

## Review

# Assessment of Risks Associated with Extreme Climate Events in Small-Scale Bivalve Fisheries: Conceptual Maps for Decision-Making Based on a Review of Recent Studies

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**Abstract:** Extreme climate events, such as heatwaves and torrential rain, affect the physiology and functioning of marine species, especially in estuarine habitats, producing severe ecological and socioeconomic impacts when the affected species support important fisheries, such as artisanal shellfisheries. Studies of the impact of sudden decreases in salinity and increases in temperature were reviewed with the aim of producing comprehensive conceptual maps to aid the management of fisheries of the native clams *Ruditapes decussatus* and *Venerupis corrugata*, the introduced *Ruditapes philippinarum*, and the cockle *Cerastoderma edule* in Galicia (NW Spain). The maps show the effects on mortality, scope for growth, ability to burrow, changes in gonad development or predation risk. While *V. corrugata* will generally be more affected by low salinity (5 to 15) or high temperature (30 °C) during only two tidal cycles, *C. edule* populations may recover. Both species are also expected to become more vulnerable to predators. The clams *R. philippinarum* and *R. decussatus* will be more resistant, unless extreme events occur after massive spawning episodes; however, the presence of the intertidal seagrass *Zostera noltei* may buffer the negative effects of high sediment temperature on the growth of some species, such as *R. decussatus*. Finally, recommendations for assessing climate risk and designing management actions for shellfisheries are given.

**Keywords:** extreme events; salinity; temperature; heatwave; bivalves; conceptual maps; artisanal shellfishery management



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## 1. Introduction

Small-scale fisheries (SSFs), i.e., small-scale, spatially structured fisheries targeting sedentary resources with artisanal gear, sensu [1], are considered key actors in the governance of ocean sustainability. Artisanal shellfisheries are SSFs that provide important socioeconomic benefits to coastal communities [2,3] and that have a low environmental impact, as bivalves feed on naturally occurring phytoplankton in the ecosystem [4]. Bivalves are also important components of the sedimentary ecosystem [5], as their infaunal activities enhance primary productivity [6,7] and can be considered for habitat restoration [8]. Bivalves are widely promoted as a healthy, sustainable food source and are increasingly in demand. China is the largest shellfish producer in the world, and the European Union represents the largest market for mussels, clams, scallops and oysters [9,10].

Spain, France and the Netherlands are the top producers of marine bivalves in Europe. Some industrial bivalve shellfisheries use bottom trawling and dredging [9–11], which have a high impact on the ecosystems [12]; however, in other areas, such as Galicia (NW Spain), artisanal methods are still in use for extraction, with manual gear used in both intertidal (on foot) and subtidal (from small boats) zones [13]. These shellfisheries work under a comanagement system involving cofradías (fisher's guilds) and fisheries authorities and are based on territorial use rights for fishing (TURFs) over a large area and on the associated

resources [14,15]. The entire process, from harvesting to processing of the final product, is of great socioeconomic importance [2,3,16], and it is mostly performed by women, which enhances the social value of the activity [17]. Overall, this activity makes a significant contribution to the sustainable development of coastal areas [3,18].

The native clams *Ruditapes decussatus* (Linnaeus, 1758) and *Venerupis corrugata* (Gmelin, 1791), the introduced *Ruditapes philippinarum* (Adams and Reeve, 1850) and the cockle *Cerastoderma edule* (Linnaeus, 1758) represent the vast majority of bivalve landings and market benefits and constitute the largest artisanal fishery in Galicia in terms of landings and employment (~7.9 Tm of bivalves worth ~74 millions of euros and involving ~7100 fishers in 2022) ([www.pescadegalicia.com](http://www.pescadegalicia.com), accessed on 1 March 2023). The Manila clam *Ruditapes philippinarum* was introduced for culture, as in other areas of Europe, because of its high adaptability [19], rapid growth rate, rapid depuration of toxins from algal blooms, large stock biomass, ease of capture (due to its shallow burrowing depth), strong market demand and resistance to pathogens [20,21]. Moreover, it is one of the most frequently exploited molluscan species worldwide [9].

These fisheries, however, experience large spatial and temporal variations in catches [22], which have been associated with strong fluctuations in environmental conditions, including heatwaves [23–27] and sudden decreases in salinity due to heavy rainfall [25,28]. Such fluctuations have favoured the introduction of *R. philippinarum*, although sustained periods of low salinity can also be lethal for this species [25,26]. For example, episodes of mass mortality were reported in the inner part of the Ría de Arousa after the heavy rainfall events that occurred in 2000–2001 [24], 2002–2003 [25,29,30], 2006 and 2013–2014 ([www.pescadegalicia.com](http://www.pescadegalicia.com), accessed on 1 March 2023), causing large economic losses.

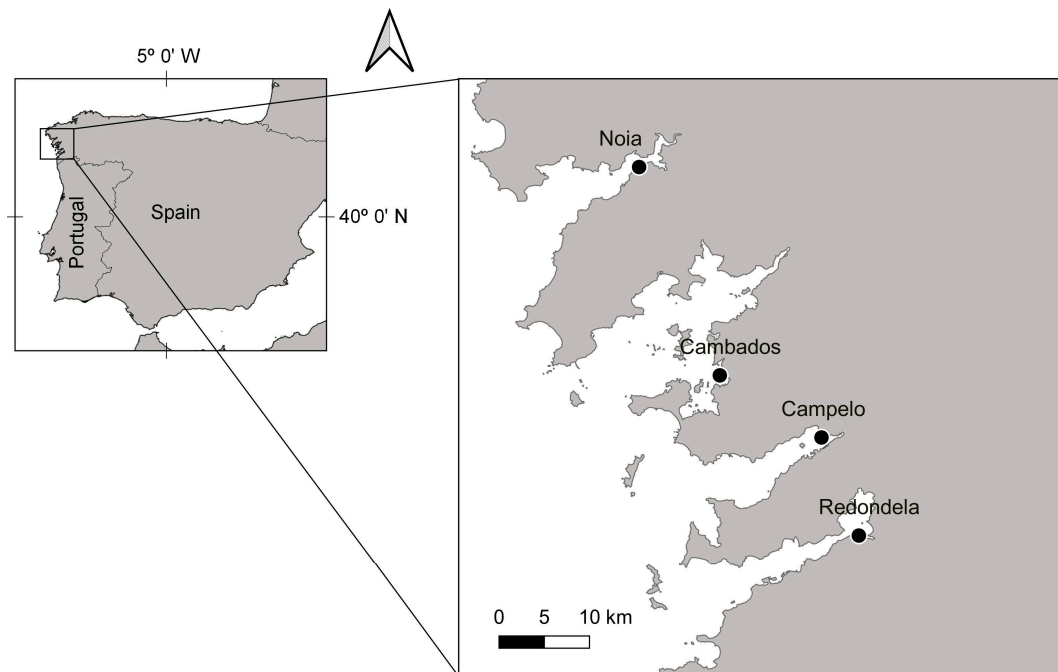
The fluctuations in catches are of particular importance in the context of climate change, as extreme climate events, such as heavy rainfall and marine heatwaves are expected to increase in frequency, duration, spatial extent and intensity [30–32] (although see [33,34]). For instance, in January 2011 in Galicia (NW Spain), bottom salinity at high tide remained below 10 for two consecutive days and below 5 for one day [35]. In 2013 and 2014, strong precipitation led to salinity falling below 15 during 35 and 38 days in autumn, 70 and 81 days in winter, and 35 and 28 days in spring, respectively [36]. In fact, the effects of climate change are expected to be more acute in shellfish beds located in the southernmost rias, the Galician Rías Baixas [37,38] (Figure 1). Although marine organisms are to some extent adapted to cyclic changes (e.g., daily, tidal, seasonal) [39], they may not be able to adapt to an increased frequency or intensity.

Environmental stress not only causes mortality in the short term, but also has sub-lethal effects in bivalves. Behavioural responses to stress, such as burrowing and valve closure, help to prevent osmotic shock and mitigate heat damage or predation [40–42]; however, both burrowing and valve closure are energy-consuming processes [43]. In addition, prolonged periods of valve closure result in accumulation of toxic metabolites, and the temporary cessation of filtration due to valve closure also implies reduced energy acquisition, with negative impacts on growth and physiological condition [44–52] and reproductive development [53]. Moreover, production of various molecules, such as heat-shock proteins and antioxidants protects cells from structural damage [54,55], although with a high associated energetic cost.

Environmental stress can also alter species interactions, such as predation [56–58], considered a prevalent postrecruitment mortality factor in soft-sediment communities in benthic environments [59,60], as it represents more than 90% of mortality in marine invertebrates [61]. Bivalves affected by environmental stress lose the ability to use avoidance strategies, such as burrowing, defensive body structures and fast growth [60,62], consequently increasing predation rates [57,63,64].

Nonetheless, interspecific interactions can help to mitigate effects of environmental stress. This is the case of seagrass meadows that cover areas of shellfish beds to some extent, favouring climate mitigation and coastal system resilience ([65]), and enhancing the productivity of fisheries (e.g., [64]). For example, the intertidal seagrass *Zostera noltei*

Hornemann, can have positive effects on the physiological performance of bivalves exposed to thermal stress during emersion [65] and can reduce the risk of predation in stressed bivalves [66]. Due to the positive effects of these interactions, seagrass conservation and management actions within shellfish beds may help to mitigate the effects of climate change on this commercially important resource.



**Figure 1.** Location of the shellfish beds in the four Rías Baixas, from which data and specimens for the presented studies were obtained.

Galician shellfishers, like other fishing communities [67], have developed adaptation strategies to deal with the impacts of climate change [2]; however, several threats to the sustainability of shellfisheries remain, such as a decrease in the abundance of key native shellfish species. In addition, the adaptation strategies also depend on other important stakeholders (fishers' guilds, fisheries administrations and the scientific community) providing accurate, comprehensible information. Without specific actions and measures, adaptation to the impacts of climate change are likely to be less effective [68]. Population dynamic models, which can include environmental variables, are often used to simulate the effects of management measures on fisheries (closure season or minimum capture size on stocks) [69,70]. By contrast, conceptual models or maps, such as those presented by [71], transform the information into qualitative network models, including ecological processes and the relationships between the system components. These models can also include the values and thresholds of impact of stress variables beyond those included in the more synthetic conceptual models and can be used in data-poor systems or as a complimentary approach [72,73].

Therefore, the purpose of this review is to provide stakeholders and policymakers with a comprehensive understanding of the implications of the effect of low salinity events and heatwaves on the most important artisanal shellfish species in the NW Iberian Peninsula, i.e., *C. edule*, *R. philippinarum*, *R. decussatus*, and *V. corrugata*, by presenting comprehensible conceptual maps based on the results of our previously published studies. All of this information can be applied to shellfishery management, so that managers can make informed decisions based on the latest available evidence.

## 2. Materials and Methods

Here we summarize the methodological approach we used to address the lethal and sublethal effects of extreme events, particularly sudden decreases in salinity and increases in temperature of different intensities, on four commercially-important bivalve species (*C. edule*, *R. philippinarum*, *R. decussatus* and *V. corrugata*) harvested in the Galician rias.

Seven experiments were performed in a mesocosm system at the Estación de Ciencias Mariñas de Toralla (ECIMAT), which belongs to the Centro de Investigacións Mariñas (CIM-Universidade de, accessed on 1 May 2023. Vigo, Spain, <https://cim.uvigo.gal/ecimat/a-estacion-de-ciencias-marinhas-de-toralla>). A field experiment was conducted in an intertidal shellfish bed located in Cambados, in the Ría de Arousa (Figure 1). Adult bivalves and predators used for the experiments were collected from the shellfish beds in the Ría de Noia and Ría de Arousa and Ría de Pontevedra. Juveniles were provided by hatcheries, and all individuals used in the experiments were acclimated to laboratory conditions prior to the experiments. The shell length was measured, and specimens were selected according to a specific size class range for each experiment.

One laboratory experiment was performed in 2015, in which the three venerids were exposed to high temperatures often recorded during summer in the sediment at 2 cm depth. Clams ( $n = 20/\text{species}$ ) were allowed to burrow in sediment placed in two plastic beakers inside each of 12 tanks held at 21 °C (control), 27, 32, and 36 °C, at diurnal low tide during three consecutive days. The variables measured were mortality and burrowing activity [5].

Another laboratory experiment evaluated different physiological responses of two postlarvae size classes (thread drifters and settlers) of *C. edule* over a wide range of constant salinity (8 levels: 3, 5, 10, 15, 20, 25, 30 and 35 as a control) during 2 to 7 days in seawater [74]. Two replicate groups of cockles (40 and 15 individuals for drifters and settlers, respectively) per salinity treatment, size and time of exposure were used to measure clearance, respiration and excretion rates, and O:N ratio.

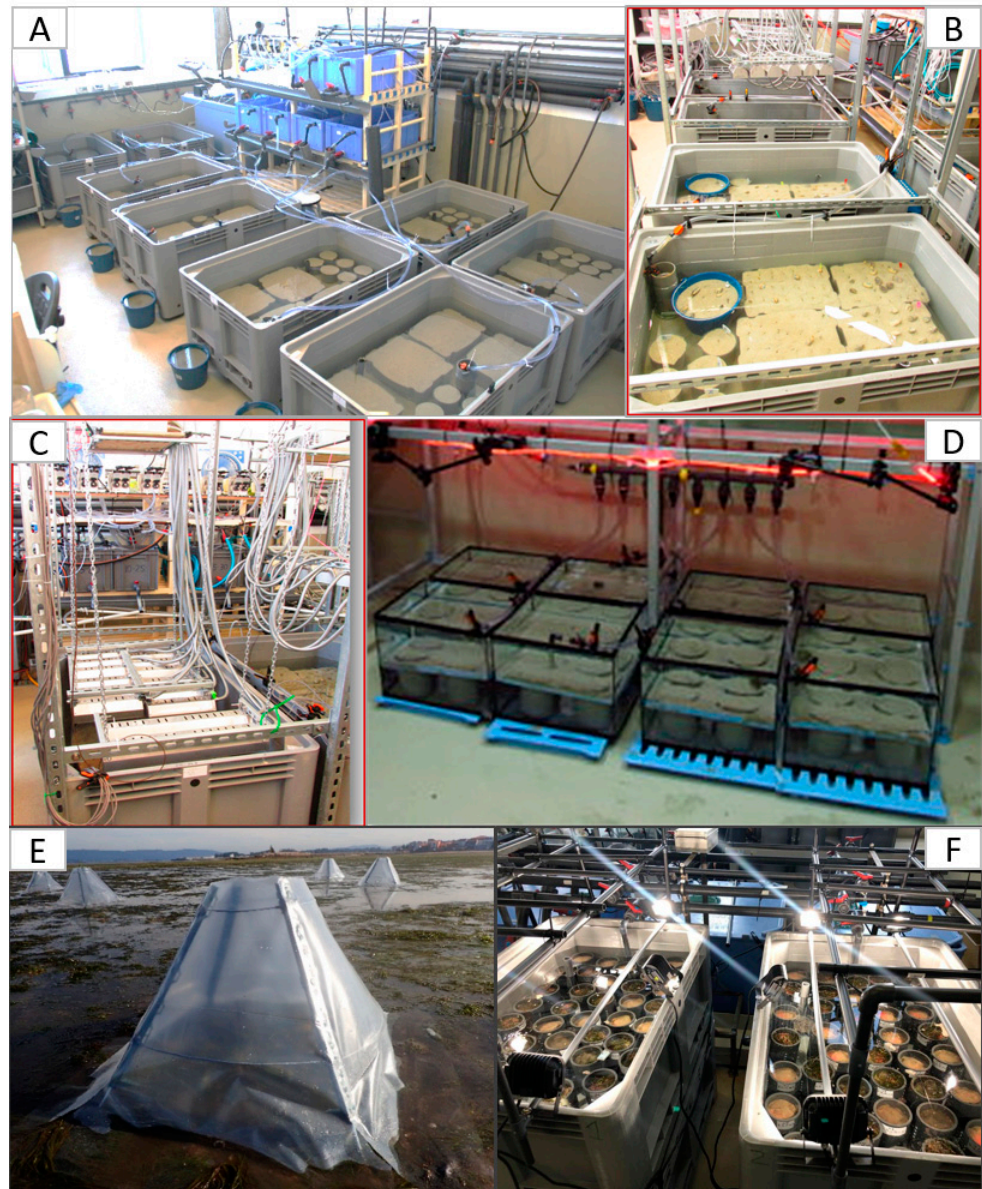
Four realistic laboratory experiments were performed with commercial-sized bivalves subjected to different levels of stress, while buried in sediment collected in the fishing beds, under simulated tidal cycles. First, three low salinity stress experiments were run independently in December 2015, March and May 2016 (Figure 2A), to examine the effect of the heavy rain season on the gonadal development stage through the year. Three different salinity fluctuations (5–20, 10–25 and 15–30) and constant, control salinity (30–30) were tested. Salinity variations were produced by mixing seawater and filtered freshwater and were monitored automatically by mini-CTDs (Star Oddi DST-CTD) placed in the tanks and manually by measurements made with a Hach HQ40D (for more details, see [50,52,75]). Bivalves ( $n = 30/\text{species}$ ) were placed in boxes with sediment simulating low-tide conditions and were subjected to a gradual decrease in salinity (for more details, see [50,53,55,75]) over 6 consecutive days; the lowest salinity levels were reached during low tide and highest levels were reached during high tide, as occurs after heavy rainfall in the estuaries where the bivalve fishing beds are located. A similar set-up was used for the heatwave experiment conducted in July 2016, but with constant salinity and a simulated temperature increase (Figure 2B,C), with four different sediment temperatures reached during the diurnal, 4 h low-tide cycle (22, 27, 32 and 37 °C) during four days (for more details, see [51,53]).

The variables examined in both low salinity and heatwave experiments included various complementary aspects of the bivalve ecophysiology: mortality; scope for growth (SFG), i.e., the difference between energy acquisition (feeding and digestion) and energy expenditure (respiration, ammonium excretion and production of faeces), as defined by [76]; and behaviour (burrowing ability, valve closure) [50,51,75]. Additionally, tissue samples were taken from stressed and non-stressed individuals of each species for histological examination to determine the effects of these environmental stressors on reproduction [53] and production of mantle-edge proteins [55].

Apart from the physiological responses of bivalves to environmental stress, the predator–prey interactions were examined in a predation experiment performed in May 2017 (Figure 2D). The experiment investigated the rates of predation of stressed juvenile bivalves



(*V. corrugata*, *C. edule*, *R. philippinarum*) exposed to continuous low salinity (5, 10 and 15) over two days, by *Bolinus brandaris* (Linnaeus, 1758) and *Carcinus maenas* (Linnaeus, 1758). In two different set-ups, each individual predator was offered 5 juveniles of each of the three species stressed under the same salinity treatment, or the same bivalve species stressed at each of the three treatment salinities; in both instances a bucket containing sediment only was included as a control. The preference of a total of 103 predators of each species was determined (for more details, see [52]).



**Figure 2.** Experimental set-up for the stress experiments. (A) low salinity, (B,C) high temperature; (D) predation under low salinity, (E) field experiment with the seagrass *Z. noltei*, and (F) laboratory experiment with *Z. noltei*.

A field experiment carried out in August 2020 evaluated the effects of warming on biological interactions between the clams *R. decussatus* and *R. philippinarum* and the seagrass *Z. noltei* during two consecutive spring tides (33 days). For this purpose, 32 perforated plastic boxes were buried in the sediment in the midintertidal zone (Figure 2E). Half of the boxes were randomly placed inside seagrass patches and the others were placed in bare sediment; all boxes were covered with plastic netting to exclude large predators. Clams were previously acclimated and immersed in a calcein solution for marking. Groups

comprising 12 specimens of *R. decussatus* and 13 specimens of *R. philippinarum* were then placed in half of the boxes, i.e., eight boxes with bare sediment and eight with *Z. noltei* cover. To increase the temperature (up to 8 °C in air and 3 °C in the sediment surface), 16 cone-shaped structures were placed over half of the experimental boxes, and the temperature variations were recorded (for further details, see [65]). Measured variables were some physiological parameters of *Z. noltei* (photosynthetic efficiency, carbohydrate reserves, above and belowground biomass, and nutrient contents) and clam growth was measured as shell length.

Finally, in September–October 2020, the effects of heatwaves on clam–seagrass interactions were investigated in the laboratory (Figure 2F), using the same species as in the field experiment, although this time using juvenile bivalves (96 marked individuals were selected for seeding: 24 cores with sediment were seeded with two specimens of *R. decussatus*, 24 cores were seeding with *R. philippinarum* and 24 cores were left without clams; half of this treatments had *Z. noltei* and half only bare sediment). Thermal stress was applied during simulated low tides, for 4 h, on 4 consecutive days. The variables measured in bivalves were shell growth and burrowing activity (for more details see [66]).

A comprehensive socioeconomic analysis of the shellfisheries of the four species [2] complemented and incorporated new data to the results of the above-mentioned experiments. The information allowed us to develop conceptual maps to describe the effects of each stressor on each bivalve species and the expected effects on their populations and fisheries. Such maps can contribute to the understanding of climate-driven impacts on these shellfisheries and serve as management tools.

### 3. Results: Conceptual Maps for Fisheries Management

#### 3.1. Results for *Cerastoderma edule*

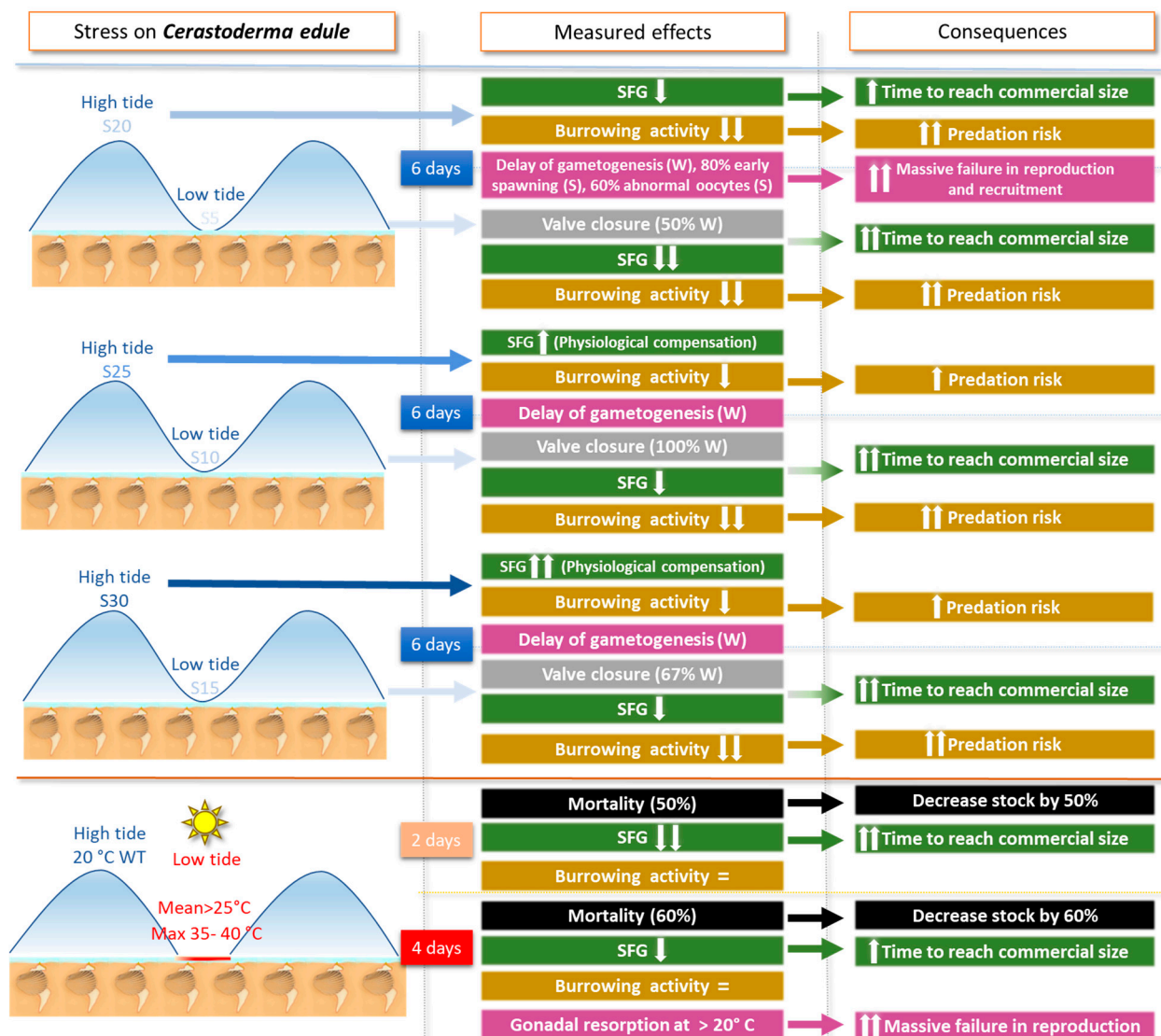
At low salinities (15 and below), adult and juvenile *C. edule* (Figure 3), which live in the upper 2 cm of sediment, closed their valves and were unable to burrow, indicating a general cessation of activity [50,74]. Recovery of salinity when the tide rose allowed recovery of filtration and burrowing activity in the bivalves. As a consequence, two days after the stress event, the SFG recovered to normal values, except in spring. Gametogenesis is also negatively affected by low salinity [53] and there is some evidence suggesting that the change in reproduction affects the molecular stress response to very low salinity (around five) [55]. In winter, during sexual resting and the beginning of gametogenesis, a delay in this process was recorded, while at the peak of the reproductive period, low salinity levels triggered spawning, which may have resulted in a mismatch between the presence of larvae and phytoplankton, potentially causing starvation and diminishing the recruitment success [53]. Burrowing activity was affected in at least 75% of the individuals subjected to low salinity (15 and below), thus increasing the predation risk by up to eight times relative to that in non-stressed individuals [52]. In the only experiment conducted with early *C. edule* settlers, a salinity level of 15 was also the lethal limit for thread drifters and sedentary settlers [74], although the former showed greater physiological plasticity than the latter, probably due to differences in habitat (not shown in the conceptual map).

The cockle underwent the greatest mortality after only two days of exposure to sediment temperatures starting at 25 °C and reaching 35 °C during the diurnal 4 h low tide (Figure 3) [51]. After 4 days, only about 40% of the individuals had survived, and a continuous decrease in their SFG was recorded. The high temperatures provoked gonadal resorption, negatively affecting the natural spawning process [53].

#### 3.2. Results for *Ruditapes philippinarum*

The Manila clam *R. philippinarum* (Figure 4) closed its valves and reduced its burrowing activity at low salinity (15 and below) [50,75]. The decrease in SFG was notable, particularly in spring, although two days after the stress event, SFG recovered to normal values, except in spring. Low salinity also increased the predation risk by up to three times at salinity levels below 10, even though this species is not the preferred prey of benthic fauna [52].

Gametogenesis was delayed at low salinity levels in winter, and in spring gametes were reabsorbed, with haemocytic infiltration in the gonads [53].

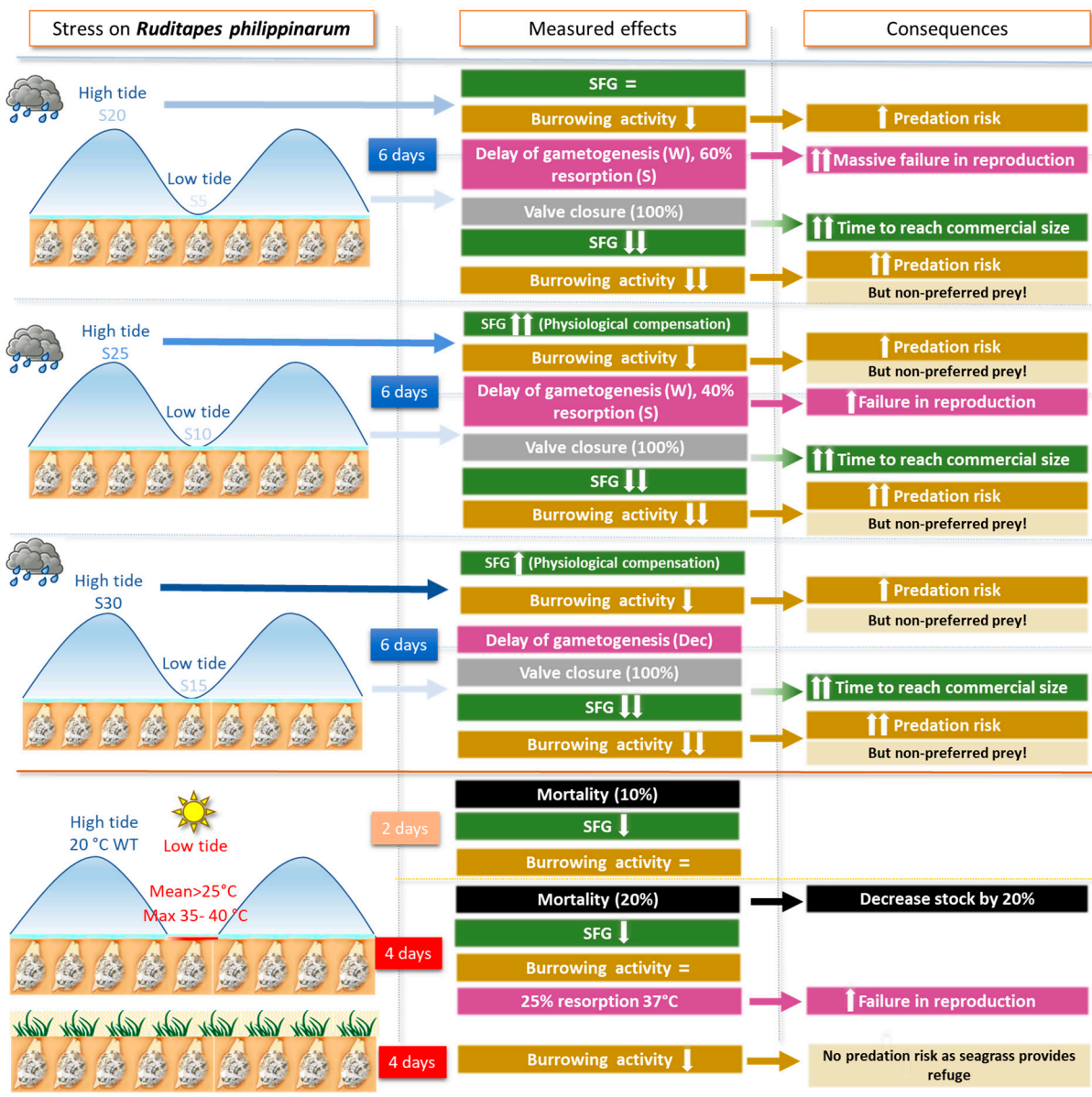


**Figure 3.** Conceptual map showing responses of *Cerastoderma edule* to exposure to different low-salinity and high-temperature conditions. The map is based on the results reported in [50–52] and [53,74,75]. Effects of the lowest salinity levels (i.e., 5, 10 and 15) were only measured in December. Burrowing activity and mortality were based on the results of [50,51]. W: winter (experiments conducted in December); S: spring (experiments conducted in March and May).

Manila clams, which inhabit the upper 5 cm of sediment, suffered 20% mortality after four days of exposure to a temperature of 36 °C in sediment during a diurnal 4 h low tide [5]. After two days, a general decrease in the SFG at temperatures above 36 °C was also observed [51]. The high sediment temperatures, reaching up to 36 °C during low tide, induced resorption of gonads in 25% of the individuals [53].

In the field, the mean increase in growth was approximately  $3.03 \pm 0.51$  (mm) after 33 days, i.e., a growth rate of  $\sim 0.09$  mm day<sup>-1</sup>. Shell growth rate was not different in clams inhabiting bare sediment and those living in sediment with *Z. noltei* cover, independently of the temperature treatment (i.e., control vs. increase in temperature of approximately 3 °C, at sediment surface in cone shape structure).





**Figure 4.** Conceptual map showing the responses of *Ruditapes philippinarum* to exposure to different low-salinity and high-temperature conditions. The map is based on the results reported in [5,50–53,75]. Effects of the lowest salinity (i.e., 5, 10 and 15) were only measured in December. Burrowing activity and mortality were based on [50,51]. W: winter (experiments conducted in December); S: spring (experiments conducted in March and May).

### 3.3. Results for *Ruditapes decussatus*

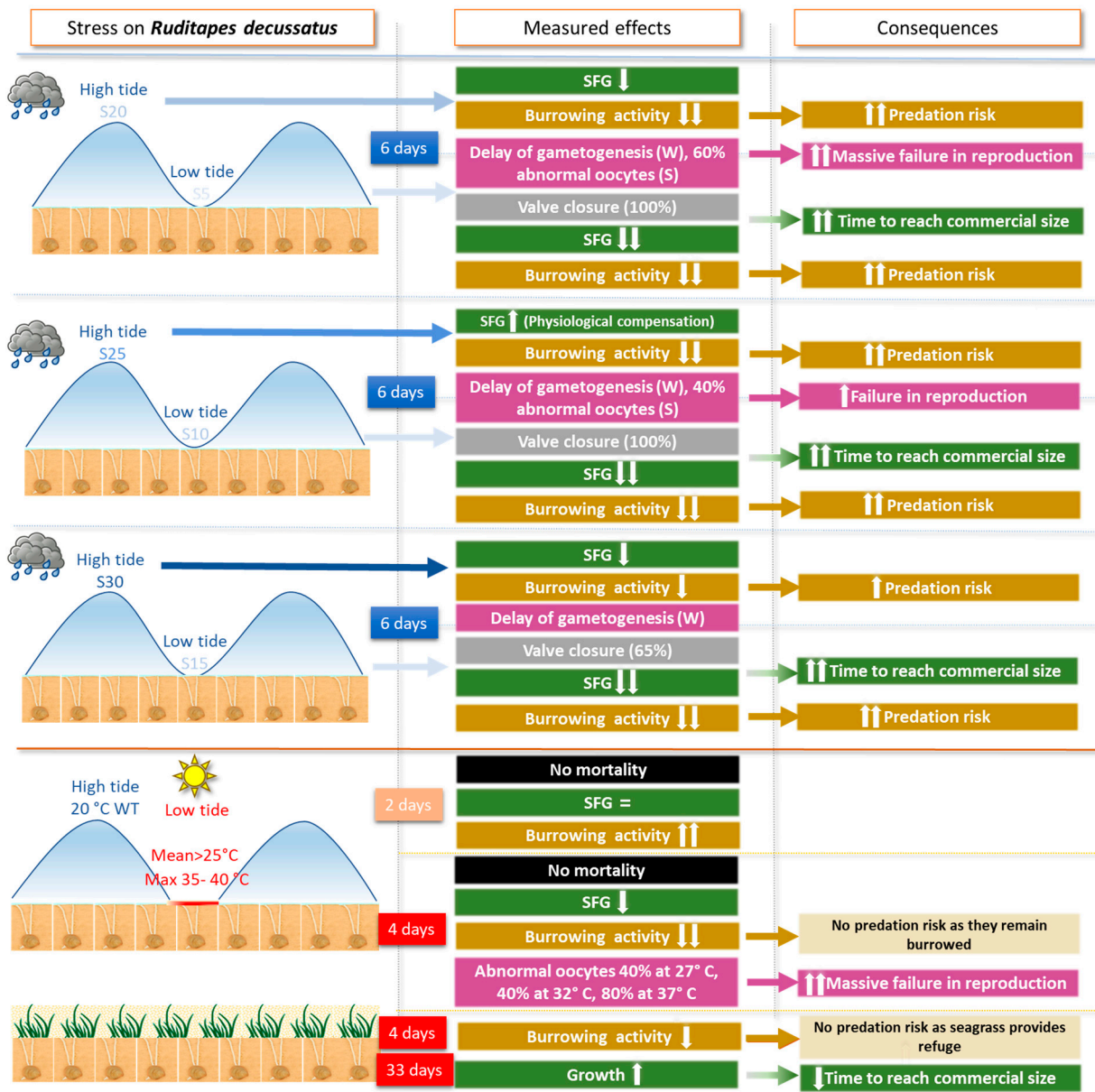
The deeper burrowing *R. decussatus* (Figure 5) clearly ceased burrowing activity and valve opening at salinity levels equal to or below 15 [50,75]. According to the experimental results, the decrease in SFG was the lowest of the four species, as the basal filtration was also the lowest. Two days after application of the stress, SFG recovered to normal values, except in spring. During sexual resting and at the beginning of gametogenesis, a delay in gametogenesis at low salinity (15 and below) was recorded, although the effect varied during late gametogenesis or maturity, when abnormal oocytes were observed [53].

This species increased its burrowing activity in sediment at temperatures up to 32 °C, while at 36 °C activity decreased notably because the clams were already deeply burrowed [5]. Thus, only after four days of stress, some effects were observed at the highest



temperature, including lower values of SFG, i.e., slower growth rates and gonadal resorption with severe haemocytic invasion [51,53].

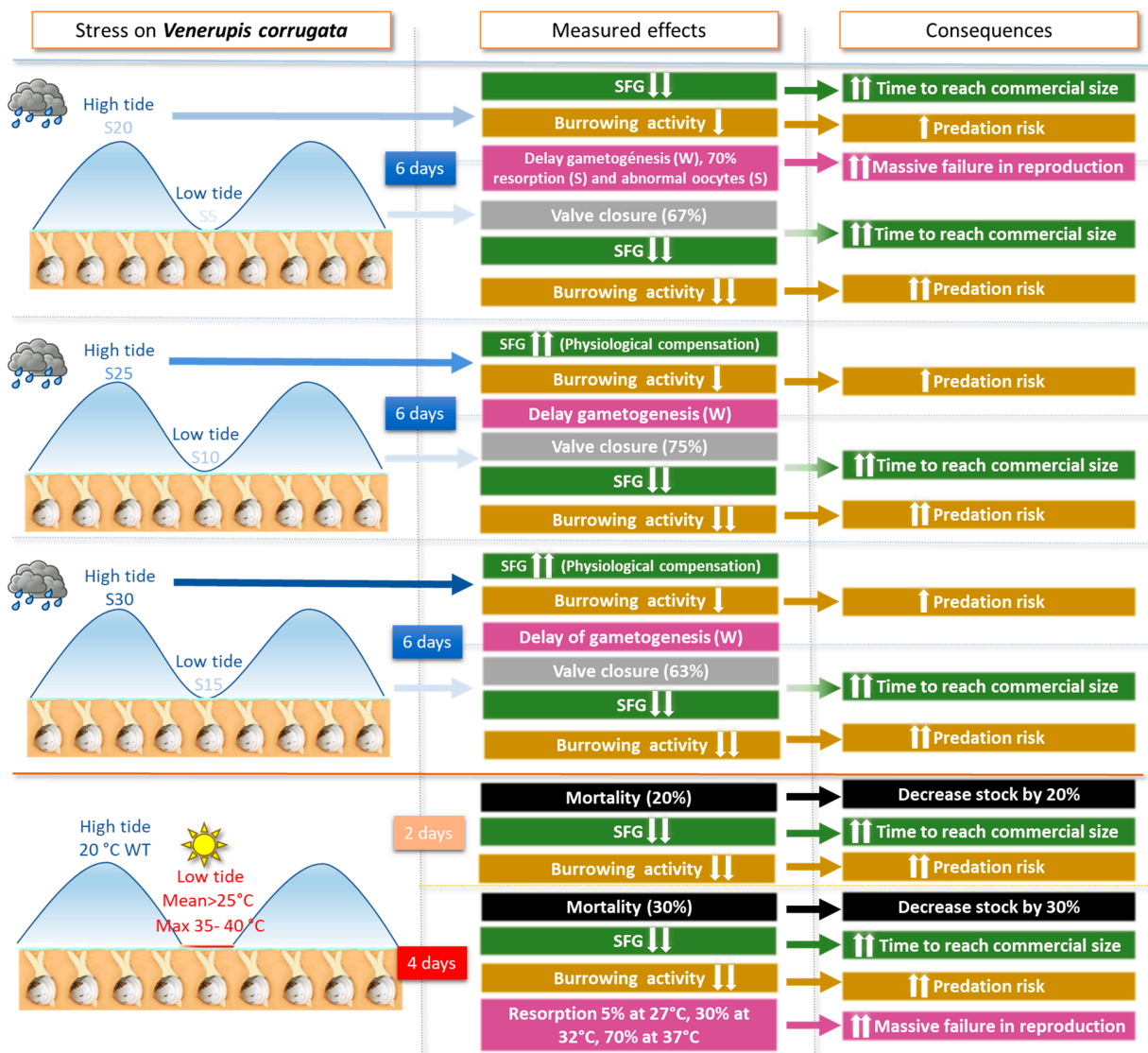
In the field, the mean increase in growth was around  $2.94 \pm 0.48$  (mm) after 33 days, i.e., a growth rate of  $\sim 0.09$  mm day<sup>-1</sup>, similar to that of *R. philippinarum*. In this case, however, the shell growth differed significantly between treatments (control vs. cone-shaped structure), depending on the type of habitat. Under *Z. noltei* cover, clams exposed to higher temperature (i.e., in boxes covered with conical structures) grew similarly to those held under control conditions, while in bare sediment, clams exposed to higher temperatures were on average 0.26 mm smaller than the clams in the control boxes.



**Figure 5.** Conceptual map showing responses of *Ruditapes decussatus* to exposure to different low-salinity and high-temperature conditions. The map is based on the results reported by [5,50–53,65,66,75]. Effects of the lowest salinity (i.e., 5, 10 and 15) were only measured in December. Burrowing activity and mortality were based on [50,51,66]. W: winter (experiments conducted in December); S: spring (experiments conducted in March and May).

### 3.4. Results for *Venerupis corrugata*

Similarly to the other species, *V. corrugata* (Figure 6) showed generalized valve closure and absence of burrowing activity at low salinity (15 or below) during low tide [50,75]. A large decrease in SFG occurred during the increase in salinity from 5 to 20, particularly in spring, as well as at the lowest salinities of the other ranges of salinity tested, i.e., 10 to 25 and 15 to 30. Physiological compensation occurred at the highest salinity levels. As in the other species, SFG recovered to normal values after the end of the period of stress, except in spring. Low salinity increased the predation risk [52] with clams exposed to salinity of 10 being the preferred prey species for the benthic predator *Bolinus brandaris*. Overall, the predation risk for *V. corrugata* was up to three times greater at salinity levels of 5 and 10. Gametogenesis was delayed by low salinity in winter, although at the peak of the reproductive period (spring), salinity below 15 induced resorption of gametes with haemocytic infiltration [53]. These modifications affected the molecular response to salinity of five, similarly to *C. edule* [55].



**Figure 6.** Conceptual map showing the responses of *Venerupis corrugata* to different degrees of exposure to low-salinity and high-temperature conditions. The map is based on the results reported in [5,50–53,75]. Effects of the lowest salinity (i.e., 5, 10 and 15) were only measured in December. Burrowing activity and mortality were based on [50,51]. W: winter (experiments conducted in December); S: spring (experiments conducted in March and May).

In relation to temperature, *V. corrugata* abruptly reduced its burrowing activity at temperatures of 27 °C or higher and died after 2 days of exposure at 36 °C during low tide and after 3 days at 32 °C [5]. After exposure to similar conditions for 4 days, the mortality increased up to 30% [51], and the reduction in SFG remained notable. Likewise, sediment temperatures higher than 32 °C induced gonadal resorption and severe haemocytic invasion [53].

#### 4. Discussion: Consequences for Shellfisheries

Low salinity events of different intensity have overall negative effects on bivalve populations, causing mass mortality in the shellfish beds (e.g., [25]). Although short-term low salinity levels did not lead to death of the bivalves under study in our experiments, repeated stress events within a short time will probably lead to similar mortality rates as caused by constant low salinity due to exhaustion [25]. Heatwaves in summer are as important as decreased salinity since exposure to high aerial temperatures of 35–40 °C (i.e., sediment surface temperature above 25 °C), even during only two consecutive diurnal tidal cycles, caused mortality levels of up to 60%, mainly in *C. edule* and *V. corrugata*, as well as in the other two *Ruditapes* species during spawning events [51,53]. Postspawning exhaustion, often reported to occur in *R. decussatus* [5,23,24,28], was also observed in *R. philippinarum* in laboratory experiments [51,53]. Thus, heatwaves can be expected to cause significant mortality levels in *R. philippinarum* and *R. decussatus* if they occur immediately after intensive spawning events; however, the presence of seagrass (e.g., *Z. noltei*) buffers the increase in sediment temperature caused by exposure to solar radiation during emersion [65,66], thus helping to mitigate the thermal stress in some species, such as *R. decussatus* [65]. Furthermore, this interaction may have other positive effects, such as allowing clams to burrow to shallower depths below *Z. noltei* [66], which implies less energy expenditure [43].

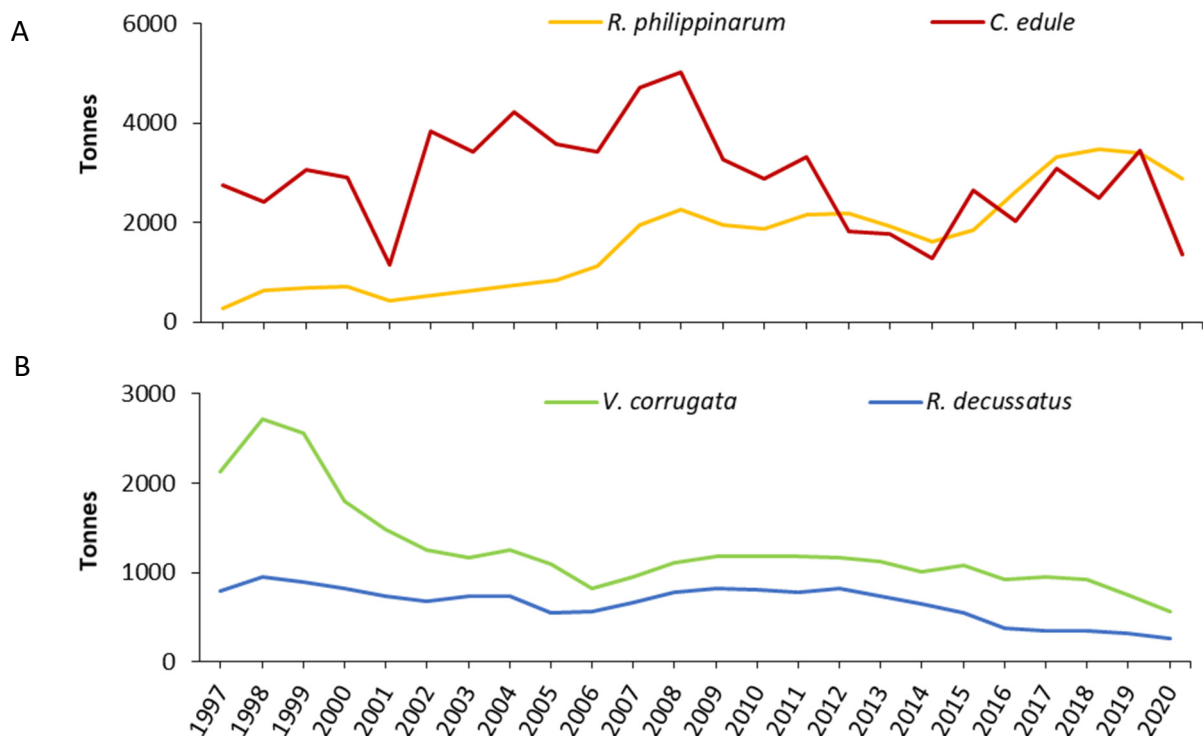
Low salinity events may also indirectly affect the survival of bivalves by altering predator–prey dynamics. If the reduction in salinity is pronounced, with salinity ranging from 5 to 10 during two days, failure of juveniles (especially *C. edule* and *V. corrugata*) to burrow might increase the risk of predation and, indirectly, increase the bivalve mortality [50,52]. Indeed, a previous study showed that extreme temperature and salinity conditions can considerably increase predation of clams, with only around 1% reaching harvestable size [77]. This prevents individuals from reaching maturity and spawning, leading to a decrease in recruitment rates and catches in subsequent years. Failure to burrow, in addition to increasing the risk of predation, also facilitates the displacement of bivalves by currents [43], leading to a reduction in harvesting yields in shellfish beds. Up to 80% of cockles in shellfish beds can be dragged by currents [78], causing important losses in this shellfishery [29]. Such mortality coupled with a failure in reproduction would probably jeopardize replenishment of shellfish beds [53] as lower reproductive output produces lower recruitment rates, and thus reduces population densities [79].

Although no mortality occurred in most cases, low salinity and heatwave events of different intensity reduce the growth potential of individuals due to cessation of filtration. In fact, experimental evidence indicated that activity ceased at low salinity (15 and below), with recovery at values above this threshold in adults of the four species [50,75] and in juvenile *C. edule* [74]. If such events occur in spring, even if followed by a short period of two days in which the salinity returns to normal values, strong negative effects can occur, with a delay in the time to reach size at first maturity and commercial size [50]. One of the species in which growth potential is most affected is *V. corrugata*, which, owing to its greater vulnerability to predators, could disappear from the intertidal zone after some years, as suggested by [5]. Moreover, coping with stressful environmental conditions implies that bivalves must spend energy to produce repair molecules (e.g., [55]; for reproduction, see [53]) and for escaping from stress, i.e., burrowing deeper in search of cooler conditions or escaping from predators, all of which are energy consuming and increase the cost of filtration [43,80], reducing growth rates even further; therefore, the additive effects of stress from heavy rainfall in spring followed by heatwaves in summer could probably increase



the risk of mortality and cause slower growth of bivalves. For instance, if hot days occur on at least two consecutive days, *C. edule* populations could be reduced by half owing to direct mortality. This proportion could be even higher if heat events occur after heavy rainfall, which could affect this species by accelerating the reproductive cycle, as observed by [53], thus leading to an increased risk of predation rates [52].

All evidence regarding the effects of extreme events related to heavy rainfall and heatwaves obtained in our experiments indicated *V. corrugata* and *C. edule* to be the most vulnerable species, placing these fisheries at risk. Indeed, such findings are already being reflected in the catches in the field (Figure 7), although it is difficult to relate changes in environmental conditions to data on bivalve catches, as the changes are often influenced by management decisions driven by economic factors [81,82]; however, the constant decline in *V. corrugata* catches after the extreme low-salinity episode of autumn–winter 2000–2001 [29] ([www.pescadegalicia.com](http://www.pescadegalicia.com), accessed on 25 April 2023) may be due to repeated stress events over the years and to the slower growth and reproduction rates in this species. By contrast, catches of the fast-growing *C. edule*, with very high reproductive and growth rates [83], increased in 2002. For some species, heavy rainfall can have positive effects, such as inhibition of parasite infections, e.g., *Marteilia cochillia* [84] and references therein, and a cleaning effect owing to increased river outflow over the shellfish beds.



**Figure 7.** Annual records of sales (tonnes) of the four studied bivalve species. (A) *Cerastoderma edule* and *Ruditapes philippinarum* and (B) *Venerupis corrugata* and *Ruditapes decussatus*. Data from [www.pescadegalicia.com](http://www.pescadegalicia.com), accessed on 25 April 2023.

Lethal and sublethal effects of extreme events on these four bivalves will probably shape the productivity of the Galician shellfish beds in the near future. Although there are no clear interannual trends in total precipitation levels in Galicia, owing to the high inter-annual variability, some data indicate an increase in heavy rainfall in autumn and winter [85–87]. The projections made by [33,34] indicate an increase in the number of days with intense precipitation, particularly in winter. In this case, the already existing problems of high mortality levels after heavy rainfall in winter will continue to occur—and may become even worse in the next few decades. Regarding temperature, in the Galician shellfish beds, exposure to air of the most productive part of the fishing beds during

low tide can last up to 3–4 h, and the temperature in the sediment and the thin upper layer of water can reach up to 40 °C, over several days during summer heatwaves [5]. Moreover, field data from the Sarrido shellfish bed in Ría de Arousa showed that the water temperature exceeded 25 °C during 10 and 22 days in spring (maximum of 31.3 °C) and during 26 and 45 days in summer (maximum of 33.8 °C) in 2008 and 2012, respectively [36]. The occurrence of these extreme events, together with weakening of upwelling along the Galician coast [88] and ocean warming [89], has led to decreased bivalve production in the last decades, with a modification of the geographic distribution of species and effects in productive areas with further socioeconomic consequences [37].

Maintaining artisanal shellfisheries is important, not only because bivalves are a sustainable resource of protein for human consumption, but also because the shellfish have positive effects on estuarine environments. They clean water and sediments by filtration, enhance primary productivity by nutrient release from the sediment to the water and pelletisation of particulate matter, and they also act as a link between primary production and predators, such as crabs, birds, fish and humans [90]. Shellfish are also very important for local communities from a socioeconomic point of view. In the case of the Galician shellfisheries, these resources are especially important for women, who constitute the majority of workers in the intertidal zone [15] and who help to sustain local economies by direct and indirect employment, representing over 60% of the total population employed in the fisheries sector [2].

## 5. Conclusions: Recommendations for Shellfishery Management

Several small-scale fisheries worldwide are facing similar problems related to climate change to those in Galicia. The collapse of some such fisheries, i.e., the soft-shell clam *Mya arenaria* fisheries in New England and Nova Scotia, has been attributed to the predation effect of the invasive *Carcinus maenas* under warmer temperatures [91,92]. Small-scale fisheries in the Pacific Islands are suffering from complex interactions between several factors, such as rising temperatures, increased incidence of extreme weather events and altered rainfall patterns [93]. In South America, the effects of extreme climate events (e.g., El Niño Southern Oscillation) are increasing the rate at which stocks are being depleted in local small-scale shellfisheries [94]. The sustainability of fisheries facing challenges derived from climate change is of global concern [95].

In order to mitigate these effects, fishery management organizations, fisher's guilds, producer organizations, cooperatives, researchers and policy-makers all have a role to play in the future of the sector. Galician shellfishers have developed adaptation strategies to anticipate and respond to climate change impacts, such as harvesting more valuable and more abundant species or increasing social involvement in shellfishery associations [2].

The following are some suggestions derived from the results of this research:

1. Habitats occupied by shellfish beds should be characterized to determine the potential effects of climatic factors and anthropogenic stress. This can be done by:
  - (i). Continuous automatic monitoring of physicochemical variables, such as water and sediment temperatures and salinity within the fishing beds. Although INTECMAR manages more than 50 oceanographic stations along the Galician coast ([www.intecmar.gal/informacion/fito/estacions/](http://www.intecmar.gal/informacion/fito/estacions/), accessed on 1 May 2023), only five of the stations record data continuously, and sediment temperature is not recorded at any of the stations. This type of data could be used in local-scale modelling to create a warning system for each species, such as that automatically running for the Miño River [96]. In this system an alert is issued, including detailed hazards maps, which help decision makers to take precise and effective mitigation measures.
  - (ii). Including other relevant variables, such as primary productivity in the models and maps [97]. With available information on food, coupled with environmental conditions, the critical conditions for each species could be predicted,

thereby helping management decisions to be made on the basis of the environmental forecasts.

- (iii). Intensifying monitoring of shellfish stocks by fisher's guilds (e.g., [98]) and standardizing and sharing field data to enhance the quality of the research. Although the fisheries authority has promoted surveys to solve specific situations that may place the fisheries at risk [29,35,84], available information about the catches of the Galician shellfisheries is not sufficient to verify the impact of climate change [24,99], since the shellfisheries are often influenced by management decisions driven by economic factors [82].
  - (iv). Compiling all information available from local, traditional, technical and scientific sources. Each ria has characteristic geomorphology, productivity, occupation and uses (e.g., [100] compiled this information for Ría de Vigo) [101].
2. Conducting experiments can be very useful for understanding species responses. Field experiments, such as those conducted by [28] in the inner parts of Ría de Arousa and Pontevedra, and those conducted by [21,22,102] in the Bay of Santander and by [70] in the Basque Country, are examples of what can be done to understand the dynamics in each area. The findings can also be useful for establishing baseline levels of natural mortality for each species to determine when exogenous factors should be considered a threat to the population or include them in an experimental design. Laboratory experiments, such as those summarized here, serve to accurately test the effects of main stressors on metrics, such as scope for growth, valve closure activity, burrowing activity, gametogenic cycle and molecular responses. Based on the results of the experiments presented, new designs can be developed, including other stress factors (e.g., pH, phytoplankton, see [103,104]), different duration or intensity of the stress events, or measuring different response variables (e.g., condition index, valve closure strength). The effects of synergistic or antagonistic interactions between environmental stressors should also be considered [28,105–108].
3. Models including experimental data can be coupled with environmental data from different sources to generate precise predictions. Hindcasting models were developed to predict changes in the distribution of intertidal species related to temperature [109,110]. A recent study developed hindcasting and forecasting models by coupling hydrological models (based on precipitation), hydrodynamics (river outflow and shellfish bed salinity), and finally, by including bivalve mortality based on lethal physiological thresholds of the species [38]. This could also be done by including sublethal effects.
4. Diversification of cultured species could diminish the risk of loss due to high mortality rates as well as overexploitation of and damage to habitats [111]. The global risk model developed by [112] shows that fisheries in Spain are at high risk due to a strong economic dependence, low diversification of cultured species and vulnerability to increased temperatures. These researchers globally identified the year 2060 as a tipping point for shellfish production. In light of the experimental results and characterization of the conditions in different shellfish beds, the most appropriate species for each habitat could be cultured, thus maintaining diversity.
5. Protection for shellfish beds from contamination and human pressure (dams, industrial or agricultural effluents, artificial barriers, water depuration plants, etc.), including control of river outflows and management plans for catastrophic events, to reduce the impacts that commonly threaten shellfishery production in Galicia [113]. The creation of marine reserves and other protective figures is contemplated in the present legislation [114], although with a low degree of success to date [78].
6. Monitoring the presence of invasive predator species on the shellfish beds [115], as such species could have unknown effects on more vulnerable species.
7. Identifying knowledge gaps. Understanding the vulnerability and resilience (including social aspects) is important for the sustainability of SSFs [116] to minimize the underlying causes of social vulnerability, when dealing with social–ecological shocks and crises [2,3].



8. Management plans, including conservation and maintenance of seagrasses patches within shellfish beds, to help sustainability and mitigation of climate change effects on harvested species.

In general, the shellfish sector would benefit from detailed knowledge of the resources and environmental conditions in each area and the scientific ability to produce models using these data. The implementation of local management plans regulating commercial sizes, capture quotas, number of days of extraction, number of fishers' licenses or closing seasons, reflects the diversity of the productive capacity of shellfish beds [81]. New steps should allow fishers to maintain sustainable production to face future threats related to climate change.

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