Critical Review

# Restrictions on UK aquaculture of Pacific oyster (*Magallana gigas*) will not prevent naturalised spread but suppress ecological and economic benefits to coastal communities

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## Abstract

The Pacific oyster (*Magallana* (*Crassostrea*) *gigas*) was introduced to UK waters in the mid-20th century and currently accounts for over 95% of UK oyster fishery landings. Recently however, its non-native origin has led policy makers to consider a limit on UK oyster aquaculture operations. *M. gigas* is effectively naturalised in the UK, with multiple records of populations originating from non-local sources, including from outside the UK. Neighbouring countries, most notably France, treat *M. gigas* as a naturalised species. The naturalised status simplifies regulation and enables the fishery to provide large quantities of nutritious and sustainable food, supporting employment in coastal communities. Further to this, alongside the potential for detrimental effects this species could have on natural habitats, *M. gigas* presence can have substantial positive environmental impacts, for example, for improving water quality and by providing living breakwaters for contemporary coastal protection schemes. Our review suggests that efforts to reduce the spread of *M. gigas* in England are unlikely to have the desired long-term effect and will fundamentally fail due to introductions in Scotland and larval connectivity throughout the southern North Sea. We recommend that UK policy on *M. gigas* should be updated to reflect the environmental and socioeconomic benefits of Pacific oysters to the shellfish fishery and to open its utility for the provision of nature-based solutions in the adaption to the effects of sea-level rise. Additional location-specific management interventions should focus on suitable mitigation for sensitive sites or to slow spreading events on a case-by-case basis.

*Key words*: Pacific oyster, *Magallana* (*Crassostrea*) *gigas*, aquaculture, naturalisation, invasive non-native species (INNS), novel ecosystems

## 1. Introduction

Since its introduction to UK and European waters, the Pacific oyster (*Magallana* (*Crassostrea*) *gigas*) has become vitally important to a fishery that dates back millennia. Historically, the industry was wholly reliant on the Native flat or European oyster (*Ostrea edulis*). However, the *O. edulis* population was decimated during the late 19th and early 20th centuries by a combination of overexploitation, poor fishery practices, pathogen introductions, habitat loss and pollution (zu Ermgassen et al., 2023). *M. gigas*, a non-native species originating from Japan and South-East Asia was identified as a suitable replacement species and, following the development of bio-secure hatchery protocols, with support of various government agencies at that time, were introduced to fisheries in the UK in 1965 (Herbert et al., 2012; Utting and Spencer, 1992). This strategy to boost shellfish aquaculture was adopted in several other countries, including Canada in the 1920s and 1930s, Ireland in the late 1960s and France throughout the 1970s (Lallias et al., 2015). The original licence for commercial use of *M. gigas* was granted based on the belief that UK water temperatures were too low for the species to reproduce and naturalise. However, this has since proved not to be the case, with *M. gigas* now regularly spawning in UK and other European waters resulting in a spreading wild population (King et al., 2021).

The UK oyster fishery relies on *M. gigas* for >95% of its landings and supported 142 jobs (full time equivalent) in 2017 (Syvret et al., 2021). These jobs are often in rural coastal communities where secure employment is scarce and therefore relatively more important (McDowell and Bonner-Thompson, 2020). Valuation of the full UK *M. gigas* supply chain suggests that the fishery was worth over £13 million to the UK economy in 2011/12, since when landings have nearly trebled from 450 tonnes in 2011 to 1150 tonnes in 2021 (FAO, 2021; Humphreys et al., 2014).

The UK *M. gigas* fishery is smaller than in some other European countries, with the French fishery alone producing an average of about 80,000 tonnes annually between 2011 and 2020 (EUMOFA, 2022). It therefore represents an opportunity for expansion, with substantial socioeconomic potential for rural and coastal communities, as well as the prospect of increased domestic production of a sustainable and high-quality food perceived by consumers as a healthy source of protein with low industrial input that contributes to the blue economy.

The non-native origin of *M. gigas*, their potential impact on coastal ecosystems and their ability to breed in the temperate waters of Northern Europe, have raised several ecological and policy concerns. These centre around their successful dispersal beyond aquaculture sites, their abilities as ecosystem engineers to alter habitats including the transformation of mudflats to oyster reefs, the possible interference with restoration efforts of native *O. edulis*, competition with other aquaculture species and their settlement on maritime infrastructure (Herbert et al., 2016; Martinez-Garcia et al., 2022). Calls are being made to limit the expansion, or even continuation, of the aquaculture of this species in some areas due to an assumption that current industry activity is the source of free-living dispersing oyster larvae; and that the proposed concerns are being realised.

The debate around the future of the UK oyster fishery was intensified in early 2023 by the decision of the Duchy of Cornwall, a private landowner that leases foreshore and riverbed areas to oyster growers in the south west of England (the counties of Devon and Cornwall), that they would be 'phasing-out' *M. gigas* production in their waters (BBC, 2023). Concurrent unsupported statements by the Department for Environment, Food and Rural Affairs (DEFRA) that they were 'considering control measures' including a stop to the issuing of new *M. gigas* aquaculture licences north of the 52 °N parallel – a line connecting the towns of Fishguard and Felixstowe – to limit the spread of this species have further added to the concerns of the aquaculture industry (BBC, 2023; HC Deb, 2023). This 'red line' proposal applies to England despite the fact that oyster farms are already positioned north of this line in both England and Scotland. There has also been increased media coverage of local concerns at some sites with varying colonisation of *M. gigas*, some where there does appear to be substantial habitat change and others not, and this has attracted volunteer programs to cull *M. gigas* colonising intertidal habitats (BBC, 2021).

Here, we examine the evidence for the realised costs of *M. gigas* naturalisation. We critically review the likely success of any efforts to slow-down or reverse the spread of this species via controls on aquaculture and discuss potential benefits of naturalised populations of this species to a contemporary coastal European landscape. We will present the current challenges faced by the *M. gigas* fishery in UK waters, examining three areas: (i) the current status of *M. gigas* around the UK and European coast, (ii) the impacts of wild populations and potential mitigation strategies, and (iii) the likely impacts of climate and coastal change on *M. gigas* in the UK.

## 2. Naturalisation and dispersal of *M. gigas*

*M. gigas* occurs extensively throughout Europe, and is now distributed from Norway in the north to Cyprus in the south (Hansen et al., 2023). Within the UK, the species can be found as far north as the Shetland Islands, although the greatest numbers are found along the South-West and South-East coastlines (McKnight, 2011; Morgan et al., 2021; Shelmerdine et al., 2017; Syvret et al., 2008). Spread from introduced populations has occurred throughout the European range of *M. gigas*, with wild populations now established in Denmark's Wadden Sea, around the Spanish, French, and UK Atlantic coasts and throughout the Mediterranean Sea (Clubley et al., 2023; Des et al., 2022; reviewed in Hansen et al., 2023).

Despite the granting of a General Licence in 1982 that allowed the release of *M. gigas* into UK waters, the species is still classified as an invasive, non-native species in the UK under the terms of current legislation (Wildlife and Countryside Act 1981). This is in contrast to the customs and legislation in other European countries, with the species not listed as 'of concern' by the European Union (Brundu et al., 2022). In France *M. gigas* is considered as sufficiently low risk that it is fully compatible with farming operations in protected (Natura 2000) areas. In Germany, *M. gigas* introduced for aquaculture is treated as exempt from EU invasive-species regulations (Haubrock et al., 2023). In the Netherlands, after unsuccessful attempts to control its spread, the presence of *M. gigas* is accepted as irreversible, and farming operations are allowed to continue (Syvret et al., 2021). Additionally, *M. gigas* and its shell substrate are provided to encourage settlement of live *M. gigas*, and deployment of *M. gigas* can be integrated as nature-based alternatives to hard-engineered structures for coastal defence (Fivash et al., 2021).

While there is little doubt that the initial introduction of *M. gigas* to UK waters was from human activity with the aim of supporting economic growth of the oyster fishery, the current contribution of UK-cultured *M. gigas* to the spread of the species is less clear. Along the coasts of Southwest England and South Wales, populations of wild *M. gigas* are genetically more closely related to French and Spanish populations than to UK hatchery stock (Lallias et al., 2015). The introductory pathway of these oysters is not fully understood, but could include illegal seed importation, transport of attached oysters on boat hulls and/or of planktonic larvae with ballast water, and natural dispersal via currents of planktonic larvae from French populations.

The official UK risk assessment for *M. gigas* states that the spread of *M. gigas* is likely primarily from extant wild populations, rather than fishery operations (Non-native Species Secretariat, 2010). Observations of wild oysters without a clear link to current local fishery sources have been made from the south coast to the Shetland Isles, as well as Lough Foyle on the Irish coast (Kochmann et al., 2012; Mills, 2016; Shelmerdine et al., 2017). Mills (2016) demonstrates that the population established in Southampton Water is genetically independent from any extant oyster fishery operations, and appears to be self-sustaining.

Although it is possible for there to be links between contemporary aquaculture activities and establishment of local populations, the typical harvesting of *M. gigas* for consumption at relatively small size may stifle development of a sufficient number of reproductive females since their life-history follows a protandrous hermaphrodite development where the probability of reproductive females increases with age. Hence, it is questionable if restrictions on aquaculture activities are likely to result in a sufficiently substantial reduction of the spread of this species, relative to the many large and older highly reproductive females in the wild populations, to warrant the detrimental socioeconomic effects on coastal communities via the loss of employment and income.

## 3. Detail of impacts and potential mitigations

*M. gigas* are often referred to as ‘ecosystem engineers’ (Troost, 2010). Ecosystem engineers are organisms that modify, maintain and/or create habitat (Alper, 1998). The potential ecological impacts of this species were comprehensively reviewed by Herbert et al. (2016) and Martinez Garcia et al. (2022), concluding that *M. gigas* are capable of altering diversity, community structure and ecosystem processes. Further concerns have been raised, including competition with native bivalves, loss of wading bird habitat and reducing the appeal of coastal areas to leisure users (Martinez-Garcia et al., 2022). Here we shall examine the potential for positive and negative effects of engineered habitats by Pacific oysters.

### 3.1. *Examples of potential positive impact of M. gigas on coastal ecosystems*.

An increasing *M. gigas* population can bring a range of benefits. Native, wild and naturalised non-native and cultured bivalve populations all deliver a wide range of ecosystem service provisions, as reviewed by van der Schatte Olivier et al. (2020). This includes benefits from an increasing *M. gigas* population. These services include, but are not limited to, water quality improvement and water-column nitrogen removal (Clements and Comeau, 2019), habitat provision (Martinez-Garcia et al., 2022), carbon sequestration (Filgueira et al., 2015) and pathogen removal (van der Schatte Olivier et al., 2020).

Bivalve reefs integrated into ‘living breakwaters’ are increasingly suggested as a strategy to mitigate against the effects of climate warming-induced sea-level rise. Live breakwaters can protect from coastal-flooding and reduce erosion of vulnerable coastal habitats such as saltmarsh while delivering additional ecological benefits (Ridge et al., 2017; Scyphers et al., 2011). Chowdhury et al. (2019) demonstrated that mudflat stability in Kutubdia Island, Bangladesh was significantly increased by the presence of the intertidal rock oyster

*Saccostrea cucullata*. The benefit of a living shellfish breakwater is that shellfish reefs can grow with a rising sea level, whereas traditional coastal defence is often limited to the costly and unsustainable installation of man-made structures, for example, groynes, seawalls or tidal barriers, that are static and have a limited lifetime (Morris et al., 2018). To be cost-effective, it is likely that future coastal defence must utilise a combination of traditional and natural engineering strategies, and coastal defence projects would benefit from the installation of rapidly establishing, low maintenance oyster reefs as demonstrated by efforts in The Netherlands (Fivash et al., 2021).

Where the ecological impacts of UK and European wild *M. gigas* populations have been studied directly, they are generally assessed to be either neutral or positive. Extensive work by Zwerschke and colleagues (2020; 2016; 2018a) at an experimental site in Strangford Lough, Ireland, and at monitoring sites throughout Europe has consistently shown that there is very little difference between *O. edulis* and *M. gigas* reefs in terms of associated ecological community assemblage, biodiversity and nutrient cycling. Furthermore, Zwerschke *et al.* (2016; 2018a) suggest that *M. gigas* may compensate for the loss of ecosystem services previously provided by *O. edulis*, and this is in addition to the socioeconomic gains associated with a functional oyster fishery. It has also been suggested that the presence of *M. gigas* may have facilitated the return of *O. edulis* along the Dutch North-Sea coast (Christianen et al., 2018), with evidence of similar facilitation of native oyster recruitment onto an established *M. gigas* reef in the river Crouch, Essex, UK (Lown, 2019).

Bazterrica et al. (2022) surveyed well established introduced (~30 year old) *M. gigas* reefs in the Argentinian south Atlantic, comparing the macrofaunal community with that found in vegetated and soft sediments in the locality. The authors found significantly higher macrofaunal diversity associated with *M. gigas* reefs, particularly during the summer months. Hansen et al. (2023) report that, in European waters, the presence of *M. gigas* is likely to lead to equal or higher biodiversity than beds of native bivalves, for example, Blue mussel (*Mytilus edulis*). Similar patterns are observed in Sweden, where the presence of *M. gigas* leads to greater abundance of associated organisms than the native *M. edulis* (Hollander et al., 2015). On UK coasts and in the Wadden Sea, this biodiversity gain is achieved without native-species displacement, and can provide substantial areas of habitat for a range of native species (Markert et al., 2010; Martinez-Garcia et al., 2022; Troost, 2010). This is not to say that more biodiversity, if it is not ’natural’ is necessarily better, however in most cases and in our own experience, *M. gigas* reefs harbour similar species to that found in other native shellfish habitats but more of them due to the more rugose three-dimensional habitat that they engineer.

Evaluation of the impact of *M. gigas* on the Wadden Sea suggests that the species has not impacted on the area's level of ecosystem-service provision (Gutow and Buschbaum, 2019). Thieltges et al. (2009) demonstrate that the presence of *M. gigas* in the List tidal basin, Germany, resulted in a decreased burden of parasitic infection of *M. edulis*. Hansen et al. (2023) further suggest that, due to their similar functional ecology to native bivalves, *M. gigas* can enhance the resilience of an ecosystem, reducing the impacts of potential future biodiversity and biomass reductions on the overall functioning of coastal ecosystems.

### 3.2. *Examples of potential negative impact of M. gigas on coastal ecosystems*

There has been reasonable concern that where *M. gigas* and *O. edulis* co-occur, the faster growth and potential for rapid reproduction of *M. gigas* may result in the native species being outcompeted (Zwerschke et al., 2018b). However, the two species are typically spatially segregated, with wild *M. gigas* residing primarily in the mid to lower intertidal and *O. edulis* more often found in the deeper subtidal. Within the UK North-Kent Marine Protected Area, some protected Ross Worm (*Sabellaria spinulosa*) reefs have been damaged and displaced by *M. gigas* (McKnight, 2011; McKnight and Chudleigh, 2015). In several cases the biodiversity gains associated with new *M. gigas* reef habitat result in part from the presence of other non-native species, including various amphipods, decapods and copepods, some of which have potentially negative effects on the native fauna (Bazterrica et al., 2022; Holmes and Minchin, 1995). Guy et al. (2018) assessed the epifauna of sympatric populations on the shells of *M. gigas* and *O. edulis* in Strangford Lough, finding significantly lower species diversity growing on Pacific oysters shells (8.4 ± 0.97 species per *M. gigas* individual, 12.6 ± 0.78 species per *O. edulis* individual, ANOVA $p<0.005$).

#### *3.2.1. Effects on food webs*

Mudflats are important coastal habitats that support high densities of infauna and provide a wide range of ecosystem services (Barbier et al., 2011). Reddin et al. (2022) showed that the colonisation of mudflats in the Bay of Bourgneuf, France, by *M. gigas* resulted in increased numbers of predatory crabs. In turn these crabs reduced grazer density, resulting in a significant increase in the levels of plant material stored in the mud. The authors suggest that increased presence of *M. gigas* in the region could result in large-scale shifts in trophic energy flows via supporting increased crab populations, but they also noted the effects were constrained to within 50-65 m of the edge of an oyster reef.

*M. gigas* can also impact on the success of other species via their filter-feeding behaviours, through both competition for food resources and by consuming planktonic larvae, which is most significant at reef margins (Joyce, 2019; Martinez-Garcia et al., 2022; Troost, 2010). Dense aggregations of *M. gigas*, and the locally concentrated waste they produce, can also have a substantial impact on the biogeochemistry and microbial ecology of sediment and pore water that alters ecosystem function (Green et al., 2012). However, when compared to *O. edulis*, there is no difference in the effect on the ecosystem (Zwerschke et al., 2020).

### *3.2.2. Effects on birds*

Throughout the Wadden Sea, *M. gigas* have spread into areas historically dominated by *M. edulis* reefs, although in many cases the two species co-exist and *M. edulis* numbers can stabilise in under 10 years (Markert et al., 2010; Schmidt et al., 2008; Troost, 2010). The Wadden Sea is a large intertidal habitat, supporting up to 12 million birds, many of which utilise *M. edulis* as a food source (Waser et al., 2016). Displacement of *M. edulis*, as well as wider impacts on the infaunal organisms predated on by resident and migratory birds is therefore a potentially significant concern. Perceived risks to foraging birds of mudflat colonising species is not new, with concerns raised about cord grass, excessive seaweed growth and Pacific oysters. However, the realised impact of *M. gigas* on species of birds that use coastal areas is unclear. Markert et al. (2013) found that foraging by Herring Gull (*Larus argentatus*) in the German Wadden Sea is hampered by *M. gigas* reefs. Contrastingly, Waser et al. (2016) suggest that *L. argentatus* were unaffected by higher *M. gigas* densities, but that four out of 22 examined species, Eurasian Oystercatcher, Common Gull (*Larus canus*), Red Knot (*Calidris canutus*) and Dunlin (*Calidris alpina*) were lower in abundance when *M. gigas* densities were highest. In the case of the Dutch Wadden Sea, Waser et al. (2016) conclude that, whilst the impacts of *M. gigas* are substantial, it is likely that the disturbance resulting from efforts to remove or limit the spread *M. gigas* would do substantially more harm than good to the avian diversity of the area. Research on the utilisation of intertidal habitats by foraging shorebirds in Delaware Bay (USA) suggests that the feeding rates are unaffected by the presence of oyster aquaculture (Maslo et al., 2020).

*M. gigas* may also provide opportunities for the recovery of desired *M. edulis* (Markert et al., 2010; OSPAR, 2023). Furthermore, Hollander et al. (2015) showed that *M. gigas* and *M. edulis* reefs are associated with similar infaunal communities, with greater abundances associated with the presence of *M. gigas*. Therefore, foraging birds might be supported in areas where *M. gigas* replaces mussel beds, unless changes in reef structure decreases foraging success independent of prey availability. Few studies have addressed the realised effects of *M. gigas* reefs on foraging, or the foraging potential of reefs that are harvested for food production or disrupted to minimise their spread. For example, a study in Essex, UK, found large invertebrate prey for three common estuary birds was at significantly higher abundance in *M. gigas* reefs and at sites where the reef had been removed to minimise the spread of *M. gigas* than in adjacent mudflats (Herbert et al., 2018). While mudflats covered larger areas and hosted more birds in total, foraging success and feeding rates were higher for oystercatchers and curlew on the *M. gigas*-associated habitats (Herbert et al., 2018). A key take-home message is that rich shellfish habitats, such as intact *M. gigas* intertidal reefs and areas managed by occasional removal of *M. gigas*, can, and often do, contribute to the mosaic of estuarine habitats that create foraging opportunities for diverse native wildlife.

### 3.3. *Effectiveness of mitigation strategies to minimise the spread of M. gigas*.

There have been concerted efforts in some areas to eradicate established wild *M. gigas* populations. These include destruction of individuals by ‘hammering’, removal by dredging or smothering of reefs with sediment. McKnight and Chudleigh (2015) report on attempts to remove *M. gigas* in a small section (1000 $m^2$) of the intertidal in the North-Kent Marine-Protected Area. The project utilised 234 hours of volunteer labour over a year, removing 34,333 oysters from the substrate, which included chalk reef, resulting in considerable reduction in oyster numbers. Guy and Roberts (2010) utilised a similar methodology in Strangford Lough to similar effect.

After concerns were raised by waterway users, a naturally established *M. gigas* reef in Brightlingsea Harbour in Essex, UK was dredged to remove the risks associated with sharp shell edges and return the area into a mudflat (Herbert et al., 2016). As a result of this operation, much of this site could currently be described as a managed intertidal mixed sediment and, while *M. gigas* persist in the area, there are no extensive intertidal reefs. This example, in which a local oyster fisherman was able to harvest commercially from an *M. gigas* population that was of concern to waterway users, illustrates a ‘win-win’ situation creating benefits to multiple coastal stakeholders while demonstrating the ease with which oyster reefs established on mudflats could be managed. Ongoing oyster harvest operations by the aquaculture industry are, in fact, uniquely placed to provide such a service in locations where such management is deemed necessary.

Smothering of oyster reefs has also been attempted as a means of control. This process involves the dumping of large quantities of dredged sediment (a layer of >0.2 m thickness) on a reef (Hansen et al., 2023). In theory, this method will choke and starve the oysters, although full mortality is unlikely to be achieved given the depths of mud in which *M. gigas* can be found in some areas such as the Colne River in Essex, UK. Both smothering and dredging of a reef involve the disturbance of substantial areas and volumes of sediment, which can negatively impact local benthic community structure and water quality (Newell et al., 1998; Schaffner, 2010). Because they are labour intensive in all these cases, efforts are limited in scale, therefore relying on volunteer labour or substantial additional funding. Furthermore, given that the underlying factors that encouraged settlement are not substantially altered, efforts will likely need to be repeated regularly to ensure that the areas remain free from a developing *M. gigas* reef.

Several authors call in to question the overall practicality of eradication efforts. Cassini (2020) suggests that, outside of isolated small-island environments, it is rarely possible to remove a species from an ecosystem. The interconnected nature of marine systems only adds to this challenge. The dispersal patterns of *M. gigas* around Europe demonstrate that long-range dispersal has occurred regularly since its introduction (Clubley et al., 2023). Lallias et al. (2015) found that there are a substantial number of wild and established *M. gigas* populations around the UK coast with closer genetic links to French hatcheries than UK and *M. gigas* with no obvious link to local aquaculture activities are present at various locations ranging from Southampton to the Shetland Isles (Kochmann et al., 2012; Mills, 2016; Shelmerdine et al., 2017). It is important to note that one large female *M. gigas* releases in excess of 50 million externally fertilised eggs per spawning and that, based on harvesting data, French oyster populations alone are likely produce one to two orders of magnitude larger propagule sizes than much smaller populations in the UK. Several modelling studies converge on the same result, that the species has a high probability for rapid and successful long-range dispersal, possibly further aided by settlement on existing off-shore installations including nautical markers, oil and gas platforms or windfarms, from all across the southern North Sea and this outcome is independent of current UK aquaculture activities (Clubley et al., 2023; Wood et al., 2021).

Eradication is the most extreme of the management options for *M. gigas*. Other options include mandating the use of unfertile triploid oysters, obtained in hatcheries by crossing female diploid oysters (2n) with male tetraploid oysters (4n) (Hansen et al., 2023). This is often suggested as a strategy in which the spread of oysters from controlled aquaculture facilities into the wild can be minimised (Nell, 2002). However the process is not completely effective, because some individuals remain fertile or can revert to a fertile state (Syvret et al., 2008). The use of triploid seed in aquaculture would likely decrease the short to medium term spread of *M. gigas* in locations without current established wild *M. gigas* populations. However, areas where such populations exist already are unlikely to benefit from enforced use of triploid stock as a strategy to reduce the potential for spread of *M. gigas*.

## 4. Impacts of Climate and Coastal Change

*M. gigas* is of subtropical origin and the future warming of waters along European and UK coastlines will likely increase the reproductive potential of this species. King et al. (2021) forecast that the majority of the NW European coastal shelf will be within the thermal niche for successful reproduction of *M. gigas* by 2100. This is further supported by modelling approaches using an ensemble of over twenty different climate models that project a substantial increase of recruitment area for *M. gigas* in UK waters (Wilson et al., 2024). Coupled with the species' already widespread distribution and extensive capacity for dispersal via planktonic larvae, it is highly likely that the wild distribution of this species will continue to expand northwards within the coming decades. Arguably, given the distribution already described, and the behaviour and dynamics of this species and its associated ecological communities across European coasts, *M. gigas* is already naturalised in UK waters.

Similar to many other native species, *O. edulis* and *M. edulis* will be challenged by factors arising from climate change including rising sea-surface temperatures, increased heatwave frequency and severity, and altered precipitation patterns resulting in changes in terrestrial run-off and water quality (Eymann et al., 2020; Fly et al., 2015; Oliver et al., 2019; Trenberth, 2011). The ecosystem service provision associated with the extant bivalve assemblage is therefore under threat, particularly in the intertidal. Coastal ecosystems in Europe may, in fact, benefit from the very similar nature of the service provisions associated with the more resilient *M. gigas,* providing a degree of redundancy in what is likely to become an increasingly stressed intertidal system (Ferreira et al., 2008; Hansen et al., 2023; King et al., 2021).

## 5. Discussion and Conclusion

Hobbs et al. (2006) and Truitt et al. (2015) argue that systems in which human-induced changes have altered the natural state should be treated as 'novel' rather than 'inferior', that the changes are often impractical to reverse and that we should *'…accept them for what they are and what benefits they provide…*' (Hobbs et al., 2006). Particularly with contemporary climates in mind, there is a shift in the narrative on how we approach non-native species on a case-by-case basis where some certainly have the potential to deliver more benefits than costs, Lundgren et al. (2024) state that the functional ecology of organisms should be considered as far more important than 'nativeness' when assessing the impact of a species. Our review suggests that *M. gigas* is a suitable candidate for such consideration, and while outlining some research knowledge gaps below, we demonstrate that any of the main concerns can be suitably mitigated.

Research on other non-native species may provide a template for future actions. For example, Zhao et al. (2023) present a case study of *Spartina alterniflora* in China, a non-native cordgrass species which is marked for eradication in the country but provides a range of beneficial ecosystem services. They suggest that the carbon storage and flood prevention capacity of the species, similar to that provided by *M. gigas*, are sufficiently beneficial that it should be allowed to remain in some areas of the foreshore. *Spartina* species in the UK have had similar changes in management. *Spartina anglica*, a species resulting from hybridisation between the non-native and native cordgrass species, has in the past been subject to eradication efforts, with unknown effects on ecosystems. However it is now understood to be a precursor to the return of saltmarsh under certain conditions, and therefore a valuable facilitator species in the restoration of this threatened habitat type (Balke et al., 2012; Lacambra et al., 2004). Likewise, it is conceivable that establishment of *M. gigas* reefs would assist with protection and re-establishment of saltmarsh environments that are desirable for ecological enhancement and coastal defence.

The benefits of a thriving UK aquaculture/mariculture industry for *M. gigas* substantially outweigh the harm that would be caused by attempts to limit the spread of the species through control of the industry, when there is little evidence of its current role in the spread of wild *M. gigas*. From a socio-economic perspective the employment opportunities directly and indirectly supported by oyster production are essential in often deprived coastal areas. Environmentally, the potential benefits of the species are substantial whether that be to see investment of this species as a nature-based solution to coastal defence or in increasing the role of low carbon, low input-cost shellfish protein in the UK diet.

Shellfish aquaculture is a key part of the aims set out in the English Aquaculture Strategy to increase UK domestic production of high quality and sustainable food, and the production of *M. gigas* is recognised as an important driver to achieve this (Huntington and Cappell, 2020). The strategy bases its forecast for the aquaculture sector in England on an assumption that the legislative approach to *M. gigas* production will become more supportive in the near future, realising that eradication is unfeasible and warming waters will encourage the natural spread of the species regardless of the activities of the UK aquaculture industry. In a global context, the recent fifth National Climate Assessment of the US Global Change Research Program (2023) recognises that marine aquaculture may prove a vital part of securing coastal livelihoods in the face of a changing climate.

The current legislative status of *M. gigas* is, however, a major barrier to the success of the industry. When considering other taxa, there has been a clear development of definitions to describe species establishing in the wild that may not have been present before. For example, in birds the British Ornithologists' Union have, in collaboration with UK statutory agencies, developed material to categorise British birds to aid protection with close reference to naturalised species (British Ornithologists' Union, 2022). This system includes a category recognising naturalised species established from translocation(s) that occur in an apparently natural state, e.g. Greylag goose (*Anser anser*). Clearly *M. gigas* populations within the UK are being established from populations in their legally and ecologically naturalised state elsewhere around the coast of the southern North Sea, and as such we suggest that a similar categorisation system would be a useful tool for recognition of the reality of *M. gigas* naturalisation in the UK.

It is likely that even if all UK *M. gigas* producers were to remove their stock overnight, the de-facto naturalisation of the species is sufficiently advanced that the wild and free-living population will continue to spread regardless. There are potential source populations outside of stocks managed for culture along both the UK and mainland European coastlines, where widespread control measures for *M. gigas* are not contemplated. These populations would likely re-seed any suitable areas within a matter of years. Additionally, in areas where *M. gigas* are genuinely problematic, oyster producers are best placed to remove wild populations, given that they have access to, and are skilled in operating, vessels and equipment specifically designed to efficiently remove oysters from the environment. Whilst it may be possible to protect small areas deemed particularly valuable or to remove *M. gigas* where reefs are a nuisance, widespread eradication is simply not feasible. The information presented here supports the view provided by Hansen et al. (2023), who after thoroughly cataloguing the spread, impacts and potential control measures of *M. gigas* concluded that any policy of control or eradication is driven by political and socioeconomic arguments rather than sound ecological evidence.

Our review suggests that the spread of *M. gigas* in UK waters will not have substantial net negative impacts on ecosystems. Further, the proposed limitations on *M. gigas* harvesting and aquaculture operations, and attempts to eradicate wild populations will be ineffective in limiting the spread of a species that has become naturalised. However, there are several substantial knowledge gaps that remain. The rate of spread following known introductions is not fully understood in the context of both the UK coast and forthcoming changes in climate. There is little in the literature about the effect of *M. gigas* on mudflat habitats. The spread of

*M. gigas* into *O. edulis* restoration areas and the impact of this on transmission of pathogens merits further work – the interaction between *M. gigas* and the parasitic and often lethal *Bonamia* spp. in particular is poorly understood (Lynch et al., 2010; Tristan et al., 1995). The potential benefits of *M. gigas* reefs as living breakwaters protecting vulnerable coastlines including saltmarshes could also be substantial, but are yet to be fully explored in Europe.

In conclusion we recommend a re-consideration of the regulatory approach towards Pacific oysters and their aquaculture in UK waters. We are now past the point where effective regulatory intervention that would have an effect on the spread of this species could occur. Current proposals will create a regulatory burden on both the aquaculture sector and regulators but fail to achieve the desired outcome of limiting spread. This same regulatory approach limits any utilisation of the species in providing nature based and hybrid-engineering solutions to contemporary coastal problems associated with climate change – such as sea level rise and erosion, and resilience in the face of increasingly warming coastal seas. With appropriate mitigation methods in place, *Magallana gigas* should be granted a legal naturalised status in the United Kingdom.

## 6. Acknowledgements

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## 7. Data and Code Availability Statement

No data/code are associated with this preprint.

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