CERES

Case study

#9 Mussels in the Mediterranean

#10 Salmon in the north-east Atlantic

#11 Meagre at the Atlantic coast

Species background and economics

Along the Mediterranean coast of Spain, bivalves are mainly cultured in the Fangar and Alfacs Bays in the Ebro Delta, with areas 12 km^2 and 50 km^2 respectively.

These shallow, semi-enclosed bays have a wide annual range of temperatures (from 6 to 31°C), salinities (between 13 and 37 psu) and total particulate matter (between 2.70 and 14.95 mg L^{-1}) (Ramón et al 2007).

Mussels (*Mytilus galloprovincialis*) are cultured using rafts that occupy 1.8% and 6.5% of the total surface area of Alfacs and Fangar Bays, respectively. Mussel seed is collected naturally using ropes hung from the rafts and mussels grow to commercial size within 18 months.

In Catalonia, mollusk aquaculture represents 54% of the total aquaculture production and the culture of Mediterranean mussel represents 95% of all mollusk aquaculture. Historically, mussel production has been between 3000 to 4000 t per year.

In 2018, 3443 tonnes of mussels were produced with an economic value of €4.5 million.

In the Ebro Delta, mussel aquaculture is responsible for ~1000 jobs (300 direct, 700 indirect), with an economic impact of €7 million per year.

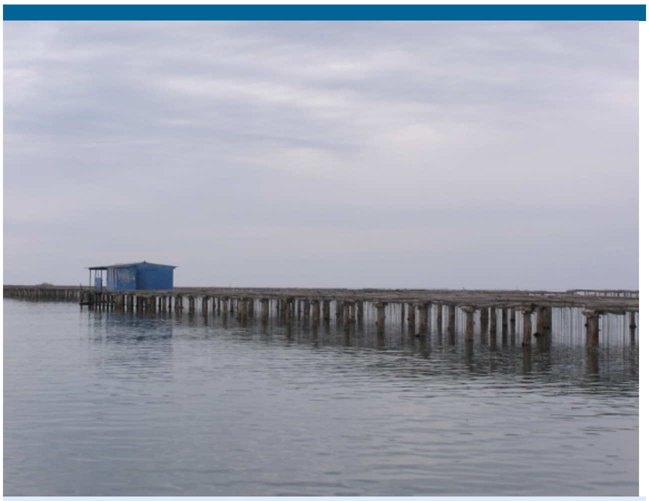


Fig.1. Mussel raft in the Ebro delta (by M. Ramón)

Several consecutive, very warm days during summer have caused partial or total mortality of mussel seed.

Seed must then be imported from Italy, France and other areas to continue the culture cycle. These die-offs have cost the industry more than €1.8 million.

Considering the importance of bivalve aquaculture and artisanal fisheries in the Ebro Delta region, if the frequency of heatwaves increases in the future, there is a potential for strong, negative socioeconomic impacts of climate change.

Expected projections under climate change

The Mediterranean Sea has been considered a 'hotspot' for climate change (Diffenbaugh et al. 2007).

According to Rosa et al. (2012), the following trends are expected in the Mediterranean basin during the 21st century: an increase in air temperatures between 2.2 and 5.1°C, a decrease in rainfall between 4 and 27%, sea level rise of about 35cm, and longer periods of drought related to an increased frequency of days with temperatures above 30°C.

The Mediterranean Sea is also becoming saltier (Borghini et al., 2014) and more acidic (Calvo et al., 2011; Kapsenberg et al., 2017).

Based on projections of climate impacts made in CERES, mean Sea Surface Temperature (SST) is projected to increase up to 2.5°C in 2080-2099 under the business-as-usual (RCP 8.5) scenario.

At the end of the century, peak increases in temperature will occur during the hottest months, in August and September, with differences of almost 4°C by the end of the century under RCP 8.

Shallow coastal sites such as the Ebro Delta exhibit greater daily and seasonal differences in temperature and salinity than deeper, offshore areas (Fig. 2).

In the Ebro Delta, the aquaculture industry already is under a growing threat from increased summer heat waves (Rodrigues et al., 2015).

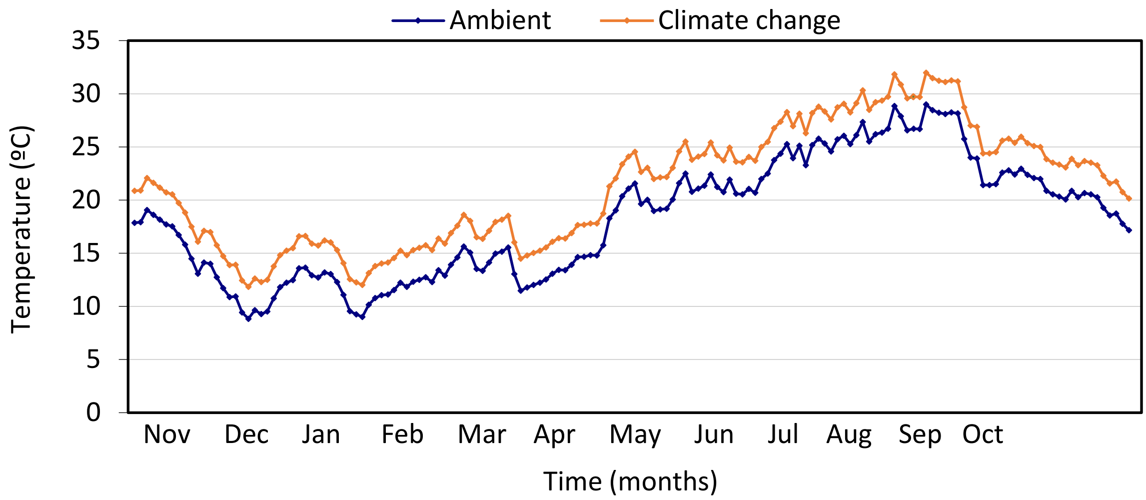


Fig. 2: representative graph with yearly ambient SST temperatures in Alfacs Bay (Ebro Delta) and those expected in RCP 8.5 scenario.

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

Socio-economic effects

Climate change will have several socio economic effects, as discussed with stakeholders.

The water temperature increase, and reductions in rainfall and river flow will cause seasonal changes in the life cycle of mussels.

Moreover, mussel cultures will likely be under increased threat from invasive species, such as the blue crab (*Callinectes sapidus*), and more active predation from native fish already observed in recent years.

In the long term under a high "Business as Usual" RCP 8.5 scenario, these effects will worsen and the culture cycle of the mussels will be shorter.

Direct effects of climate change are expected such as reduced survival due to extreme temperatures in summer.

Therefore, jobs will be seasonal with much higher unemployment in the summer period.

The cost of mussels will increase because seed will have to be purchased and maintenance costs will increase (i.e. finding and deploying management plans to prevent predation from both local and invasive species, cleaning mussels from extra fouling, etc.).

The quality of the product will also worsen if mussels need to be collected at smaller sizes.

Key research needs

Climate change is projected to cause temperatures, salinities and values of pH to exceed values previously observed and it is unknown whether these new, unique combinations of environmental factors will have simple (additive) or interactive (synergistic or antagonistic) effects on cultured fish and shellfish.

Of primary concern to organisms that build calcareous shells is the ongoing acidification (e.g. decrease of pH by 0.3 units by 2100; IPCC 2019) of ocean habitats. Declines in pH can negatively influence the survival and growth of mussels and other organisms that build calcareous shells.

It is unknown whether decreased pH will increase the sensitivity of mussels to warm temperatures.

Recent work on *Mytilus galloprovincialis* documented warm thresholds for survival (100% mortality at 25°C) and potential interaction between temperature and pH (mussels at low pH and warm summer temperatures grew less) (Gazeau et al. 2014).

These findings agree with recent reviews of the increased sensitivity of bivalves and other organisms to the combined effects of temperature and pH (Rodolfo-Metalpa et al. 2011).

Work in CERES was designed to better understand the potential risks and impacts of heatwaves in combination with ocean acidification on mussel production in the Ebro Delta during different stages of the culture cycle.

A key gap in knowledge is how the effects of climate-driven changes in key factors will impact mussels throughout the seasonal culture cycle.

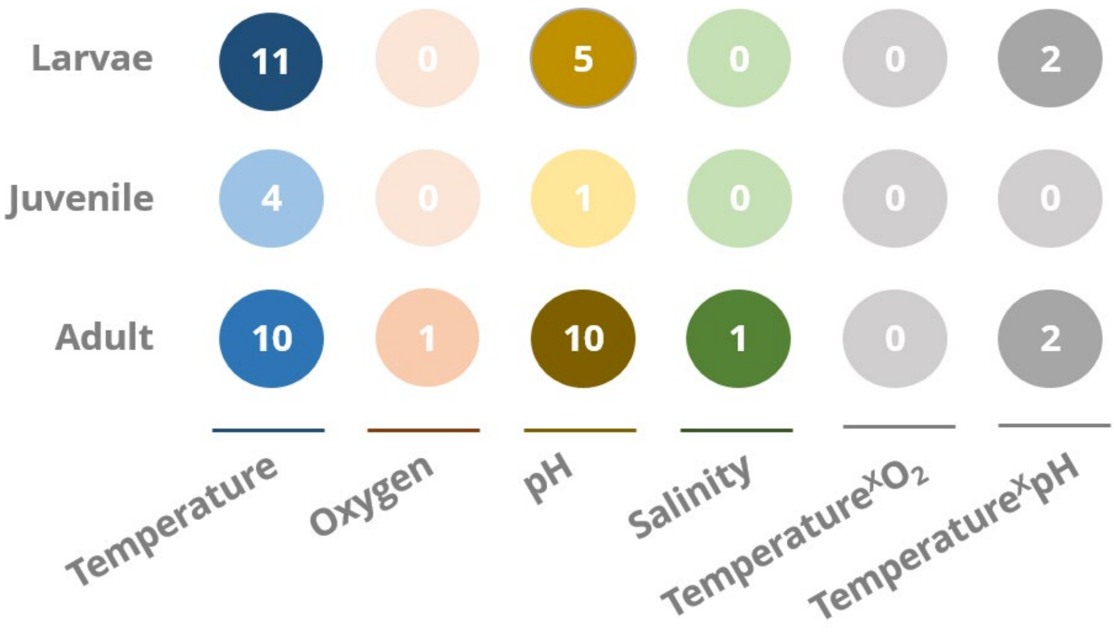
CERES research

- Compiled physiological and population-based information relating potential climate change effects (temperature, acidification, etc.) as part of a gap and meta-analysis of commercially important fish and shellfish in European waters.

- Repeatedly conducted seasonal experiments in spring, summer, and autumn 2018 and winter 2019 examining seasonal differences in the growth physiology and stress response of Mediterranean mussels to warming (ambient and +3°C) and acidification (pH 8.1, 7.7 and 7.3). To gain a cause-and-effect understanding of direct climate change impacts, key aspects were studied including mussel growth, mortality, feeding behavior, immunology, tolerance to desiccation and histopathology.

- Engaged stakeholders including local mussel farmers to explain the goals of CERES and to co-develop social-ecological research on climate change issues (including a risk mapping using a BowTie diagram).

Results



- *Mytilus* spp. ranked 3 out of 28 European fish and shellfish genera reviewed here (20 studies).
- Only 3 studies were found for Mytilus (galloprovincialis) in the Mediterranean.
- Temperature and pH effects were studied
- The only response variable studied was growth

Biological

As expected, the responses of mussels changed markedly at different stages of the culture cycle in different seasons.

In Autumn, mussels were beginning a new reproductive cycle and were developing their gonads.

At that time, mussels feeding rates were particularly high at the highest temperature.

However, higher temperatures and acidic waters influenced the impaired immune system of mussels.

Specifically, the immune cells of mussels in warm treatment groups switched from engulfing whole cells destroying potential harmful particles (phagocytosis) to producing an excess of oxygen to break and destroy health threats (Reactive Oxygen Species production).

In order to compensate, 60% of the mussels had gonadal degradation, a process that redirects energy from reproduction to immune defense to improve mussel health.

In winter, when mussels were ripe, increased temperature and decreased pH had no effect on their feeding.

However, a lower pH had the same effect as in autumn, with 45% of the mussels showing gonadal degradation (Fig 3).

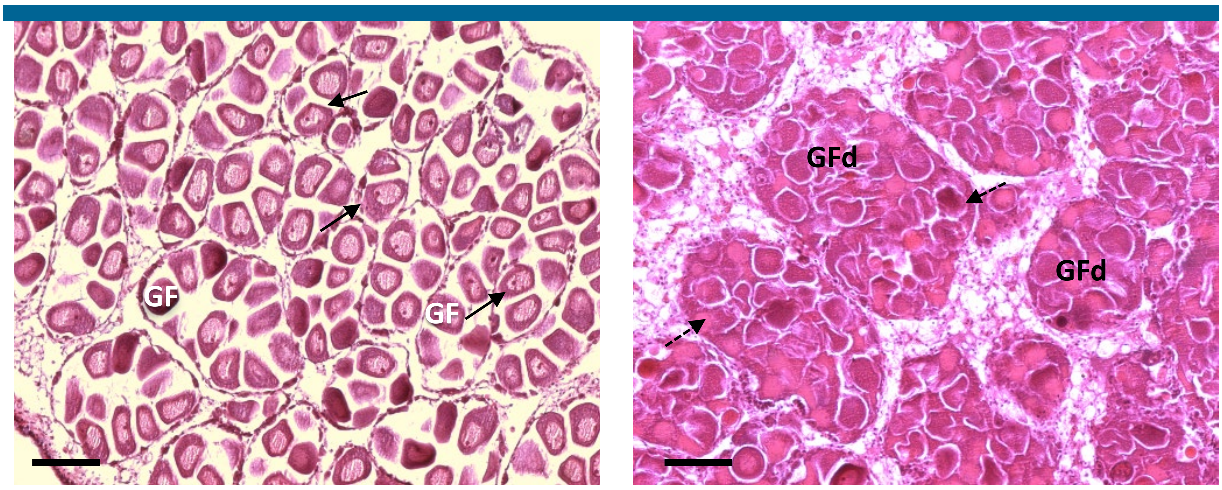


Fig 3: Microscopy images of female gonadal tissue. Left: ripe gonad. Right: degraded gonad. GF: gonadal follicle containing mature oocytes (some examples are shown with solid arrows); GFd: degraded gonadal follicle, dotted arrows indicate degraded oocytes. Scale bar 100 µm.

Winter is a very important season for mussels in the Ebro Delta because this is when spawning takes place.

Temperature plays a very important role reproduction as colder water seems to trigger the release of gametes.

After a first, massive spawn in February-March, mussels restore their gonads and keep spawning until early May.

As expected, because mussels are very sensitive to temperature at this time of year, the increased temperature predicted for future climate affected the physiology and immunology of the bivalves.

First, their feeding was inhibited at higher temperatures, showing clearance decrease (less water circulating through their gills) and a lower efficiently absorbing their food (Fig. 4A).

Moreover, the high temperature changed the functionality of their immune system.

Under CC temperature settings, the ability of their immune cells switched from producing an excess of radicals of oxygen (ROS production) to break and destroy health threats to engulfing whole cells (phagocytosis) (Fig. 4B).

As a consequence, different pathologies and abnormalities were detected such increasing the presence of parasites up to a 33.3%, showing inflammatory responses or degraded digestive glands.

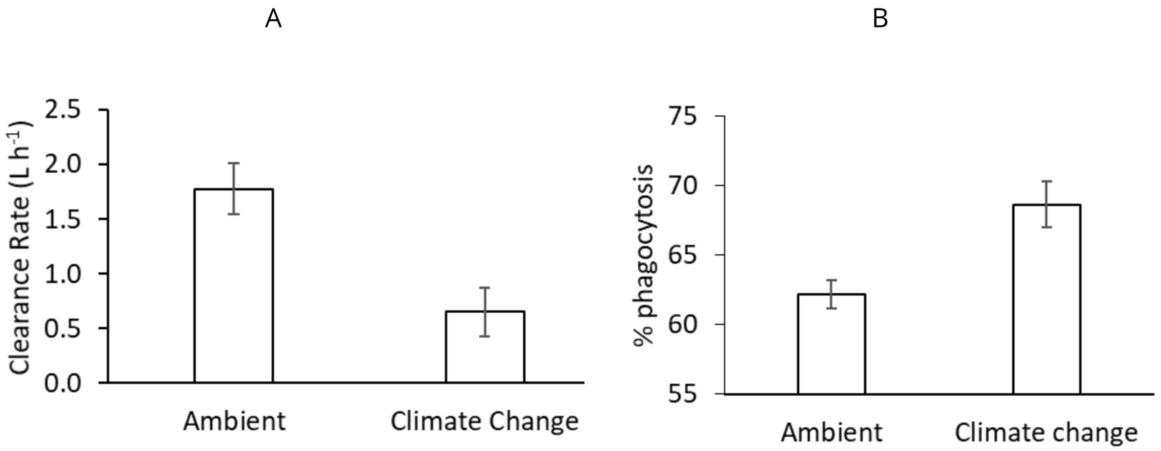


Fig 4: Clearance rate (± S.E.) from mussels in spring under ambient and climate change conditions. B. Phagocytosis ability (± S.E.) of mussels in spring under ambient and climate change conditions.

In summer, both higher temperatures and acidic waters negatively influenced their immune system, similar to what occurred in autumn.

However, because mussels are not reproductively active (resting reproductive period), the pathologies and abnormalities observed affected mainly the digestive gland, showing degradation, with hemocytes (blood cells) surrounding the digestive system in 30% of the individuals.

The broad inter and intra species variability of bivalves and their adaptation to environmental stress difficult predictions on how efficient bivalves will be in the future oceanic conditions.

Other environmental changes might help buffer the feeding decrease observed in warmer waters. For example, it is likely that the predicted higher water temperature will increase the amount of phytoplankton (Trolle et al. 2014).

Should that be the case, low clearance rates would be compensated by trapping more food in their gills as a consequence of higher phytoplankton density.

Vulnerability assessment

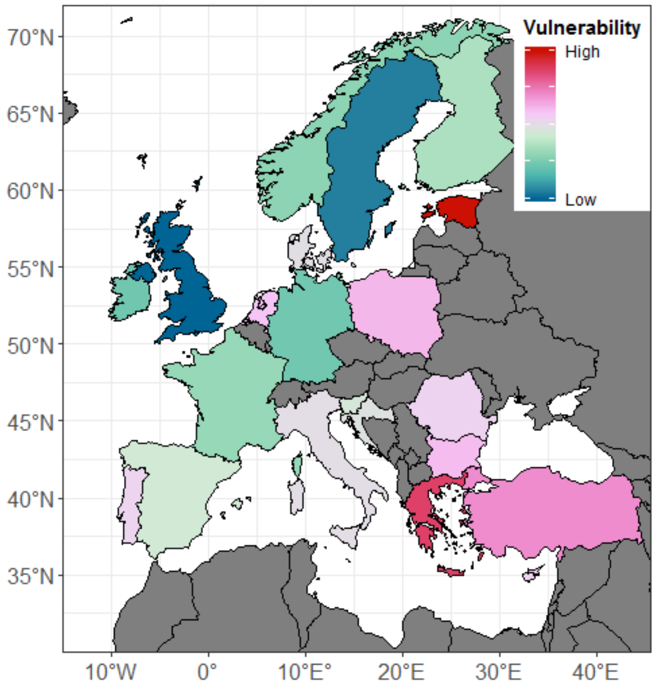


Figure 5 Climate vulnerability assessment for Europe. Colour scale is linear in the value of the corresponding score, but is presented without values, as they have little direct meaning. *Picture credit: Myron Peck*

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)

Warming by 2050 based on RCP8.5 caused reductions in the suitability of culture conditions for mussels in the NW Mediterranean. Indirect effects of climate change (e.g. on HABS or disease) were not included in the analysis.

Farming mussels is inherently vulnerable to climate change due to the lack of control of the production cycle and the fact that most firms are relatively small with low adaptive capacity.

Despite mussel culture being vulnerable, the overall vulnerability of Spanish production was intermediate due to the mixture of species farmed and because of progress made in the implementation of national level climate adaptation plans.

Policy recommendations

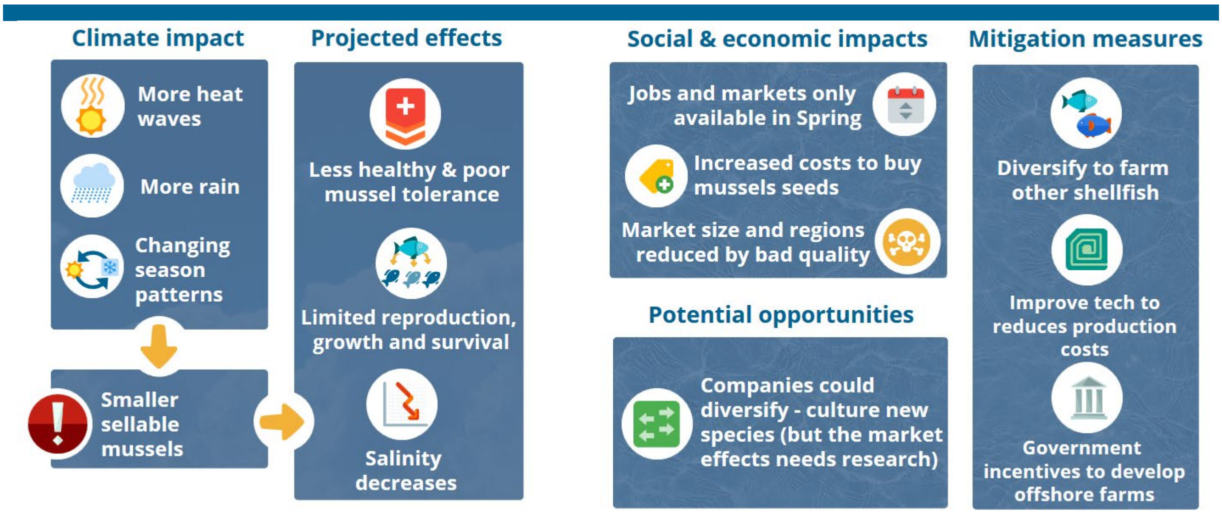


Fig 5 BowTie analysis based on stakeholder feedback. All full BowTies available http://bit.ly/CERESbowties2020

Policies and managers must encourage producers to invest in new technology to move production offshore and incentives for farms to acquire insurance.

Regional funding to advance high-resolution models depicting patterns in water circulation, sedimentation and water quality within the Delta Ebro bays is needed for spatial planning (e.g. the placement of farms in relation to other activities).

Policies are needed to help mitigate problems with natural seed collection (a critical step in the production cycle), for example, by providing funds to farmers so that they could purchase mussel seed and to encourage the use of new technology.

Further reading

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