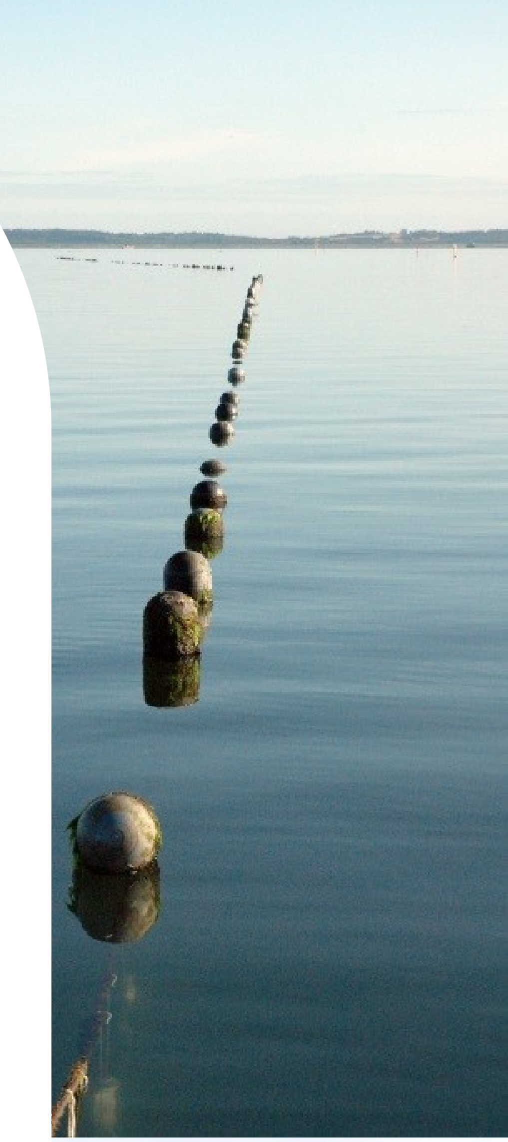
Case study

#5 Mussels in the North Sea

#6 Oysters in the North Sea

#7Mussels at the Atlantic coast



Climate change and European aquatic RESources

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Species background and economics

Of the aquaculture species produced in the EU mussels, both blue mussel (*Mytilus edulis*) and Mediterranean mussel (*Mytilus galloprovinciallis*), ranked first in weight with around 470,000 tons produced in 2014 (Eurostat, 2016) for a value of around €372 million. Within the North Sea area (Denmark, Germany, Netherlands, UK, Norway and Sweden) only *M. edulis* is produced.

In 2013 production was 90,000 tons. Although the production has declined since the 1990s, additional value has been added to the mussel market with the development of organic products and labelling. In 2012, blue mussel represented 8% by weight and 4% by value of the cultivated seafood in Europe (EU Member States DCF data submission, 2014).

Along the North Sea coast, blue mussel is a ubiquitous species in intertidal and subtidal areas. Mussels are commercially fished as adults for human consumption and as juveniles (seeds) for bottom culture (Fig. 1). Mussel seeds are also caught directly on spat collectors for both on-bottom and long-line cultures (Fig. 2).

Blue mussel culture is currently dependent on natural recruitment which, in turn, is influenced by environmental factors such as food supply and water temperature and salinity. Climate change (CC) is expected to affect the health and growth performance of farmed mussels directly via physiological responses, immuno-biological performance and acclimation to the new environmental conditions and indirectly via potential pressure from Harmful Algal Blooms (HABs) and diseases.

The expectation is that the southern boundary where *M. edulis* can be cultured may shift northwards and conditions for the Mediterranean mussel (*Mytilus galloprovinciallis*), a species that occurs but is not abundant in the North Sea area may markedly improve.

Figure 1 Bottom culture – The Netherlands. *Credit: Jacob Capelle, Wageningen Marine Research*

Mussels are not provided food in culture but feed naturally, taking nutrients directly from the water column and do not require feeding, thus production is dependent on the environmental conditions. The main physical factor influencing its distribution is temperature (Seed 1976) which affects the survival and growth of both adults and larvae.

Other external pressures for mussel aquaculture development in the coastal zone include pollution, biotoxins, invasive species, water quality and competition for space with other activities.

Bivalves are sensitive to climate change-induced changes in temperature and salinity which affect behaviour, physiological rates and the immune system (Matozzo and Marin 2011).

Recent mass mortality of blue mussels in Europe is potentially linked to stress from multiple factors (Bechemin et al 2014; Perperzak and Poelman 2008) and could jeopardise the mussel industry.

The goal in CERES is to determine and predict the changes in blue mussel productivity (and resulting socio-economic effects) from direct and indirect effects of climate change on physical, biochemical and biological aspects of the environment.

Figure 2 Longline culture, spat collectors – Denmark. *Credit: Camille Saurel, DTU Aqua*

Scenarios describing future society and economy

CERES uses models to estimate economic developments in Europe’s fishery and aquaculture based on select, pre-defined physical and socio-economical future scenarios.

These future scenarios were specified by industry partners and stakeholders in the first year of CERES (e.g. fish prices, fuel prices, technological advancements, regional policy issues, etc.).

‘World Markets’	‘National enterprise’
• Personal independence, high mobility and consumerism • Reduced taxes, stripped-away regulations • Privatised public services • High fossil fuel dependency • Highly engineered infrastructure and ecosystems	• National isolation and independence • Protection of national industry • High resource intensity and fossil fuel dependency • Low investment in technological development and education • Low priority for environmental protection
‘Global sustainability’	**‘Local stewardship’**
• High priority for welfare and environmental protection • Cooperative local society • Intense international cooperation • Increased income equality • Low resource intensity and fossil fuel dependency	• Promotion of small scale and regional economy • Less attention for global (environmental) problems • Moderate population growth • Income of industrialised and developing countries converge • No overarching strategy to manage ecosystems

Table 1 Outline of the four social-political scenarios developed by CERES partners and stakeholders

Expected projections under climate change

The North Sea shows a temperature increase by 2°C in 2080-2099 under RCP 8.5 (Fig. 3). For local changes in near shore mussel culture areas such as Oosterschelde and Limfjorden (circles in figure 3) models with a higher spatial resolution are used as input for the biological modelling.

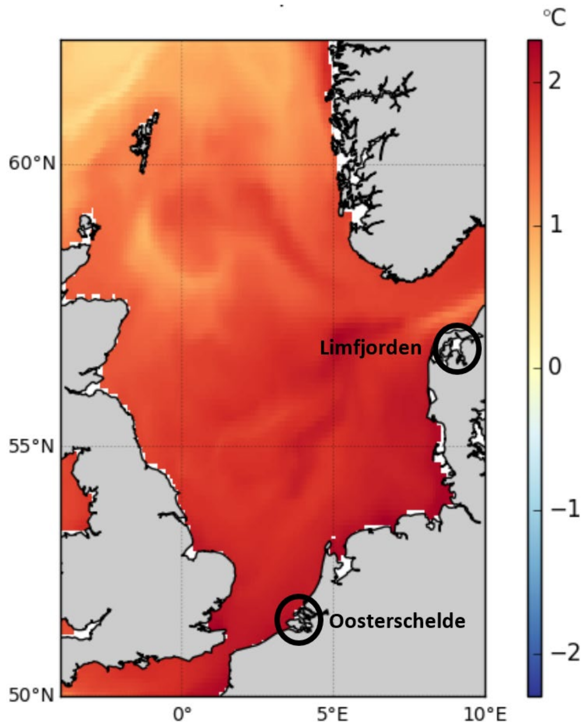


Figure 3 Difference in bottom temperature for North Sea, 2080-2099 compared to 2000-2019, RCP 8.5

Socio-economic effects The Dutch government has developed four future scenarios for the marine spatial planning in figure 3.

The scenarios show strong overlap with the four CERES scenarios:

Slowly forward = National Enterprise [RCP 8.5, SSP3]

Pragmatic sustainable = Local Stewardship [RCP 6.0, SSP2]

Fast forward = World Markets [RCP 8.5, SSP5]

Together sustainable = Global Sustainability [RCP 4.5, SSP1]

Depending on the scenario a decline or strong increase in aquaculture activities is foreseen.

Developments such as building of large-scale off-shore wind farms can create multi-use opportunities for shellfish farmers. However, this requires large investments and confidence that the market will expand instead of shift from near-shore to off-shore.

In addition, there was also concern about areas claimed by wind farms and nature conservation. Increased sand extraction for coastal defence can affect the shellfish industry. Suspended matter concentrations may temporarily increase to undesired levels for shellfish farming.

Another core issue to the sector is the occurrence of toxic algal blooms that intensify in warm water, which can have dramatic impacts on the sector. Predictive models can help with that.

In addition, stakeholders are interested in opportunities for new species, cost-efficient technological innovation (off shore, multiuse, predator control) and opportunities for the market (adaptation marketing strategies).

In Denmark, the climate change strategy uses scenarios based on IPCC SRES, A2 and B2 with projections on flooding, erosion along the coasts, extreme rainfall, and a rising sea level based on RCP2.6, RCP4.5 and RCP8.5.

In 2012, an 'Action Plan for Climate Protection of Denmark' was launched. There are thirteen key priority sectors studied for climate change impacts and development. Amongst them, fishery and aquaculture.

Most of the foreseen impacts of climate change toward fish aquaculture have been identified as the possibility to breed new fish species such as seabream and seabass in warmer seawater temperature, potential need of more fish medication, a combination of offshore aquaculture and land-based recirculation systems (RAS) to palliate the high temperature variation with seasons.

Regarding shellfish aquaculture, which is currently developing in Denmark, indirect impacts such as oxygen depletion, and potential threats such as competitive invasive species (e.g. Pacific oyster), toxic algal bloom and acidification have been identified.

Overall, there is a strong governmental incentive to development and innovation in the blue growth economy and, similarly to the Netherlands, emphasis on an increase development of aquaculture toward the off-shore areas.

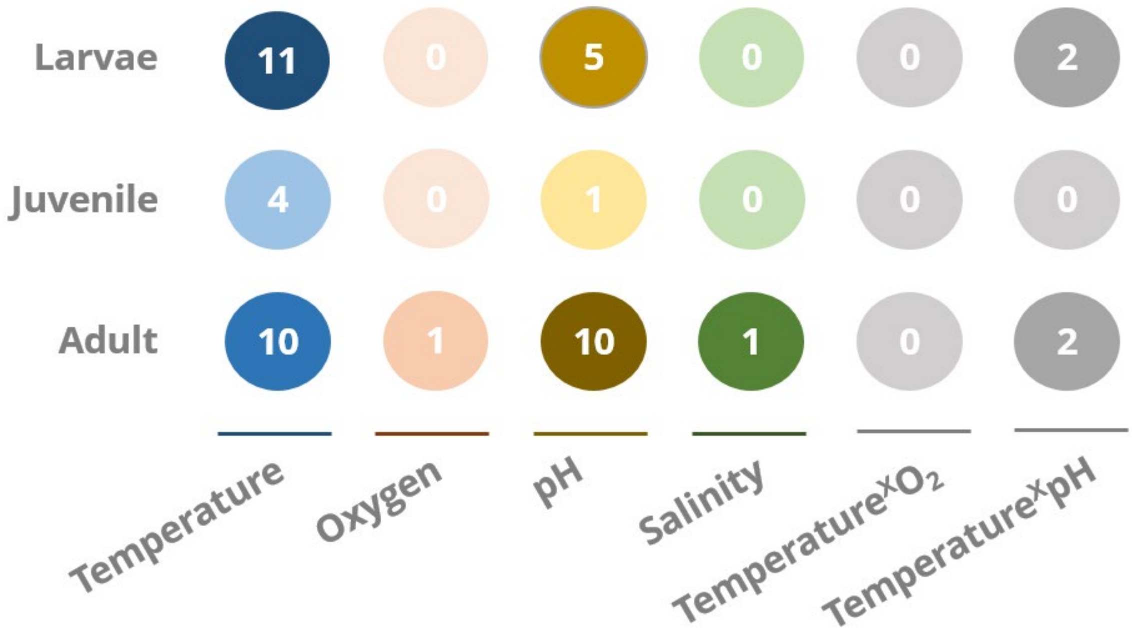
In connection with the EU's current European Maritime and Fisheries Fund programme, the Danish government launched an aquaculture strategy focusing on development of the primary sector including using mussel farming as a mitigation tool for nutrient extraction e.g. in relation to off-coast finfish farming.

Key research needs

It is unknown how extreme temperatures and hypoxia (low oxygen conditions) will influence the feeding and growth of blue mussels and, despite some previous studies, new experiments are needed to improve production models to make projections of climate impacts.

Other experiments are needed to assess how climate-driven changes in indirect factors such as the amounts of food including toxic algae will impact mussel productivity and mortality.

Regarding indirect pressures from HABs and pathogens, early warning techniques are not yet developed for the culture areas in Denmark and the Netherlands to take preventive actions to protect cultured mussels.



- Mytilus spp., comprising two species, ranked 3 out of 28 European fish and shellfish genera reviewed here (20 studies).
- 14 studies were found in the North Sea area. Further data is found in SL 7 and 10, further European areas (2) and outside Europe (8).
- Studies on Mytilus spp. were equally found in countries adjacent to the North Sea and Spain.
- The majority of studies focused on adults and studied pH and temperature
- The most common response studied was growth, followed by mortality and physiology

CERES research

- Performed a literature review to assess knowledge gaps on the direct effects of climate on blue mussels.
- Conducted 'common-garden' experiments (a collaboration among four CERES partner institutions) to determine climate change (CC) effects (temperature x feeding level x oxygen) on functional response (feeding rate versus food concentration) curves. Additional experiments examined the effects of temperature and salinity on the expression of the toxic substance Tetrodotoxin (TTX) in mussels and the marine environment.
- Calibrated a growth model for blue mussels using these new laboratory data and used the model make projections of changes in productivity under various CC scenarios. The individual growth models were incorporated into the local-scale Farm Aquaculture Resource Management (FARM) model to examine direct climate-driven responses on harvest and environmental effects of culture at the farm scale, using a layout which reflects typical culture practices for *M. edulis* in northern Europe.
- Created 'virtual farms' for bio-economic projections of CC impacts using stakeholder information and 2016 DCF data for the farms in the Netherlands, UK and Denmark and projected the impacts of CC on profits of different types of farms.
- Ranked the vulnerability of mussels to CC in relation to other, major European aquaculture target species.

- Engaged with external stakeholders (mussel farmers and policy makers) through a meeting in which socio-economic developments were discussed, a questionnaire in which information was gathered for a bow-tie analysis and a final meeting in which results were presented and discussed.

Results

Biological

Multi-stressor experiments (temperature x food concentration x oxygen saturation) examined the physiological response of similar-sized (2-3cm) mussels from different origins (*M. edulis* from the Netherlands, *M. edulis* from Denmark and *M. galloprovincialis* from Portugal).

Figure 4 Set up of experiment to study combined effect of food concentration and temperature – Netherlands. *Credit: Pauline Kamermans, Wageningen Marine Research*

Mussels were exposed to six temperatures (3, 8, 15, 20, 25 and 30 °C) at each of two feeding levels (2 and 10 µg Chl a L^{-1}) for six weeks (Fig. 4). A second experiment focused on physiological responses and growth rates of blue mussels from the Netherlands and Denmark to three different temperatures (15, 20 and 25°C), three different oxygen saturation (30%, 50% and 100%) and two feeding levels (2 and > 8 µg Chl *a* L^{-1}) for 3-4 weeks.

The growth performance, survival and physiology (clearance rate and oxygen consumption rate) were monitored weekly and the results were supplied to modellers for calibration of the growth model in shellfish aquaculture.

Temperature and food had a significant effect on i) growth with higher optimal temperatures for growth at high food conditions, and ii) clearance rate with lower clearance at high food conditions and increased clearance rates with increased temperature at high food and iii) oxygen consumption with increased oxygen consumption with increasing temperature. Clearance rates were significantly reduced at low oxygen concentration and together with high temperature.

The clearance rates of Danish and Dutch mussels responded in a similar way to differences in temperature, food and oxygen concentration; however, the Dutch mussels had a significantly lower growth rate than the Danish mussel for the size class 2-3cm.

Indirect effects

Followed by reports from the UK and Greece, a new toxin was discovered in shellfish in 2015 in the Netherlands, Tetrodotoxin (TTX). When consumed in large quantities TTX can be harmful to humans.

As the first in Europe, the Dutch authorities developed and implemented a maximum level for TTX in shellfish in 2016. TTX occurs every year for a few weeks in the period

June-July in the beginning of the mussel harvesting season.

When monitoring programs reveal exceedance of the maximum values, the harvest is closed until the levels are below the standard again. When the shellfish are kept in clean water (depuration), the toxin is excreted again. Detoxification periods still need to be established (1-several days).

We investigated the effects of salinity and temperature on the potential to trigger TTX production in different environmental samples, sediment, raw sea water and filtered (10-50um) seawater.

These experiments did not demonstrate any direct effects of salinity and temperature. However, new insights showed that the causative organism (to be published soon) is present at relatively low concentrations.

This formed the basis for analysis of water quality parameters in the affected area in the Oosterschelde, which resulted in a likely temperature related trigger of the causative organism to produce or release TTX.

Based on the two-year data set the temperature-sum may be a key indicator, which in turn may be effected by climate change in the future.

Predicted impact of climate-driven changes on blue mussel productivity

Direct effects of CC

The Netherlands and Denmark use different cultivation methods: intertidal bottom culture in the Netherlands and suspended culture in Denmark.

The cultivation period in the Netherlands doubles the Danish one (794 instead of 365 days) while the farm area in Denmark doubles the Dutch one (16.3 vs. 8 ha). Stocking densities are much greater in the Netherlands (5,000 vs. 300 ind. m^{-2}), leading to higher mortalities (98% vs 40% $cycle^{-1}$), specially at the seed stage.

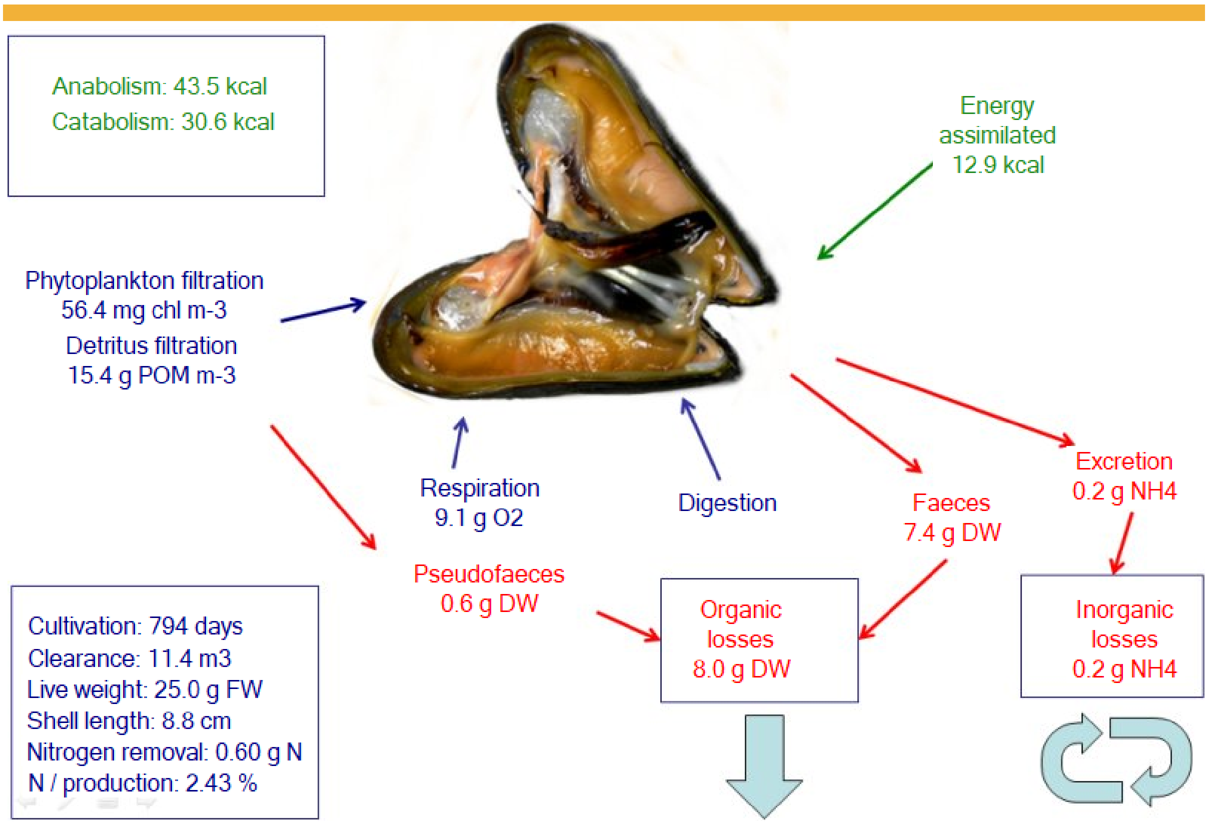


Figure 5 Mass balance results for an individual blue mussel over a full growth cycle at the Oosterschelde farm. DW (FW): dry (fresh) weight.

We have studied the performance of two typical blue mussel farms, one in the Oosterschelde in the Netherlands (Figure 5) and one in Limfjorden Denmark in present (2000-2019), near-future (2040-2059), and far-future (2080-2099) conditions under two emission scenarios: RCP 4.5 –more conservative, and RCP 8.5 –more severe.

On average, mussels in the Netherlands grow bigger under RCP 4.5 than under 8.5, although if we consider the whole range of values there are no statistical differences between the low and the high emission scenarios for Dutch mussels (Figure 6A). Food depletion and farm yield follow the same pattern (Figure 6B and C).

In general, average harvest size and production values decrease in the far-future for both emission scenarios; except for average harvest weight, which only presents lower values in the far-future under the low-emission scenario (Figure 6A and B).

The DO depletion is greater in the high-emission scenario, especially in the far-future where we observe much greater metabolic energy expenditure (Figure 6D).

On average, mussels in the Limfjorden grow bigger under the low-emission scenario, although if we consider the whole range of values there are no statistical differences between the low and the high emission scenarios for Danish mussels (Figure 7A).

Farm yield follow the same pattern and the farmer would obtain on average greater production under RCP 4.5 (Figure 7B). The general trend for average harvest size and production values is to decrease in the far-future especially in the high emission scenario (Figure 7A and B).

Food depletion is greater in the low-emission scenario (Figure 7C).

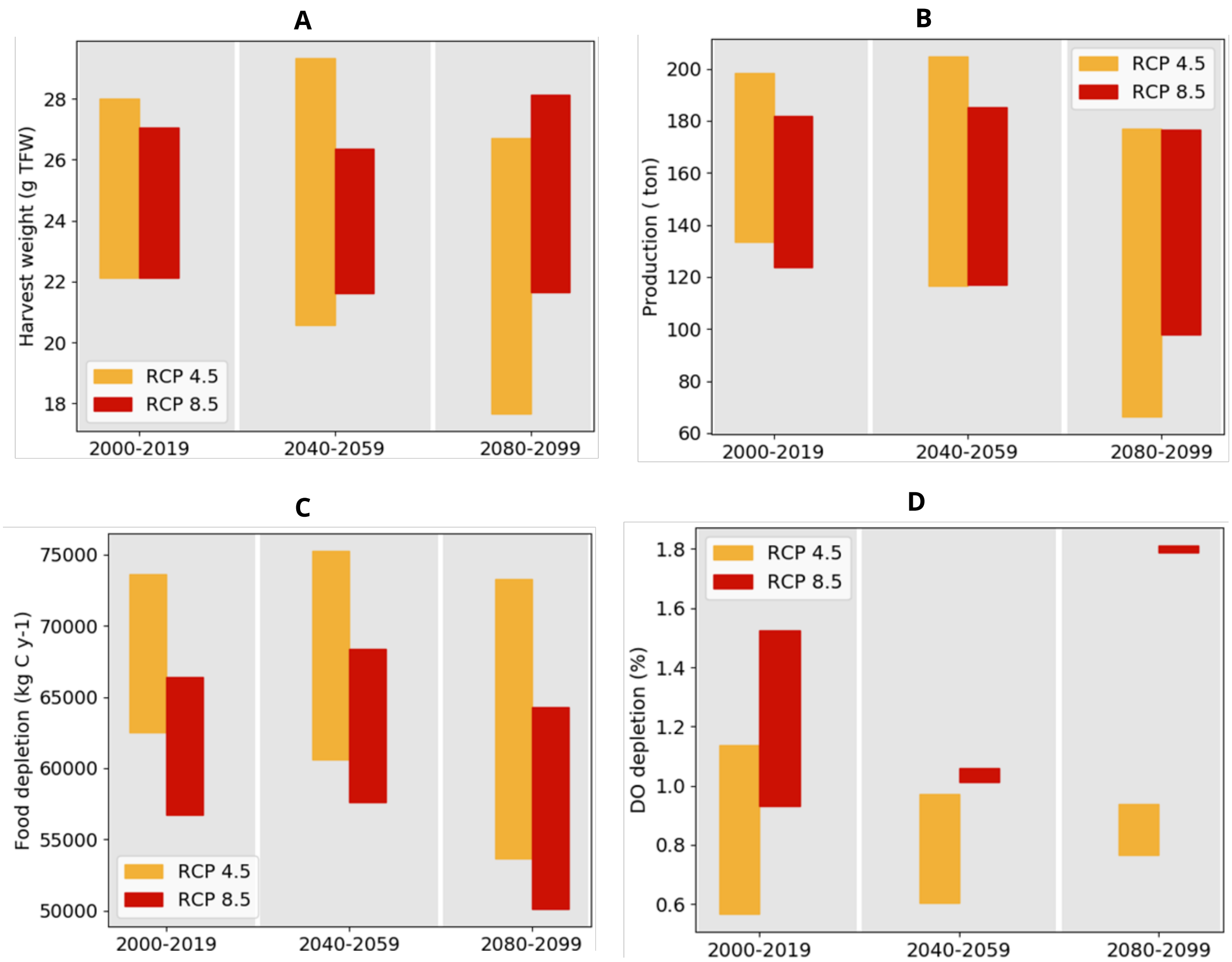


Figure 6 Range of FARM outputs for the typical blue mussel farm in the North Sea (Oosterschelde, Netherlands) under the different climate change scenarios. Green and red bars represent the range (spread) of simulation values for the low- and the high- emission scenario, respectively. FW: live weight; DO: dissolved oxygen.

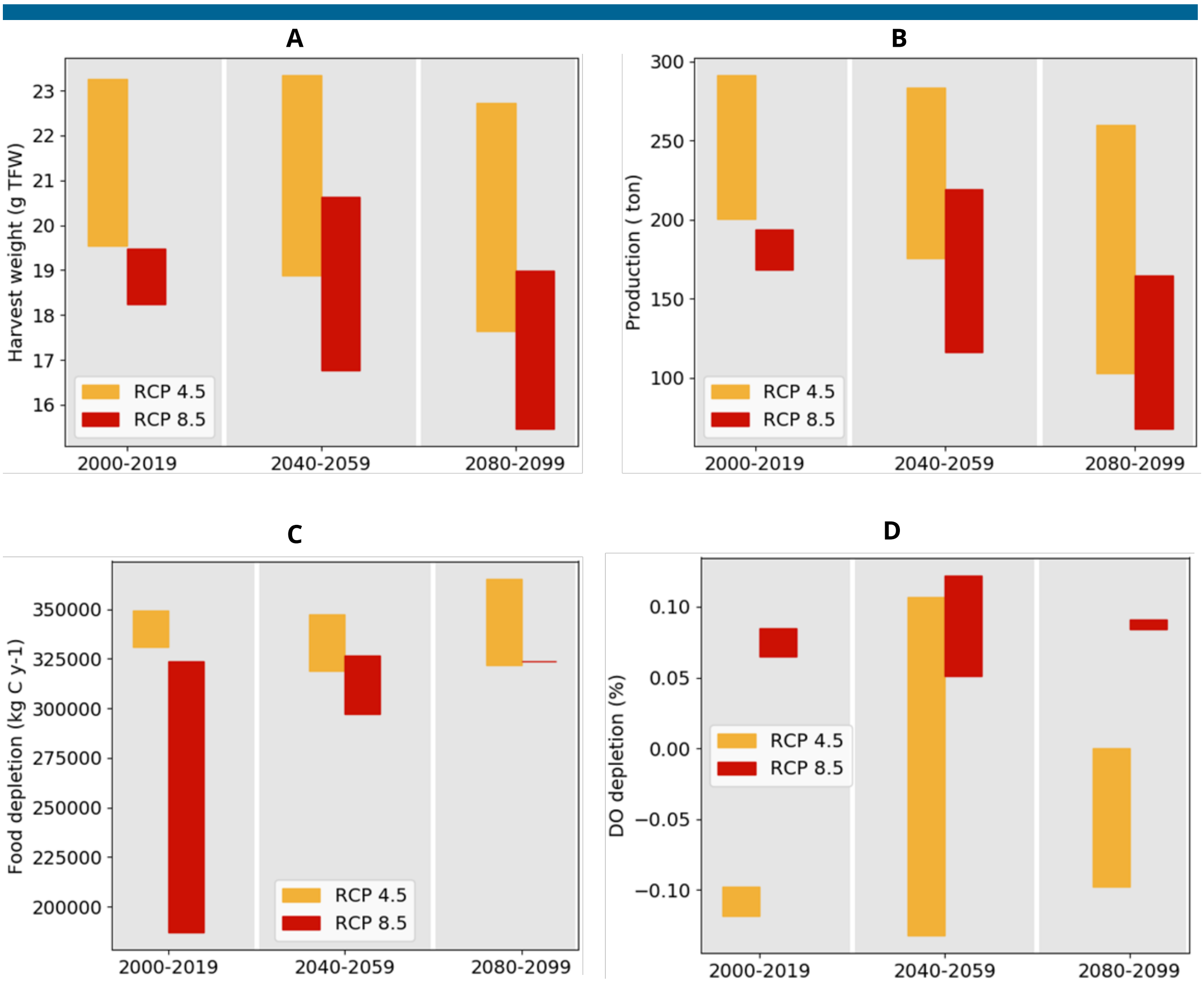


Figure 7 Range of FARM outputs for the typical blue mussel farm in the North Sea (Limfjorden, Denmark) under the different climate change scenarios. Green and red bars represent the range (spread) of simulation values for the low- and the high- emission scenario, respectively. FW: live weight; DO: dissolved oxygen.

Economic consequences

To represent the mussel sector in the North Sea region, individual model farms were defined by experts within the consortium and based on individual farm economic data of the whole national sector and most important production regions for Denmark (Limjorden) and the Netherlands (Oosterschelde). The results from the biological production models were considered within the relative change in operative earnings for the whole farm as here also changed returns relative to production volume changes are considered.

Typically labour, ship maintenance, and fuel costs are most important cost factors, but these differ between production systems and countries (Table 1).

The highest cost for both farms is seed collection, making up around a third of overall cash costs.

Market returns are mostly between €1-€2/kg and, based on the data up to 2014, the North Sea sector is overall profitable, although some unprofitable farms do exist (2014 DCF data Netherlands and Denmark, communication C. Saurel for Danish sector). Future profitability is calculated by taking into account total harvestable biomass under RCP 4.5/8.5 environmental conditions from physiological models as well as projections of future energy prices (fuel, electricity) and mussel prices under the CERES scenarios from the external MAGNET model.

DK-MUS-900	2016
Operating earnings (€/kg)	0.61
Most prominent costs in % from operational costs	
Seed allocated costs	30.10
Labour grow-out	30.10
Other variable costs	16.70
Minor equipment	11.67
Maintenance machinery	3.93

NL-MUS-1090	2015
Operating earnings (€/kg)	0.27
Most prominent costs in % from operational costs	
Labour grow-out	25.14
Seed allocated costs	18.56
Maintenance machinery	16.66
Sea area use	14.75
Diesel for vehicles	7.70

Table 1 Present operating earnings and most prominent costs in percent from overall operational costs for the two model mussel farm analysed in CERES

Figure 8 and 9 are displaying the stacked cash costs and returns for the current year (2016 DK and 2015 NL) and profitability changes under the four CERES scenarios based on cost/return and the harvest weight changes range of best and worst production years in the year 2050 including potential future price variation.

Based on the present operative earnings, which are illustrated in the difference between the red dot for returns and the stacked costs in Fig. 8 and 9 and listed in Table 1, the capacity of the Danish farm to buffer future increased costs or variations in harvest weight is about twice as high as for the Dutch farm.

When considering only future energy and mussel price trends the Danish farm shows increased profits under all scenarios except for GS, where a slight decrease in profits is observed. The Dutch farm, however, shows a loss of in operating earnings under both RCP 8.5 scenarios WM (-8.9%) and GS (-57.5%) based on future price trends.

This picture changes significantly when taking future harvest weight developments into account as displayed in Figure 8 and 9. Both farms show most favourable future profits in best production years under the LS scenario and the patterns under the remaining scenarios are similar as well.

Mussel production is less profitable than today under all worst production year scenarios and thereby most pronounced under WM (up to -70% operating earnings) in DK-MUS-900 (Fig. 8) and under GS (up to -150% operating earnings) in NL-MUS-1090 (Fig. 9).

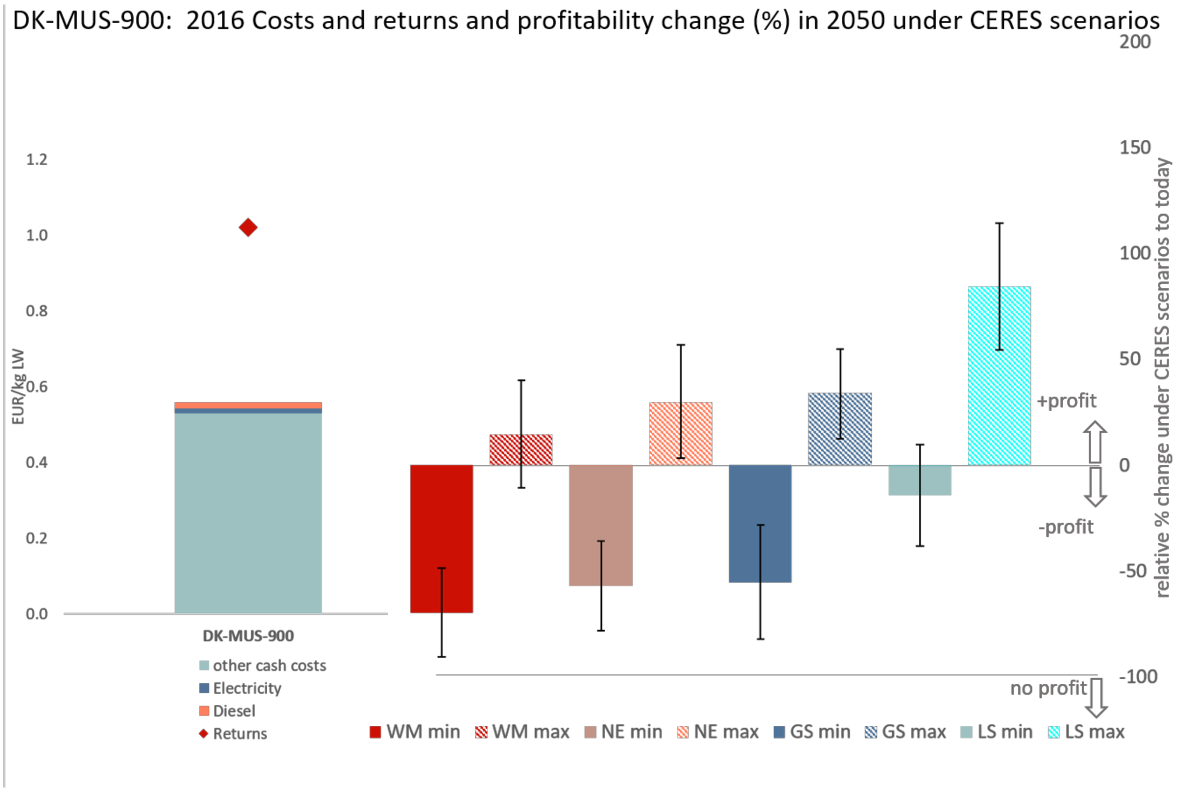


Figure 8 Stacked plot of cost and returns of a typical Danish blue mussel farm (DK-MUS-900) in 2016 (left) and relative changes in profitability (returns against costs in the year 2050 under the CERES scenarios WM (World Markets), National Enterprise (NE), GS (Global Sustainability), Local Stewardship (LS) compared to today (right). 'min' and 'max' refer to the best and worst production years from the biological model. Error bars indicate 95% upper and lower probability ranges from Monte Carlo simulation results. Grey lines indicate higher or lower probability compared to 2016.

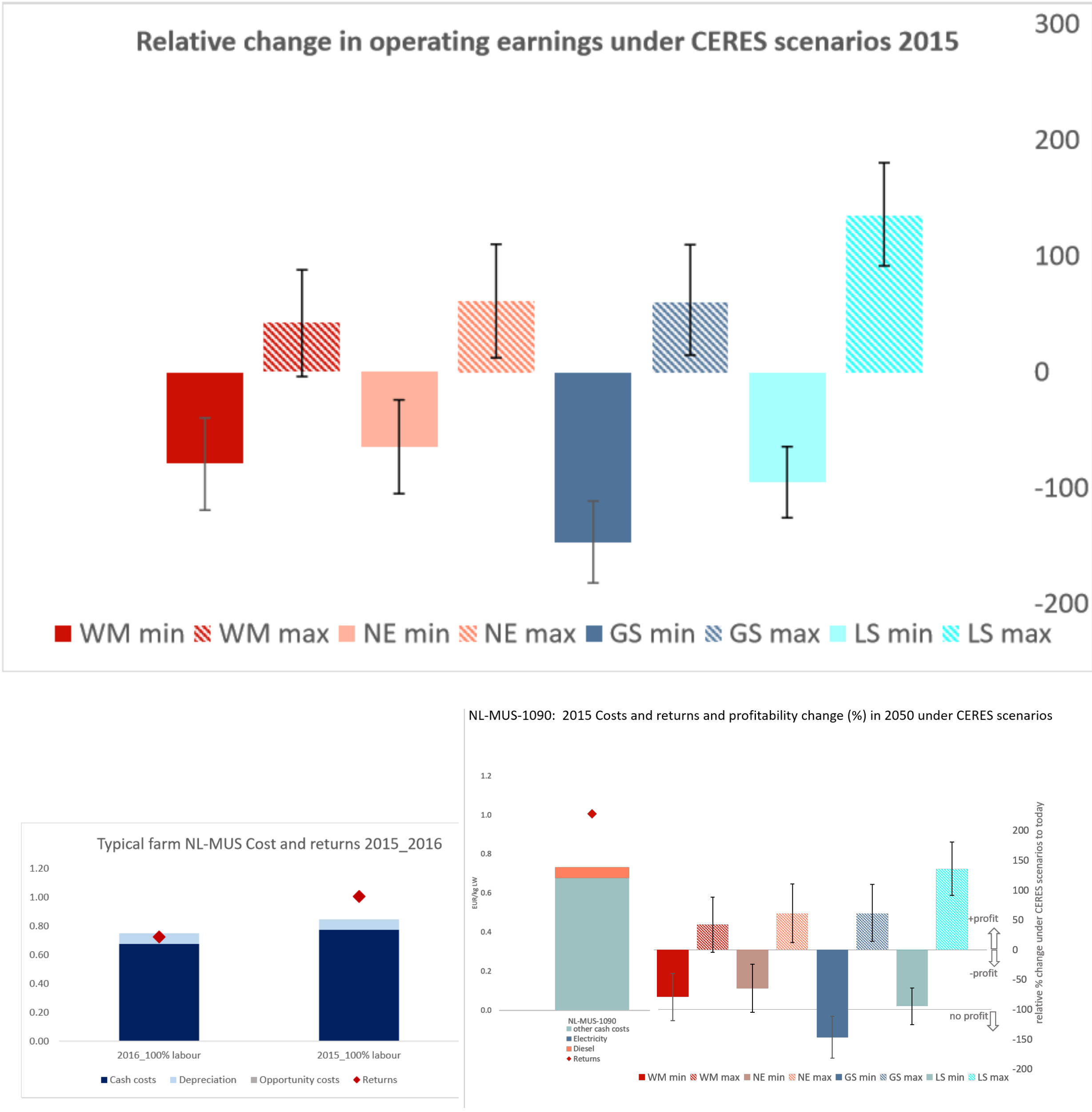


Figure 9 Stacked plot and returns of a model Dutch blue mussel farm (NL-MUS-1118) in 2016 (left) and relative changes in profitability (returns against costs) in the year 2050 under the CERES scenarios WM (World Markets), National Enterprise (NE), GS (Global Sustainability), Local Stewardship (LS) compared to today (right). ‘min’ and ‘max’ refer to the best and worst production years from the biological model. Error bars indicate 95% upper and lower probability ranges from Monte Carlo simulation results. Grey lines indicate higher or lower probability compared to 2015.

Climate vulnerability

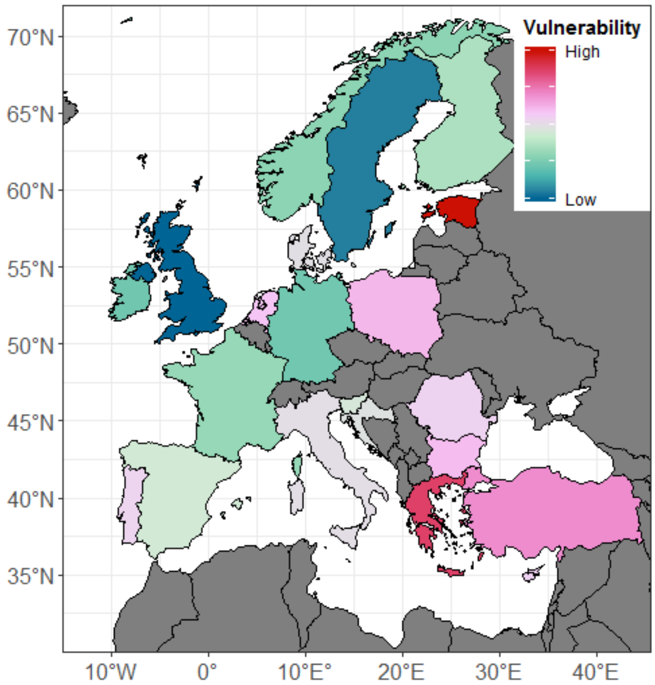


Figure 6 Climate vulnerability assessment for Europe. Colour scale is linear in the value of the corresponding score, but is presented without values, as they have little direct meaning. *Picture credit: Myron Peck*

A climate vulnerability assessment (CVA) was conducted on the European aquaculture sector using the FAO model of Exposure + Sensitivity + Adaptive Capacity.

The CVA included the physiological and farming methods of seven species (Atlantic salmon, sea bass, sea bream, trout, carp, mussels, oysters and clams) representing > 95% of the value for the region.

Based on available economic data, the vulnerability of 22 countries – the top producers in the Europe28 as well as Norway and Turkey – was ranked and relative values are shown (right). By 2050 in RCP8.5, warming caused little change in the suitability of culture conditions for most species in most regions, including mussels in the North Sea. Direct effects of warming were small.

Farming mussels is inherently vulnerable due to the lack of control of the production cycle and the fact that most firms are relatively small with low adaptive capacity. Most countries in the southern North Sea have made good progress implementing climate adaptation plans and have relatively strong national economies.

Climate-ready solutions

For bottom-up - mitigation measures

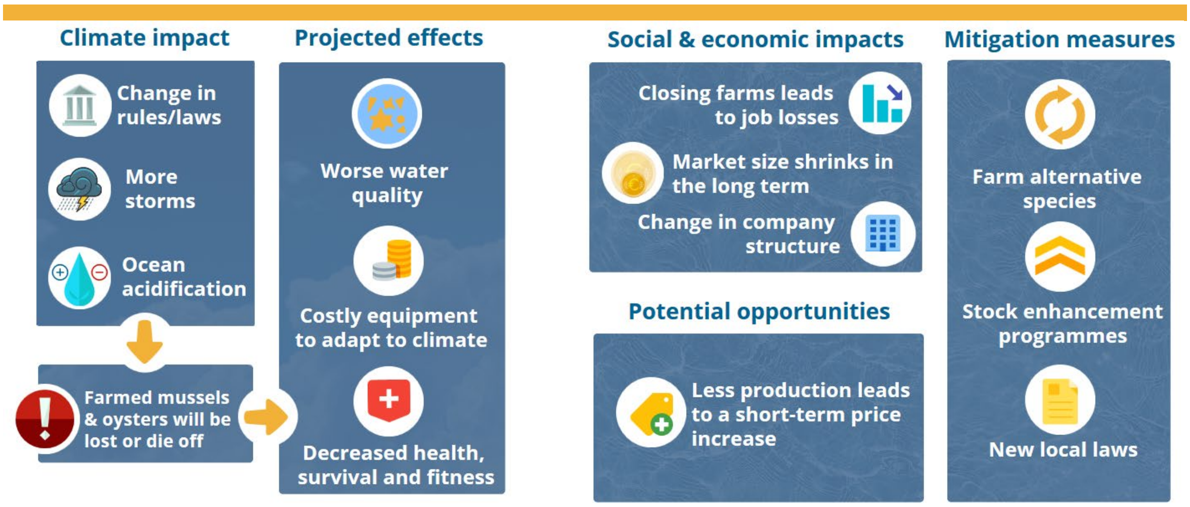


Figure 10 Summary BowTie analysis based on stakeholder feedback. Full bowtie available http://bit.ly/CERESbowtie56

Policy recommendations

Dutch shellfish farmers have shown to be flexible to changes in their harvest. After the severe winter in 1963 killed almost all European flat oysters the farmers switched to a different oyster species. To ensure this flexibility in the future and prepare for climate change, room for experimentation is desired.

It is important that national policy facilitates experimentation with new techniques through providing licences and space for these activities.

E.g. investment in off-shore production is only feasible when the farmers are allowed to experiment for many years and, when successful, can remain on that location to earn back the investment.

To counteract economic consequences of climate-change related shifts in growth and mortality Dutch shellfish farmers should focus more on quality of the product and less on bulk production.

Since the Netherlands' climate adaptation plans are mainly about security against flooding the sector should develop a plan for climate adaptation in the future.

Further reading

CERES publications

Soma K, SWK van den Burg, et al. 2018. Social innovation–A future pathway for Blue growth?, Marine Policy 87, 363-370.

Soma K, SWK van den Burg, et al. 2019. Assessing social innovation across offshore sectors in the Dutch North Sea, Ocean & Coastal Management 167, 42-51.