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Review

A Framework to Advance the Understanding of the Ecological Effects of Extreme Climate Events

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Abstract: Climate change is modifying disturbance regimes, affecting the severity and occurrence of extreme events. Current experiments investigating extreme events have a large diversity of experimental approaches and key aspects such as the interaction with other disturbances, the timing, and long-term effects are not usually incorporated in a standardized way. This lack of comparability among studies limits advances in this field of research. This study presents a framework that is comprised of two experimental approaches designed to test expected changes on disturbance regime due to climate change. These approaches test the effects of disturbances becoming more clustered and more extreme. They use common descriptor variables regardless of the type of disturbance and ecosystem. This framework is completed with a compilation of procedures that increase the realism of experiments in the aforementioned key aspects. The proposed framework favours comparability among studies and increases our understanding of extreme events. Examples to implement this framework are given using rocky shores as a case study. Far from being perfect, the purpose of this framework is to act as a starting point that triggers the comparability and refinement of these types of experiments needed to advance our understanding of the ecological effects of extreme events.

Keywords: climate change; disturbance; driver of environmental change; extreme event; legacy; long-term effects; multiple disturbances; perturbation; resilience; anthropogenic environmental stressor; timing

1. Introduction

Climate change is the major threat to sustainable development [1]. The excessive and increasing emissions of greenhouse gases derived from anthropic activities have led to significant changes in climate that translate into severe environmental, economic and societal impacts [2]. Climate change is posing major environmental threats, modifying the ecosystems and the services they provide to society [3]. Despite most scientific efforts focused on studying the effects on the trends of mean climate values, extreme events have emerged as a key driver of ecosystems [4]. Climate change is already modifying the disturbance regimes (e.g., patterns of severity, frequency, and timing; sensu [3]), increasing the severity of climate events [5] and modifying their timing [6]. This change in the disturbance regimes is expected to become greater in the next decades [2]. Extreme climate events (from now on named as "extreme events") can be defined as climate events with high intensity and low frequency [7]. The catastrophic nature of these types of events provides them a dominant role in modulating ecosystems [8]. Consequently, in recent years there has been a growing number of studies dealing with extreme events [9].

A large number of studies on the ecological effects of extreme events are observational and to some extent opportunistic [10]. Despite their utility as preliminary approaches [11] and if well designed, notable contribution to this research topic [12], they have limited capacity to deepen our understanding. This is because environmental parameters that can affect the outcome of the study cannot be controlled or at least set up to the same level. Thus, the cause of the observed effect cannot be attributed unambiguously to the studied parameter. For example, if an observational study about the effect of the intensity of storms on the rocky shore community is carried out, samplings will be either spatially or temporally separated, because storms with different intensities cannot occur at the same time and location. Therefore, some environmental conditions that can influence the response of the community assembly may be different depending on locations or periods of time. This fact precludes the possibility that these types of experiments demonstrate causality. Thus, it cannot be concluded that more intense storms yield stronger responses of the community assembly, despite the findings of this study indicating so.

To demonstrate that a more intense storm affects more of a community assembly on the rocky shore than a less intense one, a manipulative experiment is needed. For example, storms with different intensities could be simulated on the same location simultaneously. By doing this, environmental parameters that are not manipulated, if not controlled, are at least kept equal (*ceteris paribus*) [13]. Therefore, it can be stated that, at that specific location and time of the year, the reported effects on the community assembly are due to the differences in the intensities of the storms, since the rest of the environmental parameters are kept equal. To demonstrate that the findings are not specific to the location and period of the study, the experiment should be replicated in other locations and at different times of the year.

Accordingly, to advance our understanding of the ecological effects of extreme events, manipulative experiments that allow us to demonstrate causality are needed [14]. Despite the current increase in the number of manipulative extreme event studies, the diverse experimental designs and metrics used preclude comparison among them and limit the progress in this discipline [15].

Different ecosystems harbour communities with specific successional dynamics, as well as, different disturbances have specific recurrence times. Thus, different ecosystems and disturbances must be measured and simulated adaptively using relevant parameters and temporal scales. For example, it is not realistic to monitor the recovery of the rocky shore community after suffering from an extreme event without taking into account its seasonal variation [16] or simulate an extreme storm every week [17]. This diversity of methods to adequately set up the experiments should not translate to diverse methods for analysing the derived data which can tamper with comparison among studies. A research effort is needed to use common approaches that facilitate comparability. This is a necessary step to synthesize research and advance in this field [18].

Moreover, key issues that modulate the effects of extreme events on ecosystems are not generally taken into account. Currently, many ecosystems are already affected by one or more disturbances [19], which can lower the ecosystem's resistance and resilience towards an extreme event [20]. The extent of the effect of the extreme event on the ecosystem can notably vary depending on the timing, occurrence of another disturbance [21], and the time of the year that it takes place [22]. Likewise, extreme events can yield severe long-term ecosystem effects [23,24] despite the fact that they are not frequently studied. Specific procedures need to be designed to incorporate these key issues in extreme event experiments in a standardized way that favours comparison.

All these considerations need to be incorporated in studies supported by a common framework of experimental approaches and procedures. This will permit comparisons among different disturbances and ecosystems under realistic set-ups and allow the comprehensive assessment of the effects of these types of disturbances.

The aim of this manuscript is to design a framework that allows us to gain knowledge of the ecological effects of extreme events. The framework is based on two experimental approaches and a compilation of procedures on a "brick by brick" basis to perform manipulative experiments. This framework facilitates comparability among studies since the descriptor variables of the approaches are the same, irrespective of the ecosystem and the extreme event, while the procedures increase realism. Examples of how to apply the proposed framework are given using rocky shores as a case study.

2. Disturbances

Disturbance, *sensu* Rykiel [25], is "a physical force, agent or process, either abiotic or biotic, causing a perturbation in an ecological component or system". Disturbances embrace abiotic processes, including fire, landslides, wave exposure, and floods as well as biotic processes, such as predation and grazing. Natural disturbances are generally characterized by their discrete nature with a limited frequency of occurrence over time (pulse disturbance) [26]. Global-change drivers of environmental change tend to be chronic (press disturbance), including contamination or invasive species, or prolonged in time with an increasing trend in their average values related to climate change, such as a rise in temperature or ocean acidification (ramp disturbance) [27]. Disturbances affect ecosystem composition, structure, or function [28], being in some cases responsible for maintaining a high diversity [29]. Disturbances are integrated into the dynamics of ecosystems to the point that some species need disturbances to complete their life cycle [30].

Ecosystems are in a dynamic equilibrium. They are intimately linked to the natural disturbance regime they suffer from but have an effective capacity of recovery (resilience). Nevertheless, changes in environmental conditions and disturbance regimes can greatly affect the resilience of ecosystems [3]. Climate change is expected to intensify disturbances [5] and modify their disturbance regime [2], which can have ecological effects in the long-term [31].

Among disturbances, extreme events may be particularly important in disrupting the equilibrium between species traits and disturbance characteristics, which provide ecosystem resilience. For example, in the case of fire, increasing its frequency or size can reduce tree recruitment or exceed seed dispersal distance, both tampering with tree regeneration [3]. In coral reefs, heatwaves cause bleaching. Climate change is increasing the frequency of heatwaves, leaving a narrow time span for recovery from bleaching events, promoting the collapse of coral [32]. Contrastingly, the occurrence of cyclones is expected the be more temporally clustered due to climate change leaving a relatively long period of quiescence. This temporal clustering is expected to be less deleterious than if these cyclones occurred randomly, enabling coral more time to recover [33].

Disturbances, when they become strong enough such as in extreme events, can notably reduce the abundance of species, releasing niches to be colonized by invasive species. For example, in semi-arid ecosystems, extreme events can favour the invasiveness of exotic species [34]. Disturbances, if they have enough intensity, can surpass the resistance threshold of a community, especially if extreme events co-occur with other disturbances. Above this threshold, legacy (long-lasting) effects can occur, limiting recovery to previous community status [24]. These legacy effects can also promote the invasiveness of exotic species [23].

These are just some examples of the paramount relevance of extreme events on ecosystems. Studying these types of disturbances should be a priority to propose guidelines that will help to design adaptation and mitigation measures against them. The long tradition of experiments studying disturbances can be a good starting point, but the methods should be adapted to the forecasted changes in the disturbance regime due to climate change.

3. Studying Extreme Events

Intensity and frequency are two of the main components that characterize, not only extreme events, but disturbances in general. These two parameters have been generally used as predictor variables in studies aiming to test the effects of disturbances [35]. Regularly, their effects have been tested alone (e.g., [36]) or in combination, using fully factorial designs tested through analysis of variance (ANOVA) or similar discrete-type statistical analyses (e.g., [37]) (Figure 1A). This approach, despite giving useful insights about the ecological effects of disturbances, can have several limitations when the focus is on extreme events.

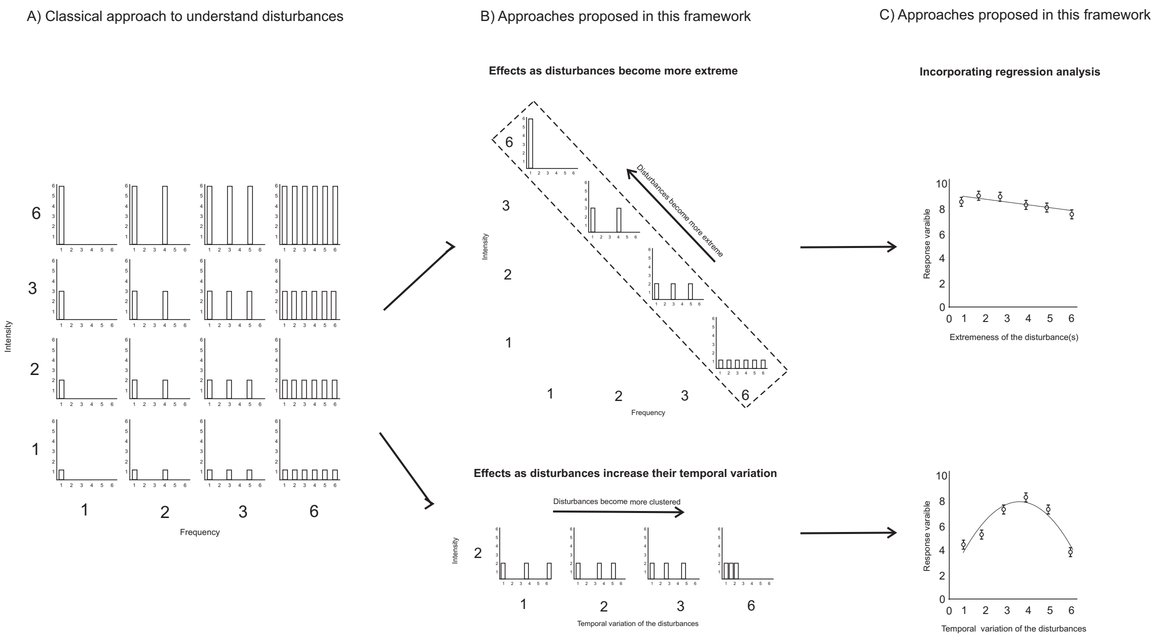


Figure 1. (**A**) Example of a classical fully factorial design to study the effect of disturbances. (**B**) The experimental approaches proposed to study the ecological effects as disturbances become more extreme or increase their temporal variance. (**C**) The experimental approaches are analysed through regressions. Curves exemplify the best-fit regression model. The intensity and temporal scales are specific of the disturbance, ecosystem, and geographical area of study.

The first limitation is related to the discrete nature of the ANOVA, which hinders its utility to analyse extreme events. ANOVA designs test for differences among discrete levels of the predictor variable of interest. Consequently, a preselection of the levels of this variable is needed. The relatively low number of extreme event experiments performed prevents us from knowing if there are specific levels that are more important to study than others [10]. More importantly, the discrete nature of the ANOVA does not allow us to analyse the tendency of relevant ecological parameters of a given community along disturbance gradients. This fact precludes answering key questions about extreme events, such as "how a community assembly is affected as a disturbance becomes more extreme?", "is the effect on the assembly proportional to the degree of extremeness?", or "is there a threshold above which catastrophic consequences are expected on the assembly?"

Regressions are suitable to detect possible thresholds or abrupt changes that could indicate a regime shift in the ecosystems [38,39]. This is especially relevant in the case of extreme events that, due to their catastrophic nature, have the potential to shift communities' alternative stable states more easily than other disturbances [40,41]. Furthermore, the output provided by regression is more suitable to be incorporated in models related to the ecological effects of extreme events, which would be the next step in advancing our understanding of this issue once there is enough experimental information [42]. Despite the recommendation of designing experiments using regression type analyses (predictor variables with continuous scales) [10,18,43], most studies continue using ANOVA designs (but see e.g., [44]).

The second limitation is derived from the ANOVA approach. It relates to the usage of a full factorial experimental design due to the manipulation of several levels of intensity and frequency. From an ANOVA analyses perspective, it is desirable to have all the levels of a predictor variable included in all levels of the other predictor variable, so then not only the main effects but also the interactions between the two predictor variables can be tested. Despite the statistical logic, this experimental design leads to multiple overall intensities among the different levels of the predictor variable which can bias our results preventing comparison among levels.

This bias arises from the fact that when using frequency, the occurrence and the overall intensity of the disturbance are varied jointly [45]. Community assemblies with more frequent disturbances are expected to suffer more negative effects not only due to higher frequency but also due to higher overall intensity when disturbances have the same intensity. Therefore, a community assembly undergoing three disturbances will suffer an overall intensity three times larger than a treatment undergoing just one disturbance.

4. A Framework to Advance in Extreme Event Experiments

4.1. Experimental Approaches

To study extreme events and overcome the aforementioned issues, two different approaches that assess two expected changes in the regime of disturbances due to climate change were utilized (Figure 2). The expected changes examined disturbances becoming either more clustered or more extreme. In the first case, the temporal variation of the occurrence of events can be changed from constant to increasingly clustered events. Using temporal variation as a predictor variable instead of frequency lets us separate occurrence from overall intensity, avoiding confounding effects [45]. In this way, the hypothesis of how disturbances can affect ecosystems as they become more clustered events due to climate change (e.g., [33]) compared to disturbances that have a more homogeneous occurrence can be tested (Figure 1B). Adding intensity as another predictor variable to the experimental design can help us to predict possible synergistic or antagonistic effects of temporal variation with intensity [45]. Nevertheless, it should be kept in mind that the overall intensity would vary within each level of intensity, and a regression for each level of intensity would be desired [39].

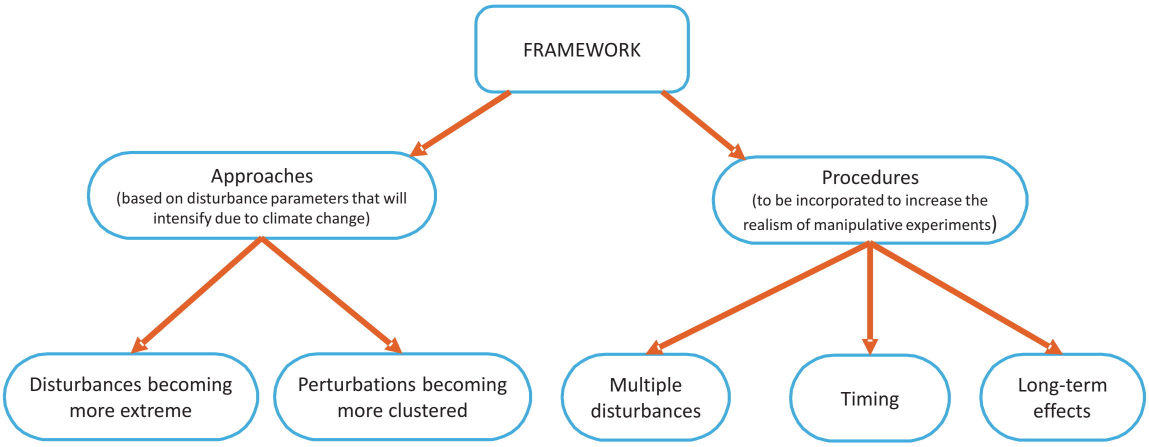


Figure 2. Flow chart explaining the structure of the framework proposed in the present work to advance in the understanding of the ecological effects of extreme climate events.

If the aim of the present study is to test the effects of disturbances as they become more extreme, then a different approach is necessary. In this case, an extreme event needs to be compared against several mild disturbances. To avoid confounding effects, the overall intensity needs to be kept constant. This can be achieved by creating levels of the descriptor variable (extremeness) of a disturbance with inverse intensities and frequencies. This approach allows us to analyse the response of the community towards a disturbance that becomes more extreme (Figure 1B). Seldom frequency and intensity have been manipulated inversely to investigate the effects of extreme events (but see [46]), and to the best of my knowledge, only once it has been performed following a regression type analyses [47].

The aforementioned approaches of this proposed framework can be obtained by creating a gradient of disturbances. In the first approach, the gradient will include different levels of temporal variation. Each level will have the same number disturbances that will be differently distributed along time, from a regular basis to an increasing temporal heterogeneity (clustering) (sensu [45]). In the second approach, the gradient will include disturbances becoming more extreme by inversely manipulating intensity and frequency resulting in different levels of extremeness of the disturbance [47] (Figure 1C).

In both cases, the levels of the corresponding predictor variable (extremeness or temporal variation of the disturbance) should be adaptive to the studied extreme event using realistic intensities and temporal scales. For example, when studying the effects of prolonged low tides as they become more extreme, the maximum recorded duration of a prolonged low tide is approximately six days in the Mediterranean [48]. Thus, the highest level of extremeness should be a prolonged low tide with an intensity of no more than six days. Accordingly, the rest of the treatments should be created by reducing the intensity and augmenting the frequency inversely. The resulting categories of prolonged low tides becoming more extreme will embrace the situations expected to occur in nature and constitute the levels of the continuous predictor variable from which the regression is created. If the same methodology is followed for another disturbance in another ecosystem, the categories defined will also include the different possibilities that are expected to occur in nature. The results are comparable among both types of disturbances and ecosystems, despite the different intensities and temporal scales (Figure 1C).

The statistical analyses that can be done for both approaches are identical. The trends of the response variable as the disturbance increases its temporal variation or becomes more extreme can be tested through regression analysis. If an unmanipulated treatment is added to the experimental design, it cannot be introduced in the regression analyses but can be used to test through a priori contrasts if the other levels (manipulated treatments) significantly differ from the undisturbed conditions with respect to the response variable of study.

4.2. Procedures

These approaches are complemented with a series of procedures to integrate different relevant parameters (Figure 2). Next, these procedures are introduced and classified in general groups. The examples given on each group are just some examples of the vast number of possibilities. One of the advantages of this framework is that each of the following procedures can be combined to increase the realism of the experiments according to the aim and resources of each study.

4.2.1. Multiple Disturbances

Currently, many ecosystems are affected by several anthropogenic drivers of environmental change [19], which results in multiple disturbances that are increasing species extinction rates exceptionally [49]. Biodiversity supports key ecosystem functions such as ecosystem stability and resilience against disturbances [50]. Specifically, biodiversity can stabilize productivity and other related ecosystem services by increasing resistance to extreme events [51]. Thus, biodiversity impoverished ecosystems are expected to be less stable against extreme events [52].

Floods in estuaries or volcanic eruptions liberate ecological niches that promote the spread of invasive species leaving communities permanently altered [53]. In forests affected by drought, temperature rise can enhance disturbances associated with fire or pathogen insects [54]. The ecosystems that are suffering from press or ramp disturbances due to global change (temperature rise, acidification, and eutrophication among others) are more likely to collapse or experience a regime shift under the occurrence of an extreme event [38]. In Australia, the co-occurrence of extreme events with press disturbances derived from climate-change drivers of environmental change, including a temperature rise, has produced profound changes in several ecosystems such as a kelp forest shifting into an urchin barren after a heatwave, or extensive mangrove dieback due to drought events [55].

In some cases, the effects can be hard to predict, and the potential for more deleterious consequences may depend on the existence of interactions among disturbances even if some of these disturbances do not become more intense. For example, variations in the fire regime due to climate change during the wet season do not diminish the resistance of forests against subsequent hurricanes. But if the variation of the fire regime takes place during the dry season, it can decrease the natural resistance to wind disturbances, even if storms do not become more intense [20]. The already reported deleterious effects of extreme events when co-occurring with other disturbances and the difficulty in predicting these exact effects suggests that extreme event studies should embrace scenarios with multiple disturbances.

To date, few studies have performed manipulative experiments integrating extreme events with other disturbances (but see [22]). While simulating pulse disturbances can be relatively easy, when aiming to simulate a press or ramp disturbance in a field experiment, the scale at which the desired variable needs to be manipulated could be intractable. This could be the case when trying to simulate the consequences of long-term drought or the future acidification of the ocean in situ. In these cases, mensurative experiments (e.g., [56]) can be a good compromise between losing replicability and being able to do a field manipulative experiment. Another option is to simulate the forecasted consequences of the anthropogenic driver of environmental change. For example, the reduction of the abundance of species that are more prone to suffer the effects of the disturbance based on previous studies can be simulated. Moreover, micro- and mesocosms could also be a good choice depending on the aim of the study or could complement field experiments.

No matter how the experiment is carried out, regression type analyses should still be preferred [42]. The continuous predictor variable will be the extremeness or temporal variation of the disturbance and the categorical predictor factor will be the disturbance derived from the anthropogenic driver of environmental change. There is a general feeling among the scientific community that gradient approaches are less suited to study interactions of two or more predictor variables and the effects of increased extremeness compared to ANOVA-like approaches [57]. Despite this, in regressions, the interactions among predictor variables can be tested through ANCOVA. Therefore, not only the trend of the effects on ecosystems as the disturbance increases its temporal variation or becomes more extreme can be modelled but also it can be compared if the trend varies similarly in the presence or absence of another disturbance. ANCOVA can integrate more disturbances by including more predictor variables, and the corresponding interactions can be tested (Figure 3A).

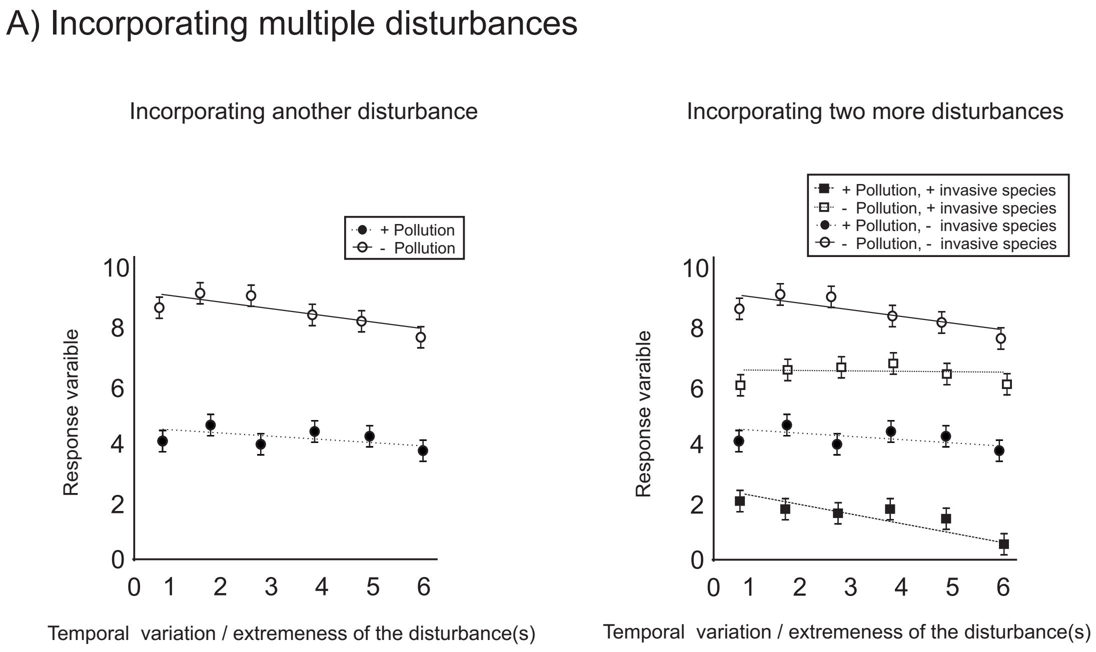
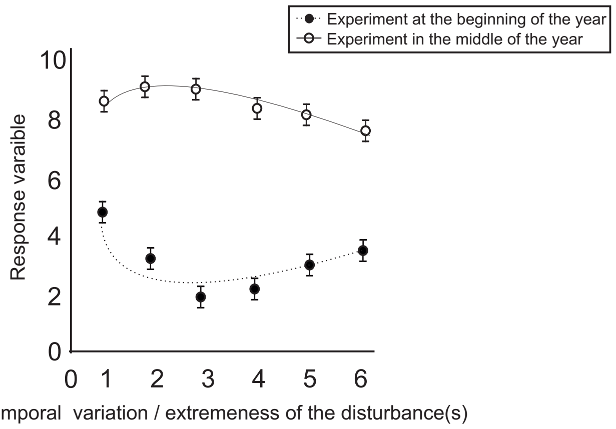


Figure 3. *Cont.*

B) Incorporating timing



C) Incorporating long-term effects

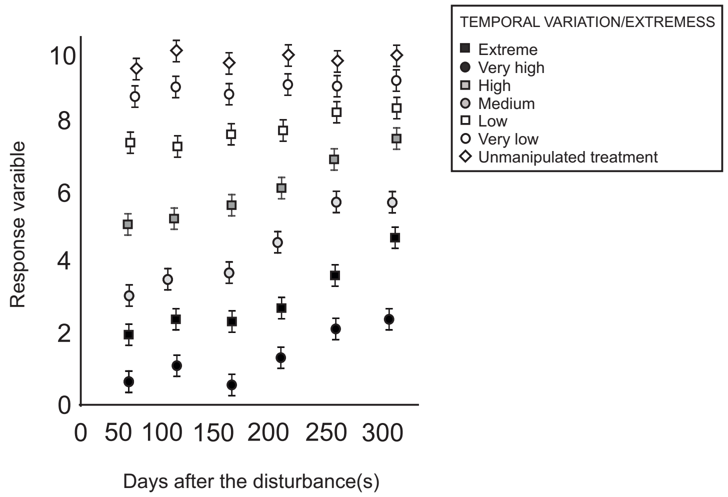


Figure 3. Procedures proposed to increase the realism of extreme event experiments. (**A**) When incorporating other disturbances, they are incorporated as categorical predictor variables. (**B**) When the experiment is performed at different periods of time, each run of the experiment is incorporated as a level of the categorical predictor variable *timing*. (**C**) When the aim is to assess long-term effects, the continuous predictor variable will be the time after the experimental disturbances have been performed, and the levels will include all the planned samplings after performing the disturbances. Curves exemplify the best-fit regression model. In C, regressions are not shown to facilitate visualization. The intensity and temporal scales are specific of the disturbance, ecosystem, and geographical area of study.

Moreover, the differences between predictor variables at the intercept with the y-axis, i.e., when the continuous predictor variable has a value of 0, can be statistically compared. This comparison can be performed at another point of interest on the gradient. For example, when the disturbance shows the highest temporal variation or becomes extreme, it can be set as the intercept in the regression model (e.g., [58]). Thus, the basal level and the level of the categorical predictor variable with regard to the response variable of the study at a given level of the continuous predictor variable (extremeness or temporal variation of the disturbance) can be tested for significant differences. For example, we could compare if a response variable significantly changed due to eutrophication when a disturbance becomes more extreme or at the highest level of the temporal variation of the disturbance.

4.2.2. Timing

Climate change can also modify the timing of the occurrence of the disturbance. This aspect is not generally taken into account despite the fact that it can have relevant consequences. Seasonal variation of environment can greatly modulate the effect of extreme events on the ecosystems. For example, heatwaves and droughts can greatly affect terrestrial plant communities during summer when water deficits are profound. Autumn can also affect its recovery when the growing season is finishing [22]. Extreme events can have acute effects on bird populations if occurring during the breeding season [59]. The effects of extreme events on ecosystems with marked changes in their assemblies during the year, such as the rocky shore community, can result in different community responses depending on the timing [47]. The timing of the occurrence of the extreme event, along with other disturbances, can lead to a series of positive and negative feedbacks that can have immediate and long-term consequences. These consequences are difficult to predict, yet crucial to understanding the ecological effects of extreme events [21]. Thus, it is also important that experiments incorporate these possibilities.

This aspect can be incorporated by repeating the experiment to take into account periods of time that are relevant to the studied ecosystem, including recruitment, and reproductive or dormancy periods of relevant species. Therefore, periods can be compared to account for possible effects of extreme events depending on the timing; previous knowledge of the system is important to specifically adapt the scale and sampling periods. In order to do this, contrasting relevant periods must be integrated. Still, if this previous knowledge is lacking, the repetition of the experiment at different periods of time is recommended. By doing so, a temporal replication to the study is provided, which allows us check if the results obtained indicate that the pattern is repeated in time and is likely to be extrapolated to other time periods or if the responses can vary depending on the period (Figure 3B).

Important issues associated with timing also arise when more than one disturbance is included. Whether the two extreme events occur at the same time or in a different order is an important aspect that needs to be tested because the outcomes can differ. For example, a summer drought can have more deleterious effects if the previous spring was unusually warm [21].

4.2.3. Long-Term Effects

Extreme events can produce long-term consequences on ecosystems [31]. Since their successional trajectory depends on their past suffered disturbances, the alteration of the disturbance regimes can affect their recovery [3]. The modification of the disturbance regime due to climate change can lead to contrasting ecological effects depending on the parameter of interest. An extreme event can bring the community to an earlier successional stage than several mild disturbances [47], while the clustering of disturbances due to climate change can help ecosystems to reach more mature successional stages [33]. The invasibility of exotic species can be favoured by changes in the interactions among disturbances [60] and by extreme events [23], which in turn, may affect its resilience [34]. Thus, studying the recovery of ecosystems from extreme events can help us to increase the knowledge not only on the duration and patterns of recovery but also on possible legacy effects that otherwise could not be noticed.

Long-term effects can be studied by monitoring the response variables of interest after conducting the simulations of the changing disturbance regimes with the proposed approaches. In this case, regression analyses should include time as a continuous predictor variable. The continuous predictor variable will include all the sampling times after the performing of the disturbances. The duration of the monitoring and the sampling times within the monitoring would depend on the temporal dynamics of the studied community.

The extremeness or temporal variation of the disturbance will now become a categorical predictor variable. Therefore, replicated regression designs [42], i.e., designs that create a gradient through several replicated levels of the predictor variable, allow us to easily transform the previous continuous variable into a categorical one. Each level will be added in the regression model, so change along time after the occurrence of the disturbance of the given response variable will be specifically estimated for each level of the predictor variable. The unmanipulated treatment will also be included as another level of the categorical predictor variable and taken as reference, setting it up as the baseline of the regression model. Through ANCOVA the trend of the unmanipulated treatment will be pairwise compared with the other levels of the categorical variable, facilitating the assessment of recovery and legacy effects (Figure 3C).

4.2.4. Combining Several Procedures

The ability to gain insight into the ecological effects of extreme events lies on the capacity of researchers to create innovative and realistic scenarios. The aforementioned groups of procedures can be, in many cases, interconnected and combined to meet the needs mentioned above. This will allow us to achieve the maximum realism possible and take into account direct and indirect as well as immediate and long-term effects of extreme events. The framework proposed is designed in a "brick by brick" basis, where different combinations of the proposed procedures can be specifically included together in extreme events experiments.

The statistical analyses are no more complicated than adding new predictor variables to the regression model. Although the interpretation and plotting can be more complicated in terms of time dedicated to understanding all the interactions and time organizing the data in the simplest manner, the rationale of the analysis remains unchanged.

5. A Pledge to do More Integrative Approaches Considering both Marine and Terrestrial Realms

On many occasions, terrestrial and marine ecologists use distinct approaches in ecological studies and do not collaborate with one another. Global issues such as extreme events need the collaboration of ecologists of both realms. Sharing different points of view facing ecological questions as well as using and adapting different tools and metrics would create a rich interdisciplinary forum that would boost scientific advances. The framework proposed is to allow comparisons among different disturbances in same or different ecosystems because they use gradients with comparable scales irrespective of the type of disturbance or ecosystem. This fact can enhance further collaboration among ecologists from both realms.

If extreme events are a suitable area of research to enhance collaboration among ecologists from both realms, rocky shores, where land and sea meet, can be the ideal starting point. Marine ecosystems, and specifically rocky shores, have widely contributed to the advancement of Ecology (e.g., [35,61–63]) and have a great potential to do so in extreme events [45,47]. Nevertheless, key review papers giving recommendations on improving manipulative experiments for extreme events focus on the terrestrial realm (e.g., [4,10,18]). Sharing and incorporating advances from marine ecologists will provide a broader pool of ideas and experimental approaches that would enrich the development of these types of experiments, in both marine and terrestrial ecosystems.

6. Rocky Shores as A Case Study

Rocky shores possess key characteristics that made them ideal candidates to study extreme events. The changing environmental conditions of rocky shores made them one of the most variable and stressed ecosystems in the world. Consequently, the life cycle of the inhabiting species and the successional cycle of the community assemblies are notably fast compared to other marine or terrestrial systems. Despite, the highly variable environmental conditions, rocky shores communities have a remarkable diversity and variety of species, exhibiting different opportunist-competitive strategies. In addition, this ecosystem has other key characteristics, including the easy manipulation of the community assembly and accessibility [64].

Rocky shores are vulnerable not only to several extreme events, such as heavy storms, heatwaves, and prolonged low tides [47,48,65], but also to other multiple disturbances not necessarily related to climate change. Habitat modification, ocean acidification, invasion of exotic species, and eutrophication are just some examples [66]. All the noted characteristics of rocky shores make them a suitable candidate to be used from a case study perspective to help develop hypotheses and theories that could be tested in other ecosystems. Next, some examples of the possible experiments that can be designed with the proposed framework in rocky shores are given.

6.1. Experimental Approaches Adapted to Rocky Shores

To implement the proposed framework, first, a disturbance that is relevant for the ecosystem and area of study needs to be selected. Storms could be used as disturbance to study since they greatly modulate rocky shore ecosystems. Rocky shore communities have a strong competence for space, and heavy storms break up rocks, creating new substratum for colonization [45]. Prolonged desiccation events are another likely type of disturbance to change its disturbance regime and notably affect rocky shore communities by producing large mortalities [48]. Either of these disturbances could be selected to perform an extreme event study following the present framework.

Then, the explained approaches can be created through a gradient of disturbances becoming either more extreme or more clustered as explained in Section 4.1 (Figure 1). Either type of disturbance should be simulated within realistic scales of intensity and time according to their geographical area. For example, if aiming to perform this experiment in the Mediterranean, the occurrence of a heavy storm could be every six months to a year [17], while the duration of a prolonged desiccation event is expected to last less than a week [48].

Once the two approaches simulating the two types of disturbances are set up, it can be tested whether the effect of an extreme event is more accused than several mild disturbances. Additionally, it could be tested if the clustering of disturbances affects the ecosystem differently than if disturbances occurred at regularly in time. Moreover, the ecological effects of the disturbance alteration regime due to climate change for each type of disturbance can be compared separately.

6.2. Procedures Adapted to Rocky Shores

6.2.1. Multiple Disturbances

Other anthropogenic drivers of environmental change are a press or ramp-type disturbance, such as eutrophication; ocean acidification; temperature rise; and species invasions and can be included to increase realism. To simulate these types of disturbances, the scale of the desired variable in a field experiment must be manipulated but could be intractable. For example, in the case of eutrophication, even local and relatively short time fertilization can be achieved in situ. Simulating scenarios with sufficient duration to have a real change in the community assemblies may be challenging, even in mesocosms [67]. This is also true if the aim is to keep in situ water at a certain higher temperature than ambient.

Mensurative experiments (e.g., [57]) can be a good option to overcome this drawback. Despite losing replicability, mensurative experiments allow us to perform a field manipulative experiment in an area that is truly affected by a disturbance, avoiding any possible artefacts derived from simulations. For example, in the case of eutrophication, an experiment either simulating storms or prolonged desiccation events could be conducted in two locations, one “naturally” affected and another one not affected by eutrophication. The locations should be in close vicinity so environmental conditions are as comparable as possible, but without affection due to eutrophication.

In the case of a temperature rise or ocean acidification, working in areas such as volcanic carbon dioxide vents may not always be feasible. In this case, the forecasted consequences of the disturbances on the ecosystems could be performed, for example by manipulatively diminishing the abundance of species that are expected to be more affected by the disturbance. Micro- and mesocosms could be previously performed as complementary experiments to define the most sensitive species to a given disturbance.

Invasive species are another relevant and widely occurring anthropogenic driver of environmental change in coastal areas [68]. By performing the experiment in an area with an invasive (preferably sessile) species, its abundance can be manipulated having a treatment where the abundance is removed and another treatment where no removal is performed and acts as a control. Invasive algae could be suitable candidates since they are common invasive species in rocky shores and produce severe environmentally deleterious effects [69].

Depending on the simulated disturbance, the experiment would have a different specific set-up but the modification of the experimental design would be comparable irrespective of the disturbance used: a categorical predictor variable would be added to the regression model. The complexity of the experiment can be increased through the incorporation of more types of disturbances. By adding more predictor variables, the corresponding interactions can be tested (Figure 3A).

6.2.2. Timing

Following the rationale of the proposed framework, timing should also be incorporated in extreme event studies. Rocky shore communities are very dynamic with species assemblies markedly changing along seasons with contrasting recruiting times among species [70]. In the case of storms, since they can occur throughout the whole year, the replication of the experiment during at least two different periods of the year is desirable. In this procedure, timing will be added as the categorical predictor variable to the regression model (Figure 3B). In the case of prolonged desiccation events in the Mediterranean, examining their effects due the temporal variation may not be of sufficient interest since they mainly occur during winter months.

6.2.3. Long-term Effects

To go one step further, the long-term effects of extreme events could be studied. Since rocky shores are highly dynamic systems, recoveries are expected to occur relatively fast, within months or few years [71,72]. Therefore, the temporal scale to monitor in rocky shores should be adapted to this temporal scale, and several samplings should be done within the year to embrace seasonal variation of this ecosystem. As commented above, the continuous predictor variable will be the time that will include all the planned samplings after performing the disturbances. Through ANCOVA, the trend of the unmanipulated treatment will be pairwise compared with the other levels of the current categorical variable (extremeness or temporal variation of the disturbance), facilitating the assessment of recovery and legacy effects (Figure 3C).

6.2.4. Incorporating Complexity and Adapting this Framework to Specific Extreme Events and Ecosystems

These are just some examples of the implementation of the proposed framework in rocky shore communities. The level of complexity could be increased in different ways. For example, integrating both types of disturbances (storms and prolonged low tides) in the same experiment. Furthermore, the timing of occurrence of both disturbances could be tested by creating scenarios where disturbances are simulated in a different order.

7. Discussion

The aim of the commented case study is to show the versatility of this framework, offering a wide variety of experimental configurations, and highlight that each experiment needs to be specifically designed to the type of disturbance, ecosystem, and geographical area. This framework is not constrained by the suggested procedures. The proposed procedures should be adapted to the research question, and others can be developed, if needed. Similar experiments could be applied to other ecosystems with their specific extreme events, taking into account their corresponding spatial and temporal scales.

The proposed framework has a high potential to help us to gain knowledge of the ecological effects of extreme events. Nevertheless, it has to bear in mind that the realistic comparability among ecosystems and extreme events is always dependent on the availability of reliable climatic data(e.g., [73]). Using recurrence time or intensities of disturbances that are not likely to occur in the next decades due to climate change is not useful to forecast the ecological effects of extreme events due to climate change, and may lead to misleading conclusions or comparisons [74]. Thus, the comparability among ecosystems or extreme events may be limited by the available information on key parameters that need to be known to incorporate in the manipulative experiments.

Additionally, the proposed framework will help us to gain knowledge on two key parameters of disturbances that are going to be influenced by climate change: disturbances becoming more severe and disturbances becoming more clustered. However, other frameworks are needed to expand the knowledge on the ecological effects of extreme events. For example, the effects of biodiversity on ecosystem functioning is a fundamental topic of research due to the current alarming rates of biodiversity loss. Biodiversity and ecosystem functioning experiments can have already complex designs [75], and implementing this framework could excessively increase the level of complexity. In this case, other approaches have focused on simulating the occurrence of extreme events separately, such as in the EVENT experiment [4], or have analysed the climatic conditions of numerous biodiversity and ecosystem functioning experiments [51]. These types of work provide valuable information to understand the ecological effects of extreme events.

The proposed framework is another complementary tool to study the ecological effects of extreme events. However, there is still room for improving. Expectably, this framework, along with the previous ones, will foster the development of new ones that will allow us to keep on advancing in this topic of research.

8. Conclusions

The proposed framework is comprised of two experimental approaches specifically designed to test changes on the disturbance regime due to climate change. These approaches separately test the effects of disturbances becoming more clustered and more extreme, using descriptor variables that are common regardless of the type of disturbance and ecosystem. The presented procedures complement these approaches increasing the realism of experiments in key aspects of the ecological effects of extreme events. The proposed framework favours comparability among studies and increases the understanding of extreme events, facilitating the scientific advance on this topic. Far from being perfect, the purpose of this framework is to act as a starting point that triggers the comparability and refinement of this type of experiments needed to advance the understanding of the ecological effects of extreme events.

The versatility of this framework is expected to promote the advancement of knowledge surrounding the ecological effects of extreme events, as well as, the collaboration among ecologists studying different ecosystems. This type of frameworks is needed to produce more cohesive studies seeking to promote comparison, synthesize knowledge, facilitate meta-analyses, and finally build up ecological models with forecasting capacity. The derived results will be relevant to inform and help environmental managers and policymakers in the elaboration of adaptive measures to coming extreme events.

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References

1. United Nations. *The Sustainable Development Goals Report*; United Nations Publication: New York, NY, USA, 2017. [CrossRef]
2. IPCC. *Climate Change 2014: Synthesis Report*; IPCC: Geneva, Switzerland, 2014. [CrossRef]
3. Johnstone, J.F.; Allen, C.D.; Franklin, J.F.; Frelich, L.E.; Harvey, B.J.; Higuera, P.E.; Mack, M.C.; Meentemeyer, R.K.; Metz, M.R.; Perry, G.L.; et al. Changing disturbance regimes, ecological memory, and forest resilience. *Front. Ecol. Environ.* **2016**, *14*, 369–378. [CrossRef]
4. Jentsch, A.; Kreyling, J.; Beierkuhnlein, C. A new generation of climate change experiments: Events, not trends. *Front. Ecol. Environ.* **2007**, *5*, 365–374. [CrossRef]
5. Easterling, D.R.; Meehl, G.A.; Parmesan, C.; Changnon, S.A.; Karl, T.R.; Mearns, L.O. Climate extremes: Observations, modeling, and impacts. *Science* **2000**, *289*, 2068–2074. [CrossRef] [PubMed]
6. Trapp, R.J.; Diffenbaugh, N.S.; Brooks, H.E.; Baldwin, M.E.; Robinson, E.D.; Pal, J.S. Changes in severe thunderstorm environment frequency during the 21st century caused by anthropogenically enhanced global radiative forcing. *Proc. Natl. Acad. Sci. USA* **2007**, *104*, 19719–19723. [CrossRef]
7. Stephenson, D. Definition, diagnosis and origin of extreme weather and climate events. *Clim. Extrem. Soc.* **2011**, 11–24. [CrossRef]
8. Wernberg, T.; Smale, D.A.; Tuya, F.; Thomsen, M.S.; Langlois, T.J.; De Bettignies, T.; Bennett, S.; Rousseaux, C.S. An extreme climatic event alters marine ecosystem structure in a global biodiversity hotspot. *Nat. Clim. Chang.* **2013**. [CrossRef]
9. Ummenhofer, C.C.; Meehl, G.A. Extreme weather and climate events with ecological relevance: A review. *Philos. Trans. R. Soc. B Biol. Sci.* **2017**, *372*. [CrossRef]
10. Smith, M.D. An ecological perspective on extreme climatic events: A synthetic definition and framework to guide future research. *J. Ecol.* **2011**, *99*, 656–663. [CrossRef]
11. Editorial. Cause and effect. *Nat. Methods* **2010**, *7*, 243. [CrossRef]
12. Altwegg, R.; Visser, V.; Bailey, L.D.; Erni, B. Learning from single extreme events. *Philos. Trans. R. Soc. B Biol. Sci.* **2017**. [CrossRef]
13. Schutt, R.K.; Chambliss, D.F. *Causation and Experimental Design. Making Sense of the Social World: Methods of Investigation*, 3rd ed.; Sage Publications: Thousnad Oaks, CA, USA, 2011; pp. 106–135. [CrossRef]
14. Van de Pol, M.; Jenouvrier, S.; Visser, M.E. Behavioural, ecological and evolutionary responses to extreme climatic events: Challenges and directions. *Philos. Trans. R. Soc. B Biol. Sci.* **2017**, *372*, 20160372. [CrossRef] [PubMed]
15. Kreyling, J.; Beier, C. Complexity in Climate Change Manipulation Experiments. *Bioscience* **2014**. [CrossRef]
16. Garrabou, J.; Ballesteros, E.; Zabala, M. Structure and dynamics of north-western Mediterranean rocky benthic communities along a depth gradient. *Estuar. Coast. Shelf. Sci.* **2002**. [CrossRef]
17. Camuffo, D.; Secco, C.; Brimblecombe, P.; Martin-Vide, J. Sea storms in the Adriatic Sea and the Western Mediterranean during the last millennium. *Clim. Chang.* **2000**, *46*, 209–223. [CrossRef]
18. Kayler, Z.E.; De Boeck, H.J.; Fatichi, S.; Grünzweig, J.M.; Merbold, L.; Beier, C.; McDowell, N.; Dukes, J.S. Experiments to confront the environmental extremes of climate change. *Front. Ecol. Environ.* **2015**, *13*, 219–225. [CrossRef]
19. Halpern, B.S.; Walbridge, S.; Selkoe, K.A.; Kappel, C.V.; Micheli, F.; D'agrosa, C.; Bruno, J.F.; Casey, K.S.; Ebert, C.; Fox, H.E.; et al. A global map of human impact on marine ecosystems. *Science* **2008**. [CrossRef]
20. Buma, B. Disturbance interactions: Characterization, prediction, and the potential for cascading effects. *Ecosphere* **2015**, *6*, 1–15. [CrossRef]
21. Sippel, S.; Zscheischler, J.; Reichstein, M. Ecosystem impacts of climate extremes crucially depend on the timing. *Proc. Natl. Acad. Sci. USA* **2016**, *113*, 5768–5770. [CrossRef]
22. De Boeck, H.J.; Dreesen, F.E.; Janssens, I.A.; Nijs, I. Whole-system responses of experimental plant communities to climate extremes imposed in different seasons. *New Phytol.* **2011**. [CrossRef]
23. Meisner, A.; De Deyn, G.B.; de Boer, W.; van der Putten, W.H. Soil biotic legacy effects of extreme weather events influence plant invasiveness. *Proc. Natl. Acad. Sci. USA* **2013**, *110*, 9835–9838. [CrossRef]
24. De Boeck, H.J.; Hiltbrunner, E.; Verlinden, M.; Bassin, S.; Zeiter, M. Legacy effects of climate extremes in alpine grassland. *Front. Plant Sci.* **2018**. [CrossRef] [PubMed]
25. Rykiel, E.J. Towards a definition of ecological disturbance. *Aust. J. Ecol.* **1985**. [CrossRef]

26. Smith, M.D.; Knapp, A.K.; Collins, S.L. A framework for assessing ecosystem dynamics in response to chronic resource alterations induced by global change. *Ecology* **2009**. [CrossRef] [PubMed]
27. Lake, P.S. Disturbance, patchiness, and diversity in streams. *J. N. Am Benthol. Soc.* **2000**, *19*, 573–592. [CrossRef]
28. Barnes, B.V.; Zak, D.R.; Denton, S.; Spurr, S. *Forest Ecology*; Wiley: New York, NY, USA, 1998.
29. Connell, J.H.; Slayter, R.O. Mechanisms of succession in natural communities and their role in community stability and organization. *Am. Nat.* **1977**, *111*, 1119–1144. [CrossRef]

30. Abrahamson, W.G. Species responses to fire on the Florida Lake Wales Ridge. *Am. J. Bot.* **1984**. [CrossRef]
31. Bailey, L.D.; van de Pol, M. Tackling extremes: Challenges for ecological and evolutionary research on extreme climatic events. *J. Anim. Ecol.* **2016**, *85*, 85–96. [CrossRef]
32. Hughes, T.P.; Anderson, K.D.; Connolly, S.R.; Heron, S.F.; Kerry, J.T.; Lough, J.M.; Baird, A.H.; Baum, J.K.; Berumen, M.L.; Bridge, T.C.; et al. Spatial and temporal patterns of mass bleaching of corals in the Anthropocene. *Science* **2018**. [CrossRef]
33. Mumby, P.J.; Vitolo, R.; Stephenson, D.B. Temporal clustering of tropical cyclones and its ecosystem impacts. *Proc. Natl. Acad. Sci. USA* **2011**. [CrossRef]
34. Jiménez, M.A.; Jaksic, F.M.; Armesto, J.J.; Gaxiola, A.; Meserve, P.L.; Kelt, D.A.; Gutiérrez, J.R. Extreme climatic events change the dynamics and invasibility of semi-arid annual plant communities. *Ecol. Lett.* **2011**. [CrossRef]
35. Sousa, W.P. The Role of Disturbance in Natural Communities. *Annu. Rev. Ecol. Syst.* **1984**, *15*, 353–391. [CrossRef]
36. Collins, S.L. Disturbance Frequency and Community Stability in Native Tallgrass Prairie. *Am. Nat.* **2000**. [CrossRef] [PubMed]
37. McCabe, D.J.; Gotelli, N.J. Effects of disturbance frequency, intensity, and area on assemblages of stream macroinvertebrates. *Oecologia* **2000**. [CrossRef] [PubMed]
38. Scheffer, M.; Carpenter, S.; Foley, J.A.; Folke, C.; Walker, B. Catastrophic shifts in ecosystems. *Nature* **2001**. [CrossRef]
39. Inouye, B.D. The Importance of the Variance Around the Mean Effect Size of Ecological Processes: Comment. *Ecology* **2007**. [CrossRef]
40. Paine, R.T.; Trimble, A.C. Abrupt community change on a rocky shore—Biological mechanisms contributing to the potential formation of an alternative state. *Ecol. Lett.* **2004**. [CrossRef]
41. Petraitis, P.S.; Methratta, E.T.; Rhile, E.C.; Vidargas, N.A.; Dudgeon, S.R. Experimental confirmation of multiple community states in a marine ecosystem. *Oecologia* **2009**. [CrossRef]
42. Cottingham, K.L.; Lennon, J.T.; Brown, B.L. Knowing When to Draw the Line: Designing More Informative Ecological Experiments Published by: Ecological Society of America. *Front. Ecol. Environ.* **2005**, *3*, 145–152. [CrossRef]
43. Kreyling, J.; Jentsch, A.; Beier, C. Beyond realism in climate change experiments: Gradient approaches identify thresholds and tipping points. *Ecol. Lett.* **2014**, *17*, 10–11. [CrossRef]
44. Guerrero-Meseguer, L.; Marín, A.; Sanz-Lázaro, C. Future heat waves due to climate change threaten the survival of P. oceanica seedlings. *Environ. Pollut.* **2017**, *230*, 40–45. [CrossRef]
45. Bertocci, I.; Maggi, E.; Vaselli, S.; Benedetti-Cecchi, L. Contrasting effects of mean intensity and temporal variation of disturbance on a rocky seashore. *Ecology* **2005**. [CrossRef]
46. Fay, P.A.; Carlisle, J.D.; Knapp, A.K.; Blair, J.M.; Collins, S.L. Altering rainfall timing and quantity in a mesic grassland ecosystem: Design and performance of rainfall manipulation shelters. *Ecosystems* **2000**, *3*, 308–319. [CrossRef]
47. Sanz-Lázaro, C. Climate extremes can drive biological assemblages to early successional stages compared to several mild disturbances. *Sci. Rep.* **2016**, *6*. [CrossRef] [PubMed]
48. Zamir, R.; Alpert, P.; Rilov, G. Increase in Weather Patterns Generating Extreme Desiccation Events: Implications for Mediterranean Rocky Shore Ecosystems. *Estuaries Coasts* **2018**. [CrossRef]
49. Pimm, S.L.; Russell, G.J.; Gittleman, J.L.; Brooks, T.M. The future of biodiversity. *Science* **1995**. [CrossRef] [PubMed]
50. Hooper, D.U.; Chapin, F.S., III; Ewel, J.J.; Hector, A.; Inchausti, P.; Lavorel, S.; Lawton, J.H.; Lodge, D.M.; Loreau, M.; Naeem, S.; et al. Effects of biodiversity on ecosystem functioning: A consensus of current knowledge. *Ecol. Monogr.* **2005**. [CrossRef]
51. Isbell, F.; Craven, D.; Connolly, J.; Loreau, M.; Schmid, B.; Beierkuhnlein, C.; Bezemer, T.M.; Bonin, C.; Bruelheide, H.; De Luca, E.; et al. Biodiversity increases the resistance of ecosystem productivity to climate extremes. *Nature* **2015**. [CrossRef]
52. Hautier, Y.; Tilman, D.; Isbell, F.; Seabloom, E.W.; Borer, E.T.; Reich, P.B. Anthropogenic environmental changes affect ecosystem stability via biodiversity. *Science* **2015**. [CrossRef]
53. Paine, R.T.; Tegner, M.J.; Johnson, E.A. Compounded perturbations yield ecological surprises. *Ecosystems* **1998**. [CrossRef]

54. Seidl, R.; Thom, D.; Kautz, M.; Martin-Benito, D.; Peltoniemi, M.; Vacchiano, G.; Wild, J.; Ascoli, D.; Petr, M.; Honkaniemi, J.; et al. Forest disturbances under climate change. *Nat. Clim. Chang.* **2017**, *7*, 395–402. [CrossRef]
55. Harris, R.M.B.; Beaumont, L.J.; Vance, T.R.; Tozer, C.R.; Remenyi, T.A.; Perkins-Kirkpatrick, S.E. Biological responses to the press and pulse of climate trends and extreme events. *Nat. Clim. Chang.* **2018**, *8*, 579–587. [CrossRef]
56. Hall-Spencer, J.M.; Rodolfo-Metalpa, R.; Martin, S.; Ransome, E.; Fine, M.; Turner, S.M.; Rowley, S.J.; Tedesco, D.; Buia, M.C. Volcanic carbon dioxide vents show ecosystem effects of ocean acidification. *Nature* **2008**. [CrossRef] [PubMed]
57. Beier, C.; Beierkuhnlein, C.; Wohlgemuth, T.; Penuelas, J.; Emmett, B.; Körner, C.; de Boeck, H.; Christensen, J.H.; Leuzinger, S.; Janssens, I.A.; et al. Precipitation manipulation experiments—Challenges and recommendations for the future. *Ecol. Lett.* **2012**, *15*, 899–911. [CrossRef] [PubMed]
58. Sanz-Lázaro, C.; Rindi, L.; Maggi, E.; Dal Bello, M.; Benedetti-Cecchi, L. Effects of grazer diversity on marine microphytobenthic biofilm: A "tug of war" between complementarity and competition. *Mar. Ecol. Prog. Ser.* **2015**, *540*. [CrossRef]
59. Van De Pol, M.; Ens, B.J.; Heg, D.; Brouwer, L.; Krol, J.; Maier, M.; Exo, K.M.; Oosterbeek, K.; Lok, T.; Eising, C.M.; et al. Do changes in the frequency, magnitude and timing of extreme climatic events threaten the population viability of coastal birds? *J. Appl. Ecol.* **2010**, *47*, 720–730. [CrossRef]
60. Davies, K.W.; Svejcar, T.J.; Bates, J.D. Interaction of historical and nonhistorical disturbances maintains native plant communities. *Ecol. Appl.* **2009**, *19*, 1536–1545. [CrossRef]
61. Connell, J.H. The Influence of Interspecific Competition and Other Factors on the Distribution of the Barnacle Chthamalus Stellatus. *Ecology* **1961**. [CrossRef]
62. Stachowicz, J.J.; Bruno, J.F.; Duffy, J.E. Understanding the Effects of Marine Biodiversity on Communities and Ecosystems. *Annu. Rev. Ecol. Evol. Syst.* **2007**. [CrossRef]
63. Paine, R.T. Trophic control of production in a rocky intertidal community. *Science* **2002**. [CrossRef]
64. Denny, M. Predicting physical disturbance: Mechanistic approaches to the study of survivorship on wave-swept shores. *Ecol. Monogr.* **1995**. [CrossRef]
65. Kordas, R.L.; Dudgeon, S.; Storey, S.; Harley, C.D.G. Intertidal community responses to field-based experimental warming. *Oikos* **2015**. [CrossRef]
66. Thompson, R.C.; Crowe, T.P.; Hawkins, S.J. Rocky intertidal communities: Past environmental changes, present status and predictions for the next 25 years. *Environ. Conserv.* **2002**. [CrossRef]
67. Bokn, T.L.; Duarte, C.M.; Pedersen, M.F.; Marba, N.; Moy, F.E.; Barrón, C.; Bjerkeng, B.; Borum, J.; Christie, H.; Engelbert, S.; et al. The Response of Experimental Rocky Shore Communities to Nutrient Additions. *Ecosystems* **2003**. [CrossRef]
68. Coll, M.; Piroddi, C.; Steenbeek, J.; Kaschner, K.; Lasram, F.B.; Aguzzi, J.; Ballesteros, E.; Bianchi, C.N.; Corbera, J.; Dailianis, T.; et al. The biodiversity of the Mediterranean Sea: Estimates, patterns, and threats. *PLoS ONE* **2010**. [CrossRef]
69. Zenetos, A.; Çinar, M.E.; Pancucci-Papadopoulou, M.A.; Harmelin, J.G.; Furnari, G.; Andaloro, F.; Bellou, N.; Streftaris, N.; Zibrowius, H. Annotated list of marine alien species in the Mediterranean with records of the worst invasive species. *Mediterr. Mar. Sci.* **2005**, *6*, 63–118. [CrossRef]
70. Benedetti-Cecchi, L. Predicting direct and indirect interactions during succession in a mid-littoral rocky shore assemblage. *Ecol. Monogr.* **2000**. [CrossRef]
71. Hutchinson, N.; Williams, G.A. Disturbance and subsequent recovery of mid-shore assemblages on seasonal, tropical, rocky shores. *Mar. Ecol. Prog. Ser.* **2003**. [CrossRef]
72. Kim, H.H.; Ko, Y.W.; Yang, K.M.; Sung, G.; Kim, J.H. Effects of disturbance timing on community recovery in an intertidal habitat of a Korean rocky shore. *Algae* **2017**. [CrossRef]
73. Donat, M.G.; Alexander, L.V.; Yang, H.; Durre, I.; Vose, R.; Caesar, J. Global land-based datasets for monitoring climatic extremes. *Bull. Am. Meteorol. Soc.* **2013**. [CrossRef]

74. Wolkovich, E.M.; Cook, B.I.; Allen, J.M.; Crimmins, T.M.; Betancourt, J.L.; Travers, S.E.; Pau, S.; Regetz, J.; Davies, T.J.; Kraft, N.J.B. Warming experiments underpredict plant phenological responses to climate change. *Nature* **2012**. [CrossRef]
75. Loreau, M.; Naeem, S.; Inchausti, P.; Bengtsson, J.; Grime, J.P.; Hector, A.; Hooper, D.U.; Huston, M.A.; Raffaelli, D.; Schmid, B.; et al. Ecology: Biodiversity and ecosystem functioning: Current knowledge and future challenges. *Science* **2001**. [CrossRef] [PubMed]