and smother entire mussel beds (Dare, 1976). *Mytilus edulis* occurs in areas of high suspended particulate matter (SPM) and therefore a level of siltation is expected from the settling of SPM. In addition, the high rate of faecal and pseudofaecal matter production by the mussels naturally results in siltation of the seabed, often resulting in the formation of large mounds beneath the mussel bed. For example, at Morecambe Bay an accumulation of mussel-mud (faeces, pseudofaeces and washed sand) of 0.4-0.5m between May 1968 and September 1971 resulted in the mortality of young mussels (Daly & Mathieson, 1977). In order to survive the mussels needed to keep moving upwards to stay on the surface. Many individuals did not make it to the surface and were smothered by the accumulation of mussel-mud (Daly & Mathieson, 1977), so that whilst *Mytilus edulis* does have the capacity to vertically migrate through sediment some individuals will not survive.

Sand burial has been shown to determine the lower limit of *Mytilus edulis* beds (Daly & Mathieson, 1977a). Burial of *Mytilus edulis* beds by large scale movements of sand, and resultant mortalities have been reported from Morecambe Bay, the Cumbrian coast and Solway Firth (Holt *et al.*, 1998). Essink (1999) recorded fatal burial depths of 1-2 cm for *Mytilus edulis* and suggested that they had a low tolerance of sedimentation based on investigations by R.Bijkerk (cited by Essink, 1999). Essink (1999) suggested that deposition of sediment (mud or sand) on shallow mussel beds should be avoided. However, Widdows *et al.* (2002) noted that mussels buried by 6 cm of sandy sediment (caused by resuspension of sediment due to turbulent flow across the bed) were able to move to

the surface within one day. Conversely, Condie (2009) (cited by Last *et al.*, 2011) reported that *Mytilus edulis* was tolerant of repeated burial events.

Last *et al.*, (2011) carried out burial experiments on *Mytilus edulis* in pVORTs. They used a range of burial depths and sediment fractions and temperatures. It was found that individual mussels were able to survive burial in depths of 2, 5 and 7 cm for over 32 days although the deeper and longer the mussels were buried the higher the mortality. Only 16 % of buried mussels died after 16 days compared to almost 50 % mortality at 32 days. Mortality also increased sharply with a decrease in particle size and with increases in temperature from 8.0 and 14.5 to 20 °C. The ability of a proportion of individuals to emerge from burial was again demonstrated with approximately one quarter of the individuals buried at 2cm resurfacing. However, at depths of 5 cm and 7 cm no emergence was recorded (Last *et al.*, 2011). The lower mortality when buried in coarse sands may be related to the greater number of individuals who were able to emerge in these conditions and emergence was to be significant for survival.

It is unclear whether the same results would be recorded when mussels are joined by byssal threads or whether this would have an impact on survival (Last *et al.*, 2011), although Daly & Mathieson (1977) recorded loose attachments between juvenile mussels during a burial event and some of these were able to surface. It was not clear whether the same ability would be shown by adult mussels in a more densely packed bed.

**Sensitivity assessment.** Overburden by 5 cm of fine material (see benchmark) in a single incident is unlikely to result in significant mortality in blue mussel beds before sediments are removed by current and wave action. However, the inability of *Mytilus edulis* to emerge from sediment deeper than 2 cm (Last *et al.*, 2011, Essink, 1999, Daly & Matthieson, 1977) and the increased mussel mortality with depth and reduced particle size observed by Last *et al.* (2011) suggest that there may be some mortality and resistance is assessed as '**Medium**'. Survival will be higher in winter months when temperatures are lower and physiological demands are decreased. However, mortality will depend on the duration of smothering. Mortality is likely to be more significant in wave sheltered areas, devoid of tidal streams, where the smothering sediment remains for prolonged periods. Mortality will be more limited, and possibly avoided, where the smothering sediment is removed due to wave action or tidal streams, depending on how long the sediment remains over the individual mussels. Resilience is assessed as '**Medium**' and sensitivity is, therefore '**Medium**'.

#### Smothering and siltation rate changes (heavy)

**Low**

Q: High A: High C: Medium

**Medium**

Q: High A: Low C: Medium

**Medium**

Q: High A: Low C: Medium

The main human activity that increases sedimentation is dredging and the dumping of dredged sediments in estuarine and coastal waters. Aggregate dredging and fishing gear can cause localised sedimentation and smothering. However, changes in water flow can cause localised smothering within mussel beds (Widdows *et al.*, 2002), and storms may move large volumes of sediment and smother entire mussel beds (Dare, 1976). *Mytilus edulis* occurs in areas of high suspended particulate matter (SPM) and therefore a level of siltation is expected from the settling of SPM. In addition, the high rate of faecal and pseudofaecal matter production by the mussels naturally results in siltation of the seabed, often resulting in the formation of large mounds beneath the mussel bed. For example, at Morecambe Bay, an accumulation of mussel-mud (faeces, pseudofaeces and washed sand) of 0.4-0.5 m between May 1968 and September 1971 resulted in the mortality of young mussels (Daly & Mathieson, 1977). In order to survive the mussels needed

to keep moving upwards to stay on the surface. Many individuals did not make it to the surface and were smothered by the accumulation of mussel-mud (Daly & Mathieson, 1977), so that whilst *Mytilus edulis* does have the capacity to vertically migrate through sediment some individuals will not survive.

Sand burial has been shown to determine the lower limit of *Mytilus edulis* beds (Daly & Mathieson, 1977a). Burial of *Mytilus edulis* beds by large-scale movements of sand, and resultant mortalities have been reported from Morecambe Bay, the Cumbrian coast and Solway Firth (Holt *et al.*, 1998). Essink (1999) recorded fatal burial depths of 1-2 cm for *Mytilus edulis* and suggested that they had a low tolerance of sedimentation based on investigations by R.Bijkerk (cited by Essink, 1999). Essink (1999) suggested that deposition of sediment (mud or sand) on shallow mussel beds should be avoided. However, Widdows *et al.* (2002) noted that mussels buried by 6 cm of sandy sediment (caused by resuspension of sediment due to turbulent flow across the bed) were able to move to the surface within one day. Conversely, Condie (2009) (cited by Last *et al.*, 2011) reported that *Mytilus edulis* was tolerant of repeated burial events.

Last *et al.*, (2011) carried out burial experiments on *Mytilus edulis* in pVORTs. They used a range of burial depths and sediment fractions and temperatures. It was found that individual mussels were able to survive burial in depths of 2, 5 and 7 cm for over 32 days although the deeper and longer the mussels were buried the higher the mortality. Only 16% of buried mussels died after 16 days compared to almost 50% mortality at 32 days. Mortality also increased sharply with a decrease in particle size and with increases in temperature from 8.0 and 14.5 to 20 °C. The ability of a proportion of individuals to emerge from burial was again demonstrated with approximately one quarter of the individuals buried at 2 cm resurfacing. However, at depths of 5 cm and 7 cm no emergence was recorded (Last *et al.*, 2011). The lower mortality when buried in coarse sands may be related to the greater number of individuals who were able to emerge in these conditions and emergence was to be significant for survival.

It is unclear whether the same results would be recorded when mussels are joined by byssal threads or whether this would have an impact on survival (Last *et al.*, 2011), although Daly & Mathieson (1977) recorded loose attachments between juvenile mussels during a burial event and some of these were able to surface. It was not clear whether the same ability would be shown by adult mussels in a more densely packed bed.

**Sensitivity assessment.** Overburden by 30 cm of fine material (see benchmark) in a single incident could result in significant mortality in blue mussel beds due to the limited ability of *Mytilus edulis* to emerge from sediment deeper than 2 cm (Last *et al.*, 2011, Essink, 1999, Daly & Mathieson, 1977) and the increased mussel mortality with depth and reduced particle size observed by Last *et al.* (2011). Survival will be higher in winter months when temperatures are lower and physiological demands are decreased. However, mortality will depend on the duration of smothering. Mortality will be limited, and possibly avoided, where the smothering sediment is removed due to wave action or tidal streams, depending on how long the sediment remains over the individual mussels. However, mortality is likely to be significant in wave sheltered areas, devoid of tidal streams, where the smothering sediment remains for prolonged periods (e.g. more than 16 days). Therefore, resistance has been assessed as '**Low**' (significant mortality, loss of 25-75 % of population abundance, or extent) for the littoral mussels on sediment biotopes. Hence, resilience is assessed as '**Medium**', so that sensitivity is '**Medium**'.

Litter

Not Assessed (NA)

Q: NR A: NR C: NR

Not relevant (NR)

Q: NR A: NR C: NR

Not assessed (NA)

Q: NR A: NR C: NR

Not assessed.

<b>Electromagnetic changes</b>	No evidence (NEv)	No evidence (NEv)	No evidence (NEv)
	Q: NR A: NR C: NR	Q: NR A: NR C: NR	Q: NR A: NR C: NR

No evidence.

<b>Underwater noise changes</b>	Not relevant (NR)	Not relevant (NR)	Not relevant (NR)
	Q: NR A: NR C: NR	Q: NR A: NR C: NR	Q: NR A: NR C: NR

Not relevant.

<b>Introduction of light or shading</b>	No evidence (NEv)	No evidence (NEv)	No evidence (NEv)
	Q: NR A: NR C: NR	Q: NR A: NR C: NR	Q: NR A: NR C: NR

No evidence.

<b>Barrier to species movement</b>	Medium	High	Low
	Q: Low A: NR C: NR	Q: High A: High C: High	Q: Low A: Low C: Low

No direct evidence was found to assess this pressure. As the larvae of *Mytilus edulis* are planktonic and are transported by water movements, barriers that reduce the degree of tidal excursion may alter the supply of *Mytilus edulis* to suitable habitats from source populations. However, the presence of barriers may enhance local population supply by preventing the loss of larvae from enclosed habitats. This species is therefore potentially sensitive to barriers that restrict water movements, whether this will lead to beneficial or negative effects will depend on whether enclosed populations are sources of larvae or are 'sink' populations that depend on outside supply of larvae to sustain the local population.

**Sensitivity assessment.** As this habitat is potentially sensitive to changes in tidal excursion and exchange, resistance is assessed as '**Medium**' and resilience as '**High**', sensitivity is, therefore '**Low**'.

<b>Death or injury by collision</b>	Not relevant (NR)	Not relevant (NR)	Not relevant (NR)
	Q: NR A: NR C: NR	Q: NR A: NR C: NR	Q: NR A: NR C: NR

Not relevant' to benthic habitats. NB. Collision by grounding vessels is addressed under 'surface abrasion'.

<b>Visual disturbance</b>	Not relevant (NR)	Not relevant (NR)	Not relevant (NR)
	Q: NR A: NR C: NR	Q: NR A: NR C: NR	Q: NR A: NR C: NR

Not relevant.

## Biological Pressures

Resistance

Resilience

Sensitivity

## Genetic modification & translocation of indigenous species

No evidence (NEv)

Q: NR A: NR C: NR

No evidence (NEv)

Q: NR A: NR C: NR

No evidence (NEv)

Q: NR A: NR C: NR

Commercial cultivation of *Mytilus edulis* involves the collection of juvenile mussel 'seed' or spat (newly settled juveniles ca 1-2 cm in length) from wild populations, with subsequent transportation around the UK for re-laying in suitable habitats. As the seed is harvested from wild populations from various locations the gene pool will not necessarily be decreased by translocations. Movement of mussel seed has the potential to transport pathogens and non-native species (see relevant pressure sections). This pressure assessment is based on Mainwaring *et al.* (2014) and considers the potential impacts on natural mussel beds of genetic flow between translocated stocks and wild mussel beds.

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Two species of *Mytilus* occur in the UK, *Mytilus edulis* and *Mytilus galloprovincialis*. *Mytilus edulis* appears to maintain genetic homogeneity throughout its range whereas *Mytilus galloprovincialis* can be genetically subdivided into a Mediterranean group and an Atlantic group (Beaumont *et al.* 2007). *Mytilus edulis* and *Mytilus galloprovincialis* have the ability to hybridize in areas where their distribution overlaps e.g. around the Atlantic and European coast (Gardner, 1996; Daguin *et al.*, 2001; Bierne *et al.*, 2002; Beaumont *et al.*, 2004). In the UK overlaps occur on the North East coast, North East Scotland, South West England and in the North, West and South of Ireland (Beaumont *et al.*, 2007). It is difficult to distinguish *Mytilus edulis*, *Mytilus galloprovincialis* or hybrids based on shell shape because of the extreme plasticity of shape exhibited by mussels under environmental variation, and a genetic test is required (Beaumont *et al.*, 2007). There is some discussion questioning the distinction between the two species as the hybrids are fertile (Beaumont *et al.*, 2007). Hybrids reproduce and spawn at a similar time to both *Mytilus edulis* and *Mytilus galloprovincialis* which supports genetic flow between the taxa (Doherty *et al.*, 2009).

There is some evidence that hybrid larvae have a faster growth rate to metamorphosis than pure individuals which may leave pure individuals more vulnerable to predation (Beaumont *et al.*, 1993). As the physiology of both the hybrid and pure *Mytilus edulis* is so similar there is likely to be little impact on the tolerance of the bed to either pressure nor a change in the associated fauna. A review by Svåsand *et al.* (2007) concluded that there was a lack of evidence distinguishing between different populations to accurately assess the impacts of hybridization and in particular how the gene flow may be affected by aquaculture. Therefore, it cannot be confirmed whether farming will have an impact on the genetics of this species beyond a potential for increased hybridization.

**Sensitivity assessment.** No direct evidence was found regarding the potential for negative impacts of translocated mussel seed on adjacent natural beds. While it is possible that translocation of mussel seed could lead to genetic flow between cultivated beds and local wild populations, there is currently no evidence to assess the impact (Svåsand *et al.*, 2007). Hybrid beds perform the same



ecological functions as *Mytilus edulis* so that any impact relates to genetic integrity of a bed alone. This impact is considered to apply to all mussel bed biotopes equally, as the main habitat-forming species *Mytilus edulis* is translocated. Also, given the uncertainty in identification of the species, habitats or biotopes described as dominated by *Mytilus edulis* may well be dominated by *Mytilus galloprovincialis*, their hybrids or a mosaic of the three. Presently, there is 'No evidence' of impact due to genetic modification and translocation; therefore 'No evidence' is reported. The range of *Mytilus galloprovincialis* is thought to be extending northwards (Beaumont *et al.*, 2007) and this assessment may require updating in the future.

### Introduction or spread of invasive non-indigenous species

Low

Low

High

Q: Medium A: Medium C: Medium

Q: High A: Low C: Medium

Q: Medium A: Low C: Medium

Sewell *et al.* (2008) reviewed the evidence for invasive non-indigenous species with the potential to be introduced to and impact mussel beds. These included *Botrylloides violaceus*, *Corella eumyota*, *Crepidula fornicata*, *Didemnum vexillum*, *Rapana venosa*, and *Magallana gigas* and *Aulocomyia ater*. Littoral mussel beds on sediment were considered by (Sewell *et al.* 2008 and Mainwaring *et al.* 2014) to only be exposed to the Pacific oyster, *Magallana gigas*.

*Magallana gigas* is the most widely grown bivalve in aquaculture around the world at present and an important nuisance species in marine waters (Padilla, 2010). Adults are also long-lived so that populations can survive with infrequent recruitment. It has a high fecundity, a long-lived pelagic larval phase and hence high dispersal potential (>1000km). *Magallana gigas* does not spawn at water temperatures below ca 20°C but adults grow in colder waters so that it was thought that this species could not escape from cultivation in cold water areas. However, it has been suggested that climate change and warmer waters have allowed *Magallana gigas* to expand into and reproduce in previously unsuitable areas. Established feral populations have been reported to spread via larvae (Padilla, 2010). It is found from the mid-littoral to the upper subtidal, and grows on hard substrata but also on other bivalves (e.g. blue mussels) and polychaete reefs (Padilla, 2010).

*Magallana gigas* can out-compete *Mytilus edulis* (Padilla, 2010). In the Wadden Sea and the North Sea, *Magallana gigas* overgrows mussel beds in the intertidal zone (Diederich, 2005, 2006; Kochmann *et al.*, 2008), although larvae did show preference for settling on conspecifics before the mussels and struggled to settle on mussels with a fucoid covering. It has been observed that mussel beds in the Wadden Sea that are adjacent to oyster farms were quickly converted to oyster beds (Kochmann *et al.*, 2008). Padilla (2010) predicted that *Magallana gigas* could either displace or overgrown mussels on rocky and sedimentary habitats of low or high energy. Kent and Essex Inshore Fisheries and Conservation Authority (IFCA) (cited in Herbert *et al.*, 2012) reported that *Magallana gigas* had developed a significant stock on mussel beds on the Southend foreshore and that, by 2012, there were few mussels left in the affected area, but made no conclusions as to the reason for the decline in mussels (Kent and Essex IFCA pers comm cited in Herbert *et al.*, 2012).

Diederich (2005, 2006) examined settlement, recruitment and growth of *Magallana gigas* and *Mytilus edulis* in the northern Wadden Sea. *Magallana gigas* recruitment success was dependant on temperature, and in the northern Wadden Sea, only occurred in six of the 18 years since *Magallana gigas* was first introduced. Survival of juveniles is higher in mild than cold winters. Also, survival of both juveniles and adults on mussel beds is higher than that of the mussels themselves. However, recruitment of *Magallana gigas* was significantly higher in the intertidal than

the shallow subtidal, although the survival of adult oysters or mussels in the subtidal is limited by predation. Diederich (2005) concluded that hot summers could favour *Magallana gigas* reproduction while cold winters could lead to high mussel recruitment the following summer. Diederich (2005, 2006) noted that the high survival rate of *Magallana gigas* adults and juveniles in the intertidal was likely to compensate for years of poor recruitment. *Magallana gigas* also prefer to settle on conspecifics, so that it can build massive oyster reefs, which themselves are more resistant of storms or ice scour than the mussel beds they replace; as oysters are cemented together, rather than dependent on byssus threads. *Magallana gigas* also grows faster than *Mytilus edulis* in the intertidal and reaches by ca 2-3 times the length of mussels within one year. In addition, growth rates in *Magallana gigas* were independent of the tidal level (emergence regime, substratum, *Fucus* cover and barnacle epifauna (growing on both mussels and oysters), while the growth rate of *Mytilus edulis* was decreased by these factors. The faster growth rate could make *Magallana gigas* more competitive than *Mytilus edulis* where space or food is limiting. Diederich (2006) concluded that the massive increase in *Magallana gigas* in the northern Wadden Sea was caused by high recruitment success, itself due to anomalously warm summer temperatures, the preference for settlement on conspecifics (and hence reef formation), and high survival rates of juveniles. As oyster reefs form on former mussel beds, the available habitat for *Mytilus edulis* could be restricted (Diederich, 2006).

**Sensitivity assessment.** The Pacific oyster, *Magallana gigas* was reported to out-compete and replace mussel beds in the intertidal and was predicted to do so, on both soft sediment and rocky habitats (Padilla 2010). In the upper subtidal, *Magallana gigas* may also develop reefs or grow on mussel beds but the evidence is less clear. Herbert *et al.* (2012) noted that blue mussels were found in areas dominated by *Magallana gigas*. But small clumps or occasional individuals would not constitute a blue mussel bed so that the component biotopes would be lost. Therefore, a precautionary resistance of 'Low' is suggested (significant, 25-75%, mortality and effects on the physicochemical character of the habitat) for intertidal blue mussel beds and resilience is likely to be 'Very low' as the *Magallana gigas* population would need to be removed for recovery to occur. Therefore, a sensitivity of 'High' is reported for intertidal mussel bed biotopes on sediment.

#### Introduction of microbial pathogens

Medium Medium  
Q: Medium A: Medium C: Medium Q: High A: Low C: Medium

Medium  
Q: Medium A: Low C: Medium

Evidence for the impacts of microbial pathogens on *Mytilus edulis* was reviewed by Mainwaring *et al.* (2014) with specific reference to the shellfish pathogens *Marteilosis* and *Bonamia*. Natural *Mytilus edulis* beds are host to a diverse array of disease organisms, parasites and commensals from many animal and plant groups including bacteria, blue-green algae, green algae, protozoa, boring sponges, boring polychaetes, boring lichen, the intermediary life stages of several trematodes, copepods and decapods (Bower, 1992; Gray *et al.*, 1999; Bower, 2010).

Whilst *Bonamia* has been shown not to infect *Mytilus edulis* (Culloty *et al.*, 1999), *Marteilia refringens* can infect and have significant impacts on the health of *Mytilus edulis*. Its distribution, impacts on the host, diagnostic techniques and control measures are reviewed by Bower (2011). There is some debate as to whether there are two species of *Marteilia*, one which infects oysters (*Marteilia refringens*) and another that infects blue mussels (*Marteilia maurini*) (Le Roux *et al.*, 2001) or whether they are just two strains of the same species (Lopez-Flores *et al.*, 2004; Balseiro *et al.*, 2007). Both species are present in southern parts of the United Kingdom. The infection of *Marteilia* results in *Marteiliosis* which disrupts the digestive glands of *Mytilus edulis* especially at times of spore release. Heavy infection can result in a reduced uptake of food, reduced absorption



efficiency, lower carbohydrate levels in the haemolymph and inhibited gonad development particularly after the spring spawning resulting in an overall reduced condition of the individual (Robledo *et al.*, 1995).

Recent evidence suggests that *Marteilia* is transferred to and from *Mytilus edulis* via the copepod *Paracartia grani*. This copepod is not currently prevalent in the UK waters, with only a few records in the English Channel and along the South coast. However, it is thought to be transferred by ballast water and so localised introductions of this vector may be possible in areas of mussel seed transfer e.g. the Menai Strait. The mussel populations here are considered to be naive (i.e. not previously exposed) and, therefore, could be heavily affected, although the likelihood is slim due to the dependence on the introduction of a vector that is carrying *Marteilia* and it then being transferred to the mussels.

Berthe *et al.* (2004) concluded that *Mytilus edulis* is rarely significantly affected by *Marteilia* sp. However, occasions have been recorded of nearly 100% mortality when British spat have been transferred from a 'disease free area' to areas in France where *Marteilia* sp. are present. This suggests that there is a severe potential risk if naive spat are moved around the UK from northern waters into southern waters where the disease is resident (enzootic) or if increased temperatures allow the spread of *Marteilia* sp. northwards towards the naive northern populations. In addition, rising temperatures could allow increased densities of the *Marteilia* sp. resulting in heavier infections which can lead to mortality.

**Sensitivity assessment.** Bower (2010) noted that although *Marteilia* was a potentially lethal pathogen of mussels, most populations were not adversely affected by marteiliosis but that in some areas mortality can be significant in mariculture (Berthe *et al.*, 2004). The resultant population would be more sensitive to other pressures, even where the disease only resulted in a reduced condition. Therefore, a precautionary resistance of '**Medium**' is suggested (<25% mortality), with a resilience of '**Medium**' (2-10 years) resulting in a sensitivity of '**Medium**'.

### Removal of target species

**Low**

Q: High A: High C: High

**Medium**

Q: High A: Low C: Medium

**Medium**

Q: High A: Low C: Medium

*Mytilus edulis* is a commercially targeted species worldwide and has been fished for hundreds of years and managed in England and Wales for the last hundred years (Holt *et al.*, 1998). Mussels are collected on a commercial scale, in both the intertidal and subtidal, by dredges of various forms and by divers (Narvarte *et al.*, 2011). Damage caused by direct physical impacts which are assessed in under 'abrasion' and 'penetration and/or disturbance of the surface of the seabed' pressures, the sensitivity assessment for this pressure considers any biological effects resulting from the removal of target species on *Mytilus edulis* beds.

*Mytilus edulis* is the most important characterizing species defining the assessed biotopes and therefore any removal of the species will result in the removal of its associated fauna and a decline in species richness. Removal of most of the mussel biomass will also lead to loss of or reclassification of the biotope. The sensitivity to removal can be characterised as the immediate direct impact of harvesting and subsequent indirect effects.

Reports of dredging efficiency vary from 15% using Baird dredges on ground previously dredged for oysters (Palmer *et al.*, 2007) to 90% using artisanal dredges (Narvarte *et al.*, 2011). Mussels are also regularly hand collected by fisherman for bait and food from intertidal beds which can also result in significant damage to the bed (Holt *et al.*, 1998; Smith & Murray, 2005).

Smith & Murray (2005) examined the effects of low-level disturbance and removal on an extensive bed of *Mytilus californianus* (composed of a single layer of mussels) in southern California. They observed a significant decrease in mussel mass ( $\text{g}/\text{m}^2$ ), density ( $\text{no.}/\text{m}^2$ ), percentage cover and mean shell length due to low-intensity simulated bait-removal treatments (2 mussels/month) for 12 months (Smith & Murray 2005). They also stated that the initial effects of removal were 'overshadowed' by the loss of additional mussels during time periods between treatments, probably due to the indirect effect of the weakening of byssal threads attachments between the mussel leaving them more susceptible to wave action (Smith & Murray, 2005). The low-intensity simulated bait-removal treatments had reduced percentage cover by 57.5% at the end of the 12 month experimental period. Smith & Murray (2005) suggested that the losses occurred from collection and trampling are far greater than those that occur by natural causes. This conclusion was reached due to significant results being displayed for human impact despite the experiment taking place during a time of high natural disturbance from El Niño–Southern Oscillation (ENSO). In addition, Holt *et al.*, (1998) recorded an incident of the removal of an entire bed that is adjacent to a road in Anglesey due to fishermen bait collecting.

Commercial removal of mussels can often be responsible for the depletion of mussel stocks. For example, a substantial reduction in the mussel stock was observed in the Wash (England) during the 1990's due to high fishing mortality and low recruitment (Atkinson *et al.*, 2003). The dredging fishery for mussels in the Limfjorden, Denmark, was reported to reduce the stock size of mussels (Dolmer *et al.*, 1999). The total stock of mussel in the Limfjorden was estimated to be 771 kt to 616 kt in 1993-1994, while the mean exploitation rate of the fishery was 14%. In 1993-94 the size of mussel landings was found to correlate with a reduction in the overall stock size of the area, suggesting that mussel mortality was significantly increased by the fishery. However, in 1995 the total stock had fallen to 494kt and the mean exploitation rate was 15% but there was no significant relationship between landings and stock size (Dolmer *et al.*, 1999). Divers observed that dense beds are likely to be more efficiently dredged due to their byssal attachments detaining the dredge below the carpet of the mussels whilst mussels in low-density beds cause the dredge to bounce along the seabed resulting in reduced efficiency (Dolmer *et al.*, 1999). A low level of exploitation may actually increase the growth rate of the mussels by reducing the intraspecific competition for food (Dolmer *et al.*, 1999). However, Dolmer *et al.* (2001) observed that the mussel biomass was significantly lower in dredged areas suggesting that the lowering of the intraspecific competition does not increase the accumulation of biomass.

Recreational fishermen will often collect moulting *Carcinus maenas* or whelks by hand from intertidal mussel beds for bait. The removal of predatory crabs could actively benefit the population this effect could be beneficial to mussel populations.

**Sensitivity assessment** *Mytilus edulis* beds have no avoidance mechanisms to escape targeted harvesting and as a result, a significant proportion of the bed can be removed (Palmer *et al.*, 2007; Narvarte *et al.*, 2011). Dredging occurs on both subtidal and intertidal soft sediment and results in the removal of the mussel beds which defines the biotope. As the majority of the mussel beds that are harvested in the UK are regularly replenished with seed, the recovery rate for maintained beds should be rapid. In natural (wild) beds, the recovery could be significantly longer due to indirect effects from wave action and the sporadic nature of recruitment (Paine & Levin 1981; Seed & Suchanek 1992). Mussel beds on hard substrata are unlikely to be affected by dredges and are therefore only vulnerable in the intertidal areas where they may be accessed for hand picking. However, even hand-picking for bait can result in a significant decrease in cover, especially in beds composed of a single layer of mussels (Smith & Murray 2005). It should be noted that dense, multi-layered mussel beds may be more resistant to the gaps and bait collection, as damage to the upper

layer may not affect deeper layers, so that attachment to the substratum and each other is maintained (Brosnan & Crumrine, 1994). Based on the available evidence all *Mytilus edulis* bed biotopes are considered to have ‘**Low**’ resistance to this pressure and ‘**Medium**’ resilience so that sensitivity is assessed as ‘**Medium**’.

#### Removal of non-target species

**Low**

Q: High A: High C: High

**Medium**

Q: High A: Low C: Medium

**Medium**

Q: High A: Low C: Medium

Blue mussel beds may be removed or damaged by static or mobile gears that are targeting other species. The direct, physical impacts are assessed through the abrasion and penetration of the seabed pressures, while this pressure considers the ecological or biological effects of by-catch. Removal of a large part of the *Mytilus edulis* bed unintentionally would significantly alter the biotope as the mussels are the key characterizing, structuring and functional species.

The removal of *Mytilus edulis* predators including the starfish *Asterias rubens* and *Luidia ciliaris* and the crabs *Cancer pagurus* and *Necora puber* as by-catch through commercial fishing activities could potentially benefit beds of mussels but the population of starfish and crabs are highly mobile and probably attracted to damaging and dying organisms left after dredging, and therefore likely to recover before the mussels are able to recruit (Gubbay & Knapman, 1999). Fishing activities may expose infauna, and leave dead and damaged species on the seabed, and areas where discards and by-catch have been deposited may also attract predators and scavengers. But this potentially heightened level predation only lasts for a few days (Dolmer *et al.* 2001 observed a seven-day effect) and therefore is unlikely to have an impact on the bed as a whole.

**Sensitivity assessment.** The biogenic structure created by *Mytilus edulis* is the key characterizing, structural and functional feature of this biotope group. Removal of individuals as by-catch would substantially impact the biotope and hence this group is considered to have ‘**Low**’ resistance to this pressure and to have ‘**Medium**’ resilience. Sensitivity is, therefore, assessed as ‘**Medium**’.

## Bibliography

- Akaishi, F.M., St-Jean, S.D., Bishay, F., Clarke, J., Rabitto, I.d.S. & Ribeiro, C.A., 2007. Immunological responses, histopathological finding and disease resistance of blue mussel (*Mytilus edulis*) exposed to treated and untreated municipal wastewater. *Aquatic Toxicology*, **82** (1), 1-14.
- Alfaro, A.C., 2005. Effect of water flow and oxygen concentration on early settlement of the New Zealand green-lipped mussel, *Perna canaliculus*. *Aquaculture*, **246**, 285-94.
- Alfaro, A.C., 2006. Byssal attachment of juvenile mussels, *Perna canaliculus*, affected by water motion and air bubbles. *Aquaculture*, **255**, 357-61
- Almada-Villela P.C., 1984. The effects of reduced salinity on the shell growth of small *Mytilus edulis* L. *Journal of the Marine Biological Association of the United Kingdom*, **64**, 171-182.
- Almada-Villela, P.C., Davenport, J. & Gruffydd, L.L.D., 1982. The effects of temperature on the shell growth of young *Mytilus edulis* L. *Journal of Experimental Marine Biology and Ecology*, **59**, 275-288.
- Ameyaw-Akumfi, C. & Naylor, E., 1987. Spontaneous and induced components of salinity preference behaviour in *Carcinus maenas*. *Marine Ecology Progress Series*, **37**, 153-158.
- Atkinson, P.W., Clark, N.A., Bell, M.C., Dare, P.J., Clark, J.A. & Ireland, P.L., 2003. Changes in commercially fished shellfish stocks and shorebird populations in the Wash, England. *Biological Conservation*, **114**, 127-141.
- Auker, L.A. & Oviatt, C.A., 2007. Observations on the colonization of the invasive tunicate *Didemnum* sp. in Rhode Island In *Naturalist*, **14**, 1-4.
- Auker, L.A. & Oviatt, C.A., 2008. Factors influencing the recruitment and abundance of *Didemnum* in Narragansett Bay, Rhode Island. *ICES Journal of Marine Science: Journal du Conseil*, **65** (5), 765-769.
- Aunaas, T., Denstad, J-P. & Zachariassen, K., 1988. Ecophysiological importance of the isolation response of hibernating blue mussels (*Mytilus edulis*). *Marine Biology* **98**: 415-9
- Bahmet, I., Berger, V. & Halaman, V., 2005. Heart rate in the blue mussel *Mytilus edulis* (Bivalvia) under salinity change. *Russian Journal of Marine Biology* **31**: 314-7
- Bailey, J., Parsons, J. & Couturier, C., 1996. Salinity tolerance in the blue mussel, *Mytilus edulis*. Rep. Report no. 0840-5417, *Aquaculture Association of Canada*, New Brunswick, Canada
- Baird, R.H., 1966. Factors affecting the growth and condition of mussels (*Mytilus edulis*). *Fishery Investigations. Ministry of Agriculture, Fisheries and Food, Series II*, no. 25, 1-33.
- Balseiro P., Montes A., Ceschia G., Gestal C., Novoa B. & Figueras A., 2007. Molecular epizootiology of the European Marteilia spp., infecting mussels (*Mytilus galloprovincialis* and *M. edulis*) and oysters (*Ostrea edulis*): an update. *Bulletin of the European Association of Fish Pathologists*, **27**(4), 148-156.
- Baxter, J.M., 1997. *Aulacomya ater*: Magellan mussel: Moray Firth in Scotland in 1994 and again in 1997. *Joint Nature Conservation Committee*.
- Bayne, B., Iglesias, J., Hawkins, A., Navarro, E., Heral, M., Deslous-Paoli, J-M., 1993. Feeding behaviour of the mussel, *Mytilus edulis*: responses to variations in quantity and organic content of the seston. *Journal of the Marine Biological Association of the United Kingdom*, **73**, 813-29
- Bayne, B.L. (ed.), 1976b. *Marine mussels: their ecology and physiology*. Cambridge: Cambridge University Press. [International Biological Programme 10.]
- Bayne, B.L., Widdows, J. & Thompson, R.J., 1976. Physiological integrations. In *Marine mussels: their ecology and physiology* (ed. B.L. Bayne), pp. 261-299. Cambridge: Cambridge University Press. [International Biological Programme 10.]
- Beauchamp, K.A., Gowing, M.M., 1982. A quantitative assessment of human trampling effects on a rocky intertidal community. *Marine Environmental Research*, **7**, 279-94
- Beaumont, A., Abdul-Matin, A. & Seed, R., 1993. Early development, survival and growth in pure and hybrid larvae of *Mytilus edulis* and *M. galloprovincialis*. *Journal of Molluscan Studies*, **59**, 120-123.
- Beaumont, A.R., Gjedrem, T. & Moran, P., 2007. Blue mussel *Mytilus edulis* and Mediterranean mussel *M. galloprovincialis*. In T., S., et al. (eds.). Genetic impact of aquaculture activities on native populations. *GENIMPACT final scientific report (EU contract n. RICA-CT-2005-022802)*, pp. 62-69.
- Beaumont, A.R., Turner, G., Wood, A.R. & Skibinski, D.O.F., 2004. Hybridisations between *Mytilus edulis* and *Mytilus galloprovincialis* and performance of pure species and hybrid veliger larvae at different temperatures. *Journal of Experimental Marine Biology and Ecology*, **302** (2), 177-188.
- Berge, J., Johnsen, G., Nilsen, F., Gulliksen, B. & Slagstad, D. 2005. Ocean temperature oscillations enable reappearance of blue mussels *Mytilus edulis* in Svalbard after a 1000 year absence. *Marine Ecology Progress Series*, **303**, 167-175.
- Bergmann, M., Wiczorek, S.K., Moore, P.G., 2002. Utilisation of invertebrates discarded from the *Nephrops* fishery by variously selective benthic scavengers in the west of Scotland. *Marine Ecology Progress Series*, **233**, 185-98
- Berthe, F.C.J., Le Roux, F., Adlard, R.D. & Figueras, A., 2004. Marteiliosis in molluscs: a review. *Aquatic Living Resources*, **17** (4), 433-448.

- Bierne, N., David, P., Boudry, P. & Bonhomme, F., 2002. Assortative fertilization and selection at larval stage in the mussels *Mytilus edulis* and *M. galloprovincialis*. *Evolution*, **56**, 292-298.
- Blanchard, M., 1997. Spread of the slipper limpet *Crepidula fornicata* (L.1758) in Europe. Current state and consequences. *Scientia Marina*, **61**, Supplement 9, 109-118.
- Bokn, T.L., Moy, F.E. & Murray, S.N., 1993. Long-term effects of the water-accommodated fraction (WAF) of diesel oil on rocky shore populations maintained in experimental mesocosms. *Botanica Marina*, **36**, 313-319.
- Bourget, E., 1983. Seasonal variations of cold tolerance in intertidal molluscs and their relation to environmental conditions in the St. Lawrence Estuary. *Canadian Journal of Zoology*, **61**, 1193-1201.
- Bower S.M., 2010. Synopsis of Infectious Diseases and Parasites of Commercially Exploited Shellfish [online]. Ontario, Fisheries and Oceans, Canada. Available from: <http://dev-public.rhq.pac.dfo-mpo.gc.ca/science/species-especies/shellfish-coquillages/diseases-maladies/index-eng.htm> [Accessed: 14/02/2014]
- Bower, S.M., 2011. *Marteilia refringens/maurini* of Mussels [online]. Available from: <http://dev-public.rhq.pac.dfo-mpo.gc.ca/science/species-especies/shellfish-coquillages/diseases-maladies/pages/mrmaurmu-eng.htm> [Accessed: 05/03/2014]
- Bower, S.M., 1992. Diseases and parasites of mussels. In *The mussel Mytilus: ecology, physiology, genetics and culture* (ed. E.M. Gosling), pp. 543-563. Amsterdam: Elsevier Science Publ. [Developments in Aquaculture and Fisheries Science, no. 25.]
- Brosnan, D.M., 1993. The effect of human trampling on biodiversity of rocky shores: monitoring and management strategies. *Recent Advances in Marine Science and Technology*, **1992**, 333-341.
- Brosnan, D.M. & Crumrine, L.L., 1994. Effects of human trampling on marine rocky shore communities. *Journal of Experimental Marine Biology and Ecology*, **177**, 79-97.
- Browne, M.A., Dissanayake, A., Galloway, T.S., Lowe, D.M. & Thompson, R.C., 2008. Ingested microscopic plastic translocates to the circulatory system of the mussel, *Mytilus edulis* (L.). *Environmental Science & Technology*, **42** (13), 5026-5031.
- Buschbaum, C. & Saier, B., 2001. Growth of the mussel *Mytilus edulis* L. in the Wadden Sea affected by tidal emergence and barnacle epibionts. *Journal of Sea Research*, **45**, 27-36
- Bussell, J. A., Gidman, E. A., Causton, D. R., Gwynn-Jones, D., Malham, S. K., Jones, M. L. M., Reynolds, B. & Seed, R., 2008. Changes in the immune response and metabolic fingerprint of the mussel, *Mytilus edulis* (Linnaeus) in response to lowered salinity and physical stress. *Journal of Experimental Marine Biology and Ecology*, **358**, 78-85.
- Cohen A.N., 2011. *The Exotics Guide: Non-native Marine Species of the North American Pacific Coast*. [online]. Richmond, CA, Center for Research on Aquatic Bioinvasions. Available from: <http://www.exoticsguide.org> [Accessed: 20/03/2014]
- Cole, S., Codling, I.D., Parr, W., Zabel, T., 1999. Guidelines for managing water quality impacts within UK European marine sites [On-line]. *UK Marine SACs Project*. [Cited 26/01/16]. Available from: [http://www.ukmarinesac.org.uk/pdfs/water\\_quality.pdf](http://www.ukmarinesac.org.uk/pdfs/water_quality.pdf)
- Connor, D.W., Allen, J.H., Golding, N., Howell, K.L., Lieberknecht, L.M., Northen, K.O. & Reker, J.B., 2004. The Marine Habitat Classification for Britain and Ireland. Version 04.05. ISBN 1 861 07561 8. In JNCC (2015), *The Marine Habitat Classification for Britain and Ireland Version 15.03*. [2019-07-24]. Joint Nature Conservation Committee, Peterborough. Available from <https://mhc.jncc.gov.uk/>
- Crisp, D.J. (ed.), 1964. The effects of the severe winter of 1962-63 on marine life in Britain. *Journal of Animal Ecology*, **33**, 165-210.
- Crompton, T.R., 1997. *Toxicants in the aqueous ecosystem*. New York: John Wiley & Sons.
- Culloty, S.C., Novoa, B., Pernas, M., Longshaw, M., Mulcahy, M.F., Feist, S.W. & Figueras, A., 1999. Susceptibility of a number of bivalve species to the protozoan parasite *Bonamia ostreae* and their ability to act as vectors for this parasite. *Diseases of Aquatic Organisms*, **37** (1), 73-80.
- Daguin, C., Bonhomme, F. & Borsa, P., 2001. The zone of sympatry and hybridization of *Mytilus edulis* and *M. galloprovincialis*, as described by intron length polymorphism at locus mac-1. *Heredity*, **86**, 342-354.
- Daly, M.A. & Mathieson, A.C., 1977. The effects of sand movement on intertidal seaweeds and selected invertebrates at Bound Rock, New Hampshire, USA. *Marine Biology*, **43**, 45-55.
- Dare, P.J., 1976. Settlement, growth and production of the mussel, *Mytilus edulis* L., in Morecambe Bay, England. *Fishery Investigations, Ministry of Agriculture, Fisheries and Food, Series II*, **28**, 25pp.
- Davenport, J., 1979. The isolation response of mussels (*Mytilus edulis*) exposed to falling sea water concentrations. *Journal of the Marine Biological Association of the United Kingdom*, **59**, 124-132.
- Denny, M.W., 1987. Lift as a mechanism of patch initiation in mussel beds. *Journal of Experimental Marine Biology and Ecology*, **113**, 231-45
- Diaz, R.J. & Rosenberg, R., 1995. Marine benthic hypoxia: a review of its ecological effects and the behavioural responses of benthic macrofauna. *Oceanography and Marine Biology: an Annual Review*, **33**, 245-303.
- Diederich, S., 2005. Differential recruitment of introduced Pacific oysters and native mussels at the North Sea coast: coexistence possible? *Journal of Sea Research*, **53** (4), 269-281.
- Diederich, S., 2006. High survival and growth rates of introduced Pacific oysters may cause restrictions on habitat use by native mussels in the Wadden Sea. *Journal of Experimental Marine Biology and Ecology*, **328** (2), 211-227.
- Dijkstra, J., Harris, L.G. & Westerman, E., 2007. Distribution and long-term temporal patterns of four invasive colonial ascidians in

- the Gulf of Maine. *Journal of Experimental Marine Biology and Ecology*, **342** (1), 61-68.
- Dinesen, G.E., Timmermann K., Roth E., Markager S., Ravn-Jonsen, L., Hjorth, M., Holmer M. & Støttrup J.G., 2011. Mussel Production and Water Framework Directive Targets in the Limfjord, Denmark: an Integrated Assessment for Use in System-Based Management. *Ecology & Society*, **16**(4). 26
- Dobretsov, S. & Wahl, M., 2008. Larval recruitment of the blue mussel *Mytilus edulis*: the effect of flow and algae. *Journal of Experimental Marine Biology and Ecology*, **355**, 137-44
- Doherty, S.D., Brophy, D. & Gosling, E., 2009. Synchronous reproduction may facilitate introgression in a hybrid mussel (*Mytilus*) population. *Journal of Experimental Marine Biology and Ecology*, **378**, 1-7.
- Dolmer, P. & Svane, I. 1994. Attachment and orientation of *Mytilus edulis* L. in flowing water. *Ophelia*, **40**, 63-74
- Dolmer, P., Kristensen, T., Christiansen, M.L., Petersen, M.F., Kristensen, P.S. & Hoffmann, E., 2001. Short-term impact of blue mussel dredging (*Mytilus edulis* L.) on a benthic community. *Hydrobiologia*, **465**, 115-127.
- Dolmer, P., Sand Kristensen, P. & Hoffmann, E., 1999. Dredging of blue mussels (*Mytilus edulis* L.) in a Danish sound: stock sizes and fishery-effects on mussel population dynamic. *Fisheries Research*, **40** (1), 73-80.
- Donkin, P., Widdows, J. & Evans, S.V., 1989. Quantitative structure activity relationships for the effect of hydrophobic organic chemicals on the rate of feeding of mussels. *Aquatic Toxicology*, **14**, 277-294.
- Essink, K., 1999. Ecological effects of dumping of dredged sediments; options for management. *Journal of Coastal Conservation*, **5**, 69-80.
- Frechette, M., Butman, C.A., Geyer, W.R., 1989. The importance of boundary-layer flow in supplying phytoplankton to the benthic suspension feeder, *Mytilus edulis* L. *Limnology and Oceanography*, **34**, 19-36.
- Gardner, J.P.A., 1996. The *Mytilus edulis* species complex in southwest England: effects of hybridization and introgression upon interlocus associations and morphometric variation. *Marine Biology*, **125**(2), 385-399.
- Giltrap, M., Ronan, J., Hardenberg, S., Parkes, G., McHugh, B., McGovern, E. & Wilson, J., 2013. Assessment of biomarkers in *Mytilus edulis* to determine good environmental status for implementation of MSFD in Ireland. *Marine Pollution Bulletin*, **71** (1), 240-249.
- Gosling, E.M. (ed.), 1992a. *The mussel Mytilus: ecology, physiology, genetics and culture*. Amsterdam: Elsevier Science Publ. [Developments in Aquaculture and Fisheries Science, no. 25]
- Gray, A.R., Lucas, I.A.N., Seed, R. & Richardson, C.A., 1999. *Mytilus edulis chilensis* infested with *Coccomyxa parasitica* (Chlorococcales, Coccomyxaceae). *Journal of Molluscan Studies*, **65**, 289-294.
- Gray, J.S., Wu R.S.-S. & Or Y.Y., 2002. Effects of hypoxia and organic enrichment on the coastal marine environment. *Marine Ecology Progress Series*, **238**, 249-279.
- Groenewold, S. & Fonds, M., 2000. Effects on benthic scavengers of discards and damaged benthos produced by the beam-trawl fishery in the southern North Sea. *ICES Journal of Marine Science*, **57** (5), 1395-1406.
- Gruffydd, L.D., Huxley, R. & Crisp, D., 1984. The reduction in growth of *Mytilus edulis* in fluctuating salinity regimes measured using laser diffraction patterns and the exaggeration of this effect by using tap water as the diluting medium. *Journal of the Marine Biological Association of the United Kingdom* **64**: 401-9
- Gubbay, S., & Knapman, P.A., 1999. *A review of the effects of fishing within UK European marine sites*. Peterborough, English Nature.
- Hall, S.J., Basford, D.J. & Robertson, M.R., 1990. The impact of hydraulic dredging for razor clams *Ensis* spp. on an infaunal community. *Netherlands Journal of Sea Research*, **27**, 119-125.
- Harding, J.M. & Mann, R., 1999. Observations on the biology of the Veined Rapa whelk, *Rapana whelk* (Valenciennes, 1846) in the Chesapeake Bay. *Journal of Shellfish Research*, **18**(1), 9-17.
- Harger, J.R.E. & Landenberger, D.E., 1971. The effects of storms as a density dependent mortality factor on populations of sea mussels. *The Veliger*, **14**, 195-210.
- Hawkins, A., Smith, R., Bayne, B. & Heral, M., 1996. Novel observations underlying the fast growth of suspension-feeding shellfish in turbid environments: *Mytilus edulis*. *Marine Ecology Progress Series*, **131**, 179-90
- Herbert, R.J.H., Roberts, C., Humphreys, J., & Fletcher, S. 2012. The Pacific oyster (*Crassostrea gigas*) in the UK: economic, legal and environmental issues associated with its cultivation, wild establishment and exploitation. Available from: <http://www.dardni.gov.uk/pacific-oysters-issue-paper.pdf>
- Hillman, R.E., 1993. Relationship of environmental contaminants to occurrence of neoplasia in *Mytilus edulis* populations from east to west coast mussel-watch sites. *Journal of Shellfish Research*, **12**, 109.
- Holt, T.J., Jones, D.R., Hawkins, S.J. & Hartnoll, R.G., 1995. The sensitivity of marine communities to man induced change - a scoping report. *Countryside Council for Wales, Bangor, Contract Science Report*, no. 65.
- Holt, T.J., Rees, E.I., Hawkins, S.J. & Seed, R., 1998. Biogenic reefs (Volume IX). An overview of dynamic and sensitivity characteristics for conservation management of marine SACs. *Scottish Association for Marine Science (UK Marine SACs Project)*, 174 pp.
- Hummel, H., Groeneveld, J.P., Nieuwenhuize, J., van Liere, J.M., Bogaards, R.H. & de Wolf, L., 1989. Relationship between PCB concentrations and reproduction in mussels *Mytilus edulis*. In *Fifth International Symposium on Responses of Marine Organisms to Pollutants*, 12-14 April 1989, Plymouth (ed. M.N. Moore & J. Stegeman). *Marine Environmental Research*, **28**, 489-493.



- Jenner, H.A., Whitehouse, J.W., Taylor, C.J. & Khalanski, M. 1998. Cooling water management in European power stations Biology and control of fouling. *Hydroécologie Appliquée*, **10**, 1-225.
- JNCC, 2013. Blue Mussel Beds. Scottish MPA Project Fisheries Management Guidance, *Joint Nature Conservation Committee, Peterborough*, [http://jncc.defra.gov.uk/pdf/SMPA\\_fisheries\\_management\\_guidance\\_blue\\_mussel\\_beds\\_July\\_2013.pdf](http://jncc.defra.gov.uk/pdf/SMPA_fisheries_management_guidance_blue_mussel_beds_July_2013.pdf)
- JNCC, 2015. The Marine Habitat Classification for Britain and Ireland Version 15.03. (20/05/2015). Available from <https://mhc.jncc.gov.uk/>
- JNCC, 2015. The Marine Habitat Classification for Britain and Ireland Version 15.03. (20/05/2015). Available from <https://mhc.jncc.gov.uk/>
- Jones, S.J., Lima, F.P. & Wetthey, D.S., 2010. Rising environmental temperatures and biogeography: poleward range contraction of the blue mussel, *Mytilus edulis* L., in the western Atlantic. *Journal of Biogeography* **37**: 2243-59
- Jorgensen, B.B., 1980. Seasonal oxygen depletion in the bottom waters of a Danish fjord and its effect on the benthic community. *Oikos*, **32**, 68-76.
- Kaiser, M.J. & Spencer, B.E., 1994. Fish scavenging behaviour in recently trawled areas. *Marine Ecology Progress Series*, **112** (1-2), 41-49.
- Kittner, C. & Riisgaard, H.U., 2005. Effect of temperature on filtration rate in the mussel *Mytilus edulis*: no evidence for temperature compensation. *Marine Ecology Progress Series* **305**: 147-52
- Kochmann, J., Buschbaum, C., Volkenborn, N. & Reise, K., 2008. Shift from native mussels to alien oysters: differential effects of ecosystem engineers. *Journal of Experimental Marine Biology and Ecology*, **364** (1), 1-10.
- Koehn, R.K. & Hilbish, T.J., 1987. The biochemical genetics and physiological adaptation of an enzyme polymorphism. *American Scientist*, **75**, 134-141.
- Koehn, R.K., 1983. Biochemical genetics and adaptation in molluscs. In *The Mollusca*. vol. 2. *Environmental biochemistry and physiology*, (ed. P.W. Hochachka), pp 305-330.
- Lambert, G., 2004. The south temperate and Antarctic ascidian *Corella eumyota* reported in two harbours in north-western France. *Journal of the Marine Biological Association of the United Kingdom*, **84**, 239-241.
- Lander, T.R., Robinson, S.M., MacDonald, B.A. & Martin, J.D., 2012. Enhanced growth rates and condition index of blue mussels (*Mytilus edulis*) held at integrated multitrophic aquaculture sites in the Bay of Fundy. *Journal of Shellfish Research*, **31** (4), 997-1007.
- Langan R. & Howell W.H., 1994. Growth responses of *Mytilus edulis* to changes in water flow: A test of the "inhalant pumping speed" hypothesis. *Journal of Shellfish Research*, **13**(1), 289.
- Last, K.S., Hendrick V. J, Beveridge C. M & Davies A. J, 2011. Measuring the effects of suspended particulate matter and smothering on the behaviour, growth and survival of key species found in areas associated with aggregate dredging. *Report for the Marine Aggregate Levy Sustainability Fund*,
- Le Roux, F., Lorenzo, G., Peyret, P., Audemard, C., Figueras, A., Vivares, C., Gouy, M. & Berthe, F., 2001. Molecular evidence for the existence of two species of *Marteilia* in Europe. *Journal of Eukaryotic Microbiology*, **48** (4), 449-454.
- Liddle, M.J., 1997. *Recreational ecology. The ecological impact of outdoor recreation and ecotourism*. London: Chapman & Hall.
- Lindahl, O. & Kollberg, S., 2008. How mussels can improve coastal water quality. *Bioscience Explained*, **5** (1), 1-14.
- Liu, D.H.W. & Lee, J.M., 1975. Toxicity of selected pesticide to the bay mussel (*Mytilus edulis*). *United States Environmental Protection Agency*, EPA-660/3-75-016.
- Livingstone, D.R. & Pipe, R.K., 1992. Mussels and environmental contaminants: molecular and cellular aspects. In *The mussel Mytilus: ecology, physiology, genetics and culture*, (ed. E.M. Gosling), pp. 425-464. Amsterdam: Elsevier Science Publ. [Developments in Aquaculture and Fisheries Science, no. 25]
- Long, D., 2006. BGS detailed explanation of seabed sediment modified Folk classification. Available from: [http://www.emodnet-seabedhabitats.eu/PDF/GMHM3\\_Detailed\\_explanation\\_of\\_seabed\\_sediment\\_classification.pdf](http://www.emodnet-seabedhabitats.eu/PDF/GMHM3_Detailed_explanation_of_seabed_sediment_classification.pdf)
- Loo, L-O., 1992. Filtration, assimilation, respiration and growth of *Mytilus edulis* L. at low temperatures. *Ophelia* **35**: 123-31
- Loo, L-O. & Rosenberg, R., 1983. *Mytilus edulis* culture: Growth and production in western Sweden. *Aquaculture*, **35**, 137-150.
- Loosanoff, V.L., 1962. Effects of turbidity on some larval and adult bivalves. *Proceedings of the Gulf and Caribbean Fisheries Institute*, **14**, 80-95.
- Lopez-Flores I., De la Herran, R., Garrido-Ramos, M.A., Navas, J.I., Ruiz-Rejon, C. & Ruiz-Rejon, M., 2004. The molecular diagnosis of *Marteilia refringens* and differentiation between *Marteilia* strains infecting oysters and mussels based on the rDNA IGS sequence. *Parasitology*, **19** (4), 411-419.
- Maddock, A., 2008. UK Biodiversity Action Plan; Priority Habitat Descriptions. *UK Biodiversity Action Plan*, 94pp
- Mainwaring, K., Tillin, H. & Tyler-Walters, H., 2014. Assessing the sensitivity of blue mussel beds to pressures associated with human activities. *Joint Nature Conservation Committee, JNCC Report No. 506.*, Peterborough, 96 pp.
- Mann, R. & Harding, J.M., 2000. Invasion of the North American Atlantic coast by a large predatory Asian mollusc. *Biological Invasions*, **2** (1), 7-22.
- Mann, R. & Harding, J.M., 2003. Salinity tolerance of larval *Rapana venosa*: implications for dispersal and establishment of an invading predatory gastropod on the North American Atlantic coast. *The Biological Bulletin*, **204** (1), 96-103.
- Minchin, D. 2007. Rapid coastal survey for targeted alien species associated with floating pontoons in Ireland. *Aquatic Invasions*,



2(1), 63-70.

Minchin, D. & Sides, E., 2006. Appearance of a cryptogenic tunicate, a *Didemnum* sp. fouling marina pontoons and leisure craft in Ireland *Aquatic Invasions*, **1**(3), 143-147.

Minchin, D., 1995. Recovery of a population of the flame shell, *Lima hians*, in an Irish bay previously contaminated with TBT. *Environmental Pollution*, **90**, 259-262.

Moore, P.G., 1977a. Inorganic particulate suspensions in the sea and their effects on marine animals. *Oceanography and Marine Biology: An Annual Review*, **15**, 225-363.

Mudge, S.M., Salgado, M.A. & East, J., 1993. Preliminary investigations into sunflower oil contamination following the wreck of the *M.V. Kimya*. *Marine Pollution Bulletin*, **26**, 40-44.

Myrand, B., Guderley, H. & Himmelman, J.H., 2000. Reproduction and summer mortality of blue mussels *Mytilus edulis* in the Magdalen Islands, southern Gulf of St. Lawrence. *Marine Ecology Progress Series* **197**: 193-207

Narvarte, M., González, R., Medina, A. & Avaca, M.S., 2011. Artisanal dredges as efficient and rationale harvesting gears in a Patagonian mussel fishery. *Fisheries Research*, **111** (1), 108-115.

Nehls, G. & Thiel, M., 1993. Large-scale distribution patterns of the mussel *Mytilus edulis* in the Wadden Sea of Schleswig-Holstein: Do storms structure the ecosystems? *Netherlands Journal of Sea Research*, **31**, 181-187.

Nenonen, N.P., Hannoun, C., Horal, P., Hernroth, B. & Bergström, T., 2008. Tracing of norovirus outbreak strains in mussels collected near sewage effluents. *Applied and Environmental Microbiology*, **74** (8), 2544-2549.

Newell, R.C., 1979. *Biology of intertidal animals*. Faversham: Marine Ecological Surveys Ltd.

Newell, R.I.E., 1989. Species profiles: life histories and environmental requirements of coastal fishes and invertebrates (North - Mid-Atlantic). Blue Mussel. [on-line] <http://www.nwrc.usgs.gov/wdb/pub/0169.pdf>, 2001-02-15

Padilla, D.K., 2010. Context-dependent impacts of a non-native ecosystem engineer, the Pacific Oyster *Crassostrea gigas*. *Integrative and Comparative Biology*, **50** (2), 213-225.

Page, H. & Hubbard, D., 1987. Temporal and spatial patterns of growth in mussels *Mytilus edulis* on an offshore platform: relationships to water temperature and food availability. *Journal of Experimental Marine Biology and Ecology* **111**: 159-79

Paine, R.T. & Levin, S.A., 1981. Intertidal landscapes: disturbance and the dynamics of pattern. *Ecological Monographs*, **51**, 145-178.

Palmer, D.L., Burnett, K., Whelpdale, P., 2007. Baseline Survey of Shellfish Resources in Lough Foyle. CEFAS, C2697, pp

Parry, H., & Pipe, R., 2004. Interactive effects of temperature and copper on immunocompetence and disease susceptibility in mussels (*Mytilus edulis*). *Aquatic Toxicology* **69**: 311-25

Pernet, F., Tremblay, R. & Bourget E., 2003. Settlement success, spatial pattern and behavior of mussel larvae *Mytilus* spp. in experimental downwelling systems of varying velocity and turbulence. *Marine Ecology Progress Series*, **260**, 125-140.

Price, H., 1982. An analysis of factors determining seasonal variation in the byssal attachment strength of *Mytilus edulis*. *Journal of the Marine Biological Association of the United Kingdom*, **62** (01), 147-155

Purchon, R.D., 1937. Studies on the biology of the Bristol Channel. *Proceedings of the Bristol Naturalists' Society*, **8**, 311-329.

Ramsay, K., Kaiser, M.J. & Hughes, R.N. 1998. The responses of benthic scavengers to fishing disturbance by towed gears in different habitats. *Journal of Experimental Marine Biology and Ecology*, **224**, 73-89.

Rankin, C.J. & Davenport, J.A., 1981. *Animal Osmoregulation*. Glasgow & London: Blackie. [Tertiary Level Biology].

Rayment W.J., 2007. *Crepidula fornicata*. Slipper limpet. [online]. *Marine Life Information Network: Biology and Sensitivity Key Information Sub-programme* [On-line]. Plymouth: Marine Biological Association of the United Kingdom. Available from: <<http://www.marlin.ac.uk>>

Read, K.R.H. & Cumming, K.B., 1967. Thermal tolerance of the bivalve mollusc *Modiolus modiolus* (L.), *Mytilus edulis* (L.) and *Brachiodontes demissus* (Dillwyn). *Comparative Biochemistry and Physiology*, **22**, 149-155.

Reid, G., Liutkus, M., Bennett, A., Robinson, S., MacDonald, B. & Page, F., 2010. Absorption efficiency of blue mussels (*Mytilus edulis* and *M. trossulus*) feeding on Atlantic salmon (*Salmo salar*) feed and fecal particulates: implications for integrated multi-trophic aquaculture. *Aquaculture*, **299** (1), 165-169.

Riemann B. & Hoffmann E., 1991. Ecological consequences of dredging and bottom trawling in the Limfjord, Denmark. *Marine Ecology Progress Series*, **69**(1), 171-178.

Riisgård, H.U., Bøttiger, L. & Pleissner, D. 2012. Effect of salinity on growth of mussels, *Mytilus edulis*, with special reference to Great Belt (Denmark). *Open Journal of Marine Science*, **2**, 167-176

Riisgård, H.U., Luskow, F., Pleissner, D., Lundgreen, K. & López, M., 2013. Effect of salinity on filtration rates of mussels *Mytilus edulis* with special emphasis on dwarfed mussels from the low-saline Central Baltic Sea. *Helgoland Marine Research*, **67**, 591-8

Robledo, J.A.F., Santarem, M.M., Gonzalez, P. & Figueras, A., 1995. Seasonal variations in the biochemical composition of the serum of *Mytilus galloprovincialis* Lmk. and its relationship to the reproductive cycle and parasitic load. *Aquaculture*, **133** (3-4), 311-322.

Saier, B., 2002. Subtidal and intertidal mussel beds (*Mytilus edulis* L.) in the Wadden Sea: diversity differences of associated epifauna. *Helgoland Marine Research*, **56**, 44-50

Seed, R. & Suchanek, T.H., 1992. Population and community ecology of *Mytilus*. In *The mussel Mytilus: ecology, physiology, genetics and culture*, (ed. E.M. Gosling), pp. 87-169. Amsterdam: Elsevier Science Publ. [Developments in Aquaculture and Fisheries

Science, no. 25.]

Seed, R., 1976. Ecology. In *Marine mussels: their ecology and physiology*, (ed. B.L. Bayne), pp. 81-120. Cambridge: Cambridge University Press.

Sewell, J., Pearce, S., Bishop, J. & Evans, J.L., 2008. Investigations to determine the potential risk for certain non-native species to be introduced to North Wales with mussel seed dredged from wild seed beds. *CCW Policy Research Report*, **835**, 82 pp., Countryside Council for Wales

Shumway, S.E., 1990. A review of the effects of algal blooms on shellfish and aquaculture. *Journal of the World Aquaculture Society*, **21**, 65-104.

Smaal, A.C., 2002. European mussel cultivation along the Atlantic coast: production status, problems and perspectives. *Hydrobiologia*, **484** (1-3), 89-98.

Smaal, A.C. & Twisk, F., 1997. Filtration and absorption of *Phaeocystis* cf. *globosa* by the mussel *Mytilus edulis* L. *Journal of Experimental Marine Biology and Ecology*, **209**, 33-46

Smith, J.E. (ed.), 1968. 'Torrey Canyon'. *Pollution and marine life*. Cambridge: Cambridge University Press.

Smith, J.R. & Murray, S.N., 2005. The effects of experimental bait collection and trampling on a *Mytilus californianus* mussel bed in southern California. *Marine Biology*, **147**, 699-706

Suchanek, T.H., 1978. The ecology of *Mytilus edulis* L. in exposed rocky intertidal communities. *Journal of Experimental Marine Biology and Ecology*, **31**, 105-120.

Suchanek, T.H., 1985. Mussels and their role in structuring rocky shore communities. In *The Ecology of Rocky Coasts: essays presented to J.R. Lewis, D.Sc.*, (ed. P.G. Moore & R. Seed), pp. 70-96.

Svåsand, T., Crosetti, D., García-Vázquez, E. & Verspoor, E., 2007. Genetic impact of aquaculture activities on native populations. *Genimpact final scientific report (EU contract n. RICA-CT-2005-022802)*.

Tangen K., 1977. Blooms of *Gyrodinium aureolum* (Dinophyceae) in North European waters, accompanied by mortality in marine organisms. *Sarsia*, **6**, 123-33.

Theede, H., Ponat, A., Hiroki, K. & Schlieper, C., 1969. Studies on the resistance of marine bottom invertebrates to oxygen-deficiency and hydrogen sulphide. *Marine Biology*, **2**, 325-337.

Theisen, B.F., 1982. Variation in size of gills, labial palps, and adductor muscle in *Mytilus edulis* L.(Bivalvia) from Danish waters. *Ophelia*, **21**, 49-63.

Thieltges, D.W., 2005. Impact of an invader: epizootic American slipper limpet *Crepidula fornicata* reduces survival and growth in European mussels. *Marine Ecology Progress Series*, **286**, 13-19.

Thompson, I.S., Richardson, C.A., Seed, R. & Walker, G., 2000. Quantification of mussel (*Mytilus edulis*) growth from power station cooling waters in response to chlorination procedures. *Biofouling*, **16**, 1-15.

Thompson, I.S., Seed, R., Richardson, C.A., Hui, L. & Walker, G., 1997. Effects of low level chlorination on the recruitment, behaviour and shell growth of *Mytilus edulis* Linnaeus in power station cooling water. *Scientia Marina*, **61** (Suppl. 2), 77-85.

Tracey, G.A., 1988. Effects of inorganic and organic nutrient enrichment on growth and bioenergetics of the blue mussel, *Mytilus edulis*. *Journal of Shellfish Research*, **7**, 562.

Tsuchiya, M., 1983. Mass mortality in a population of the mussel *Mytilus edulis* L. Caused by high temperature on rocky shores. *Journal of Experimental Marine Biology and Ecology* **66**: 101-11

Tyler-Walters, H., 2002. *Mytilus edulis* and *Fucus vesiculosus* on moderately exposed mid eulittoral rock. [online]. Plymouth, Marine Biological Association of the United Kingdom. Available from:

<http://www.marlin.ac.uk/habitatbenchmarks.php?habitatid=46&code=2004> [Accessed: 05/03/2014]

Tyler-Walters, H. & Arnold, C., 2008. Sensitivity of Intertidal Benthic Habitats to Impacts Caused by Access to Fishing Grounds. *Report to Cyngor Cefn Gwlad Cymru / Countryside Council for Wales from the Marine Life Information Network (MarLIN) [Contract no. FC 73-03-327]*, Marine Biological Association of the UK, Plymouth, 48 pp. Available from: [www.marlin.ac.uk/publications](http://www.marlin.ac.uk/publications)

Tyler-Walters, H. & Durkin, O., 2001. *Mytilus edulis* beds on variable salinity infralittoral mixed sediment. *Marine Life Information Network: Biology and Sensitivity Key Information Sub-programme Plymouth: Marine Biological Association of the United Kingdom*. (05/03/2014).

UKTAG, 2014. UK Technical Advisory Group on the Water Framework Directive [online]. Available from: <http://www.wfduk.org>

Valentine, P.C., Carman, M.R., Blackwood, D.S. & Heffron, E.J., 2007. Ecological observations on the colonial ascidian *Didemnum* sp. in a New England tide pool habitat. *Journal of Experimental Marine Biology and Ecology*, **342** (1), 109-121.

Van De Werfhorst L.C. & Pearse J.S., 2007. Trampling in the rocky intertidal of central California: a follow-up study. *Bulletin of Marine Science*, **81**(2), 245-254.

Wang, W. & Widdows, J., 1991. Physiological responses of mussel larvae *Mytilus edulis* to environmental hypoxia and anoxia. *Marine Ecology Progress Series*, **70**, 223-36

Westerbom, M. & Jattu, S., 2006. Effects of wave exposure on the sublittoral distribution of blue mussels *Mytilus edulis* in a heterogeneous archipelago. *Marine Ecology Progress Series*, **306**, 191-200.

Whitehouse, J., Coughlan, J., Lewis, B., Travade, F. & Britain, G., 1985. The control of biofouling in marine and estuarine power stations: a collaborative research working group report for use by station designers and station managers. *Central Electricity*

### Generating Board

- Widdows J., Lucas J.S., Brinsley M.D., Salkeld P.N. & Staff F.J., 2002. Investigation of the effects of current velocity on mussel feeding and mussel bed stability using an annular flume. *Helgoland Marine Research*, **56**(1), 3-12.
- Widdows, J. & Donkin, P., 1992. Mussels and environmental contaminants: bioaccumulation and physiological aspects. In *The mussel Mytilus: ecology, physiology, genetics and culture*, (ed. E.M. Gosling), pp. 383-424. Amsterdam: Elsevier Science Publ. [Developments in Aquaculture and Fisheries Science, no. 25]
- Widdows, J., Bayne, B.L., Livingstone, D.R., Newell, R.I.E. & Donkin, P., 1979a. Physiological and biochemical responses of bivalve molluscs to exposure to air. *Comparative Biochemistry and Physiology*, **62A**, 301-308.
- Widdows, J., Donkin, P. & Evans, S.V., 1987. Physiological responses of *Mytilus edulis* during chronic oil exposure and recovery. *Marine Environmental Research*, **23**, 15-32.
- Widdows, J., Donkin, P., Brinsley, M.D., Evans, S.V., Salkeld, P.N., Franklin, A., Law, R.J. & Waldock, M.J., 1995. Scope for growth and contaminant levels in North Sea mussels *Mytilus edulis*. *Marine Ecology Progress Series*, **127**, 131-148.
- Widdows, J., Moore, M., Lowe, D. & Salkeld, P., 1979b. Some effects of a dinoflagellate bloom (*Gyrodinium aureolum*) on the mussel, *Mytilus edulis*. *Journal of the Marine Biological Association of the United Kingdom*, **59** (2), 522-524.
- Williams, R.J., 1970. Freezing tolerance in *Mytilus edulis*. *Comparative Biochemistry and Physiology*, **35**, 145-161
- Winter, J., 1972. Long-term laboratory experiments on the influence of ferric hydroxide flakes on the filter-feeding behaviour, growth, iron content and mortality in *Mytilus edulis* L. *Marine pollution and sea life*. (ed. Ruvio, M.) London, England, pp. 392-396.
- Witman, J.D. & Suchanek, T.H., 1984. Mussels in flow: drag and dislodgement by epizoans. *Marine Ecology Progress Series*, **16** (3), 259-268.
- Young, G.A., 1985. Byssus thread formation by the mussel *Mytilus edulis*: effects of environmental factors. *Marine Ecology Progress Series*, **24**, 261-271.
- Zandee, D.I., Holwerda, D.A., Kluytmans, J.H. & De Zwaan, A., 1986. Metabolic adaptations to environmental anoxia in the intertidal bivalve mollusc *Mytilus edulis* L. *Netherlands Journal of Zoology*, **36**(3), 322-343.
- Zander, C.D., 1986. Tripterygiidae. In *Fishes of the North-eastern Atlantic and the Mediterranean*, Vol. 3. (ed. P.J.P. Whitehead, M.L. Bauchot, J.C. Hureau, J. Nielsen & E. Tortonese), pp. 1118-1121. Paris: UNESCO
- Zwaan de, A. & Mathieu, M., 1992. Cellular biochemistry and endocrinology. In *The mussel Mytilus: ecology, physiology, genetics and culture*, (ed. E.M. Gosling), pp. 223-307. Amsterdam: Elsevier Science Publ. [Developments in Aquaculture and Fisheries Science, no. 25]